Valuing wastes

An Integrated System Analysis of Bioenergy, Ecological Sanitation, and Soil Fertility Management in Smallholder Farming in Karagwe, Tanzania

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make compost
not war

Abstract

My dissertation had as its starting point the intention of two Tanzanian farmer's initiatives and their German partners to disseminate sustainable cooking and sanitation technologies to smallholder households in Karagwe District, in northwest Tanzania (TZ). These locally developed and adapted technologies include improved cook stoves (ICS), such as microgasifiers, and a system combining biogas digesters and burners for cooking, as well as urine-diverting dry toilets and thermal sterilization/pasteurization for ecological sanitation (EcoSan). Currently, the most common combination of technologies used for cooking and sanitation in Karagwe smallholdings is a three-stone fire and pit latrine. Switching to the new alternatives could potentially lead to (i) optimized resource consumption, (ii) lower environmental emissions, and (iii) a higher availability of domestic residues for soil fertility management. The latter include biogas slurry from anaerobic digestion, powdery biochar from microgasifiers, and sanitized human excreta from EcoSan facilities. These residues are 'locally available resources' that can be used for on-farm material cycling. Such recycling practices address an existing problem for many smallholders in sub-Saharan Africa, namely, the lack of soil amenders to sufficiently replenish soil nutrients and soil organic matter (SOM) in soils used for agricultural activity.

Using TZ as an example and local initiatives as case studies, I have examined the triple nexus of 'energy-sanitation-agriculture'. I, therefore, designed an integrated, handy, and *a priori* systems analysis of an intersectional resource management. I jointly investigated (i) cooking and sanitation technologies that are locally available alternatives to smallholder households, and (ii) recycling-driven approaches to soil fertility management. My interdisciplinary research approach has applied a broad set of methodologies including: literature reviews, accessing practitioners' data from pilot projects, laboratory analysis, a practice-oriented short-term field experiment, material flow analyses (MFA), soil nutrient balances (SNB), and, finally, a multi-criteria analysis (MCA) as a decision support with participatory elements. Overall, this extensive and cumulative research project comprises five scientific articles.

Empirically and analytically, my results shed light on agronomic potentials for circular economies and on values of material cycling in smallholder farming systems as well as on weak points in the system, from both ecological and socio-economic perspectives. For example, I demonstrated that all the treatments analyzed could enhance crop productivity in a short-term experiment on the local Andosol. Referring to maize, so-called 'CaSa-compost', the product of co-composting biochar with sanitized human excreta, has the potential to quadruple grain yields. The observed stimulation of plant nutrition and crop yield are further attributed to improved nutrient availability caused by a direct increase of soil pH and of plant-available phosphorus (P) in the soil.

To also assess lasting soil implications, I used data generated by MFA and SNB and the ‘Soil and Water Integrated Model’ (SWIM) of the Potsdam Institute for Climate Impact Research. The SWIM-modelling revealed that CaSa-compost or biogas slurry both show the long-term potential to roughly double yields of maize grains. Corresponding nutrient requirements can, meanwhile, be adequately compensated for through residue capturing and subsistence production of soil amenders. In addition, the SNB analysis shows a clear potential of the recycling-based soil fertility management to reduce currently existing depletion rates of nitrogen (N), and to reverse the annual SNB of P, to bring about a positive outcome. Composts and biogas slurry supply sufficient P to crops, while urine effectively supplements N. By using resources recovered from microgasifiers and EcoSan, sufficient CaSa-compost for sustainable subsistence farming may be produced. Human excreta contribute especially to total N and P in CaSa-compost, whilst biochar recovered from cooking with microgasifier stoves adds to total carbon (C) and P. The fact that input substrates for biogas digesters are post-agricultural in nature means that biogas slurry is not considered an ‘untapped resource’ for soil fertility management despite its ample nutrient content. Overall, the potential of CaSa-compost for sustainable soil fertility management is superior to that of standard compost, especially with respect to liming, replenishing soil P, and restoring SOM. Biogas slurry, however, yields inferior results in all aspects when compared to compost amendments.

I further showed that cooking with either ICSs or the biogas system significantly reduces firewood requirements in smallholder households. Weak points in the biogas system, however, include increased total greenhouse gas emissions and high acquisition costs. Implementation of waterless EcoSan facilities, meanwhile, is possible with moderate initial costs, significantly promotes nutrient recovery, and reduces environmental emissions. EcoSan, therefore, constitutes a viable alternative to water-based septic systems, which, in turn, place heavy pressure on already scarce water resources. With respect to the overall environmental impact of the intersectional resource management analyzed, I have also aggregated environmental emissions of the entire smallholder farming system, including cooking, sanitation, and the agroecosystems. The integrated global warming potential (GWP) clearly increases to about 250 % of current levels when using a biogas system and biogas slurry as a soil amender. The integrated GWP remains steady, when compared to current levels, when using a microgasifier for cooking, employing EcoSan with thermal sanitation, and utilizing CaSa-compost as a soil amender. With respect to emissions with eutrophying effects, all scenarios analyzed show only about half of the integrated eutrophication potential of the current state of technology use and soil management.

To complete, I developed a decision-specific, locally adapted, and participatory assessment tool: the Multi-Criteria Technology Assessment (MCTA). Pre-testing of the MCTA with representatives of Tanzanian and German partners of case study projects served as a proof-of-concept for the general design of the method and the applicability of the tool to assess the sustainability of the small-scale cooking and sanitation technologies. Significant strength of the MCTA is that it enhances transparency about individual judgements of different stakeholders.

Ultimately, I conclude that a particularly promising way of implementing an intersectional resource management around the nexus energy-sanitation- agriculture is the combination of using microgasifiers for cooking and implementing EcoSan, in addition to the *combined* recycling of biochar and sanitized excreta. This approach can achieve multiple goals including: (i) increase access to fertilizers, (ii) decrease nutrient depletion and acidification of soils, (iii) increase food production and farm income, (iv) reduce resource consumption, and (v) reduce environmental impacts, like global warming or eutrophication. For many smallholder farmers in Sub-Saharan Africa, this practical approach thus represents a viable exit strategy from the vicious circle of soil acidity and P-scarcity leading to insufficient production of food crops, which in turn leads to insufficient production of residual matter for soil fertility management and improvement.

Furthermore, using the CaSa-compost is a particular suitable method for sustainable soil fertility management, due to the following factors: (i) applied P amendments are appropriate to replenish P in exhausted soils, (ii) estimated liming effects are suitable for mitigating existing soil acidification, (iii) C inputs contribute to restoring the SOM, and (iv) potentially also to C sequestration, while (v) the overall GWP is maintained, and the total eutrophication potential is reduced.

From a methodological perspective, I further conclude that the applied inter- and transdisciplinary approach as a combination of (i) explorative data generation, (ii) model-based system analysis, and (iii) collaboration between practitioners and researchers within the associated case studies was highly suitable to evaluate the technologies developed in Karagwe from multiple perspectives related to sustainability. Moreover, combining the MCA method for structuring the evaluation with empirical and analytical methods (such as experiments, MFA, or SNB) for describing the performance of alternatives is a promising path for designing *integrated* approaches to sustainability assessments of technologies.

Future research could include: an upscaling of my results to a community level, adjusting the MCTA-tool for future applications in smallholder communities; a study of the fate of pharmaceuticals and hormones in the agroecosystem; an exploration of appropriate application techniques, dosages, and timing for the use of biogas slurry; or long-term field experiments to examine opportunities of CaSa practice to serve for C-sequestration or as a mitigation measure to climate change.

Zusammenfassung

Ausgangspunkt meiner Dissertation war das Vorhaben zweier tansanischer Initiativen und ihrer deutschen Partner*innen, nachhaltige Koch- und Sanitärtechnologien für kleinbäuerliche Haushalte im Bezirk Karagwe im Nordwesten Tansanias zu verbreiten. Die vor Ort entwickelten und an die lokalen Bedingungen angepassten Technologien umfassen verbesserte Herde (*improved cook stoves*, ICS), wie Mikrovergaser, und ein System aus Kleinst-Biogas-Anlage und -Kocher, sowie einen Ansatz zur ökologischen Sanitärversorgung (*ecological sanitation*, EcoSan) als Kombination aus Trockentrenntoilette mit thermischer Hygienisierung der Fäkalien. Die aktuell üblichste Kombination von Koch- und Sanitär-Technologien in kleinbäuerlichen Haushalten in Karagwe ist Drei-Stein-Feuer und Gruben-Latrine. Ein Technologiewechsel hin zu den neuen Alternativen führt potenziell zu (i) einer optimierten Ressourcennutzung, (ii) niedrigeren Emissionen in die Umwelt und (iii) einer höheren Verfügbarkeit von Reststoffen in den Haushalten und auf der Farm. Zu diesen Reststoffen gehören Gärreste aus der anaerober Fermentation, pulverige Biokohle aus Mikrovergasern und pasteurisierte menschliche Fäkalien aus EcoSan-Anlagen. Diese „lokal verfügbaren Ressourcen“ können für den Aufbau einer landwirtschaftlichen Kreislaufwirtschaft genutzt werden. Durch eine solche Recycling-Praxis kann ein Problem angegangen werden, das in Afrika südlich der Sahara viele Kleinbauer*innen betrifft. Oft fehlen nämlich ausreichende Mengen an Wirtschaftsdüngern um Bodennährstoffe und organische Substanz (*soil organic matter*, SOM) in landwirtschaftlich genutzten Böden wieder aufzufüllen.

In meiner Arbeit habe ich die Verflechtung von „Energiebereitstellung - Sanitärversorgung - Landwirtschaft“ am Beispiel kleinbäuerliche Haushalte in Tansania betrachtet. Die Projekte in Karagwe dienten mir dabei als Fallstudien. Um ein Sektoren übergreifendes Ressourcenmanagement-System zu bewerten, habe ich eine integrierte und handhabbare Methode zur apriorischen Systemanalyse entwickelt. Dabei habe ich sowohl (i) lokal verfügbare Koch- und Sanitärtechnologie-Alternativen, als auch (ii) Recycling-orientierte Ansätze zum Erhalt der Bodenfruchtbarkeit untersucht. Mein interdisziplinäres Forschungskonzept beinhaltet ein breites Set an Methoden wie Literaturrecherche, Datenerhebung und -sammlung, Laboranalysen, einen praxis-orientierten Kurzzeit-Feldversuch, Materialflussanalysen (*material flow analyses*, MFA), Bodennährstoffbilanzen (*soil nutrient balances*, SNB) und eine Mehrkriterienanalyse (*multi-criteria analysis*, MCA) zur Entscheidungsunterstützung mit partizipatorischen Elementen. Insgesamt umfasst das umfangreiche und kumulative Forschungsprojekt fünf wissenschaftliche Artikel.

Meine Ergebnisse beleuchten auf empirische und analytische Weise die agronomischen Potenziale für Kreislaufwirtschaften und den Wert von Stoffkreisläufen in kleinbäuerlichen Systemen sowie Schwachstellen im System aus ökologischer und sozio-ökonomischer Perspektive.

Zum Beispiel konnte ich im Kurzzeit-Feldversuch zeigen, dass alle untersuchten Dünge-Verfahren die Pflanzenproduktivität verbessern. Bei Mais hat die Verwendung des sogenannten „CaSa-Komposts“, ein Produkt der Co-Kompostierung von Biokohle und hygienisierten menschlichen Fäkalien, das Potenzial den Kornertrag kurzfristig zu vervierfachen. Die beobachte Verbesserung der Pflanzenernährung und den Anstieg der Ernteerträge konnte ich dabei auf eine direkte Erhöhung des Boden pH-Werts und des pflanzen-verfügbaren Phosphors (P) im Boden zurückführen.

Um auch länger anhaltende Auswirkungen der untersuchten Dünge-Praxen auf den Boden beurteilen zu können, habe ich Daten aus MFA und SNB in das sogenannte „*Soil and Water Integrated Model*“ des Potsdamer Instituts für Klimafolgenforschung integriert. Die Modellierung ergab, dass langfristig sowohl CaSa-Kompost als auch Gärreste die Maiskorn-Erträge verdoppeln können. Die entstehenden Nährstoffentzüge können durch die Verwendung von Reststoffen zur Eigenproduktion von Wirtschaftsdüngern ausreichend kompensiert werden. Weiterhin zeigte die SNB-Analyse, dass durch eine Recycling-orientierte Dünge-Praxis die derzeitige, kontinuierliche Erschöpfung von Stickstoff (N) im Boden verringert werden kann, während sich die jährliche SNB für P gar zu einem positiven Bilanz-Ergebnis umkehren lässt. Komposte und Gärreste tragen dabei vor allem zur P-Versorgung der Pflanzen bei, während Urin zusätzlich N liefert. Durch die Verwertung von Reststoffen aus Mikrovergasern und aus EcoSan-Anlagen kann CaSa-Kompost in ausreichenden Mengen für eine nachhaltige Subsistenz-Landwirtschaft hergestellt werden. Menschliche Fäkalien tragen insbesondere zum Gesamtgehalt an N und P in CaSa-Kompost bei, während Biokohle, die nach dem Kochen mit Mikrovergasern zurückgewonnen werden kann, Kohlenstoff (C) und P ergänzt. Im Gegensatz dazu können Gärreste nicht als „bisher ungenutzte Ressource“ betrachtet werden, da die Substrate, die in den Biogasanlagen verwendet werden, bisher auch landwirtschaftlich genutzt wurden. Insgesamt ist zum langfristigen Erhalt der Bodenfruchtbarkeit die Verwendung von CaSa-Kompost der eines Standardkomposts überlegen insbesondere bezüglich Kalkung, der Regeneration von P-Vorräten im Boden und der Wiederherstellung von SOM. Die Düngung mit Gärresten ist dem Einsatz von Kompost unter allen berücksichtigten Aspekten unterlegen.

Weiterhin konnte ich zeigen, dass die Verwendung von ICSs oder einem Biogas-System den Verbrauch an Brennholz in kleinbäuerlichen Haushalten stark reduziert. In Bezug auf das Biogas-System stellen erhöhte Treibhausgasemissionen und hohe Anschaffungskosten jedoch identifizierte Schwachstellen dar. Derweil ist die Einführung von wasserlosen EcoSan-Anlagen zu moderaten Kosten möglich, was gleichzeitig die Nährstoffrückführung signifikant fördert und Emissionen reduziert. EcoSan stellt somit eine tragfähige Alternative zu wasserbasierten Tank-Systemen dar, die wiederum einen starken Druck auf bereits knappe Wasserressourcen ausüben. Um auch die Gesamtumweltbelastung des betrachteten Sektoren-übergreifenden Ressourcenmanagement-Ansatzes zu bestimmen, habe ich die Emissionen aus dem kleinbäuerlichen Farm-System, inklusive Koch-, Sanitär- und Agrarökosystem, aggregiert. Das integrierte Treibhauspotenzial (*global warming potential*, GWP) steigt beim Einsatz eines Biogas-Systems gekoppelt mit der Verwendung von Gärresten als Bodenverbesserer auf über 250 % des gegenwärtigen Niveaus. Werden

Mikrovergaser zum Kochen und EcoSan mit thermischer Hygienisierung eingesetzt und CaSa-Kompost zur Bodenverbesserung, bleibt das GWP im Vergleich zum gegenwärtigen Niveau konstant. Beim integrierten Eutrophierungspotenzial zeigen alle untersuchten Szenarien eine Verbesserung im Sinne einer Reduktion auf etwa die Hälfte des gegenwärtigen Niveaus.

Zum Abschluss meiner Arbeit habe ich ein auf die spezifische Entscheidungssituation und die lokalen Bedingungen angepasstes, partizipatives Bewertungs-Werkzeug namens „*Multi-Criteria Technology Assessment*“ (MCTA) entwickelt. Die generelle Wirksamkeit („*proof-of-concept*“) der entwickelten Methode sowie die Anwendbarkeit des maßgefertigten Werkzeugs zur Nachhaltigkeits-Bewertung von dezentralen Koch- und Sanitärtechnologien konnte ich bestätigen. Dazu habe ich zusammen mit Vertreter*innen der tansanischen und deutschen Projektpartner*innen der untersuchten Fallstudien eine Vorab-Funktionsprüfung der MCTA durchgeführt. Eine eindeutige Stärke des entwickelten Werkzeugs ist, dass dessen Anwendung zu mehr Transparenz über die individuellen Perspektiven und die unterschiedlichen Einschätzungen der Mitglieder verschiedener Interessensgruppen führt.

Schlussendlich ist eine Kern-Schlussfolgerung meiner Arbeit, dass besonders die Kombination aus Mikrovergaser zum Kochen und dem CaSa-Ansatz als ökologische Sanitärversorgung, gekoppelt mit der konsequenten und *gemeinsamen* Rückführung der Reststoffe, ein vielversprechendes, Sektoren-übergreifenden Ressourcenmanagement darstellt. Mit diesem Ansatz können gleichzeitig mehrere Ziele erreicht werden, nämlich: (i) Verbesserung des Zugangs zu Dünger durch Eigenproduktion, (ii) Sanierung der ausgelaugten und versauerten Böden, (iii) positiver Beitrag zur Ernährungssouveränität und Einkommensgrundlage der Kleinbauer*innen, (iv) Senkung des Ressourcenverbrauchs, und (v) Reduktion der negativen Umweltwirkungen wie Treibhausgasemissionen und Eutrophierung. Dieser praktische Ansatz ist daher eine geeignete Strategie, um einen Teufelskreis zu durchbrechen, in dem sich viele Kleinbauer*innen in Afrika südlich der Sahara befinden. Dabei führen Bodenversauerung und P-Knappheit zu einer unzureichenden Produktion von Nahrungsmitteln, und somit auch zu einer unzureichenden Produktion von pflanzlichen Reststoffen, welche wiederum zum Erhalt bzw. zur Verbesserung der Bodenfruchtbarkeit benötigt werden.

Weiterhin schlussfolgere ich, dass für ein nachhaltiges Bodenfruchtbarkeitsmanagement insbesondere die Verwendung des CaSa-Kompost geeignet ist. Dafür sprechen die folgenden, identifizierten Gründe: (i) die zugeführte P-Düngung ist ausreichend, um die P-Vorräte in den ausgelaugten Böden wieder aufzufüllen, (ii) das ermittelte Kalkungspotential ist geeignet, um die vorhandene Bodenversauerung abzuschwächen, (iii) die C-Einträge tragen sowohl zur Wiederherstellung von SOM bei, als auch (iv) möglicherweise zur langfristigen Festlegung von C im Boden, bei gleichzeitig (v) gleichbleibendem GWP und sinkendem Eutrophierungspotenzial.

Aus methodologischer Sicht schlussfolgere ich weiterhin, dass die angewandte inter- und transdisziplinäre Methode, als Kombination aus (i) explorativer Datenerhebung, (ii) rechenmodellgestützer Systemanalyse, und (iii) Zusammenarbeit von Forscher*innen und Praktiker*innen in den begleiteten Pilotprojekten, zielführend gewesen ist, um die in Karagwe entwickelten Technologien mehr-perspektivisch zu bewerten. Dabei erscheint die Kombination aus MC(D)A, als Methode zur Strukturierung der Bewertung, mit empirischen und analytischen Methoden (wie Feldversuch, MFA oder SNB) zur Beschreibung des Verhaltens und der Leistung der untersuchten Alternativen, vielversprechend um integrierte Ansätze für die Nachhaltigkeits-Bewertung von Technologien zu entwickeln.

Zukünftige Forschungsvorhaben könnten sein: meine Ergebnisse auf Gemeinschafts- oder Kommunalebene hochzuskalieren; das MCTA-Werkzeug für die Anwendung in kleinbäuerlichen Gemeinschaften und Kommunen anzupassen; Möglichkeiten des Abbaus und der Diffusion von Arzneimitteln und Hormonen im Agrarökosystem zu untersuchen; geeignete Techniken, Dosierungen und Zeitpunkte für die Düngung mit Gärresten zu erforschen; oder Langzeit-Feldversuche durchzuführen, um die Potenziale der CaSa-Praxis als mögliche Maßnahme zur C-Bindung oder zur Eindämmung des Klimawandels zu untersuchen.

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Abbreviations and acronyms

Sign	Description
AM	*Arbuscular mycorrhizal*
BiogaST	Biogas Support for Tanzania
BMEL	*Bundesministerium für Ernährung und Landwirtschaft*, or German Federal Ministry of Food and Agriculture
BNF	Biological N-fixation
BO	Biowaste Ordinance, or *Bioabfallverordnung* (BioAbfV)
BV	*Bundesverband deutscher Banken e. V.*, or Association of German Banks
CAMARTEC	Centre for Agricultural Mechanisation and Rural Technology
CaSa	Carbonization and Sanitation
CC	Creative commons license
CEC_{eff}	Effective cation exchange capacity
CHEMA	'Programme for Community Habitat Environmental Management'; name of a partner organisation
C2C	Cradle-to-Cradle
Destatis	*Statistisches Bundesamt*, or German Federal Statistical Office
DGAW	*Deutsche Gesellschaft für Abfallwirtschaft*, or German Society for Waste Management
DGE	*Deutsche Gesellschaft für Ernährung*, or German Food Association
DIN	*Deutsches Institut für Normung*, or German Institute for Standardization
DM	Dry matter
DWA	*Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.*, or German Association for Water Economy, Waste Water and Waste
Eawag	Swiss Federal Institute of Aquatic Science and Technology
E. coli	*Escherichia coli*
EcoSan	Ecological sanitation
EfCoiTa	Efficient Cooking in Tanzania
EIA	Environmental impact assessment
EP	Eutrophication potential
EUR	Euro
EWB	Engineers Without Borders
FAO	Food and Agriculture Organisation
FAOSTAT	Statistical databases of the FAO
FIAN	Food First Information and Action Network
FM	Fresh matter

Sign	Description
GFA	*Gutachterausschuss Forstliche Analytik*, or panel of experts for forestal analytics
GHG	Greenhouse gas
GIZ	*Deutsche Gesellschaft für Internationale Zusammenarbeit*, or German Corporation for International Cooperation
GMO	Genetically modified organism
GWP	Global warming potential
HBS	*Hans-Böckler Stiftung* (a foundation of the *Deutscher Gewerkschaftsbund*, or, Federation of German Trade Unions)
HH	Household
HNE	*Hochschule für nachhaltige Entwicklung*, or University for Sustainable Development
HTC	Hydro-thermal carbonisation
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
ICS	Improved cook stoves
IFAD	International Fund for Agricultural Development
IGZ	*Leibniz Institut für Gemüse- und Zierpflanzenbau*, or Leibniz Institute of Vegetable and Ornamental Crops
IPCC	Intergovernmental Panel on Climate Change
IPNM	Integrated plant nutrient management
ISO	International Organization for Standardization
ITPS	Intergovernmental Technical Panel on Soils
KPT	Kitchen performance test
KTBL	*Kuratorium für Technik und Bauwesen in der Landwirtschaft*, or Association for Technology and Structures in Agriculture
MAP	Magnesium-ammonium phosphate
MAVT	Multi-attribute value theory
MAVUNO	'Harvest' in Swahili; 'MAVUNO Project for Improvement for Community Relief and Services'; name of a partner organisation
MCA	Multi-criteria analysis
MCDA	Multi-criteria decision analysis
MCTA	Multi-criteria technology assessment
MES	Microenergy system
MFA	Material flow analysis
MFI	Micro finance institutions
MIT	Massachusetts Institute of Technology
MSW	Municipal solid waste
OMP	Organic micro pollutants
P1	First publication
P2	Second publication
P3	Third publication
P4	Fourth publication
P5	Fifth publication

Sign	Description
PIK	*Potsdam-Institut für Klimafolgenforschung*, or Potsdam Institute for Climate Impact Research
PRA	Participatory rural appraisal
PQ	Practitioners' questions
PSS	Product-service system, or producer-service system
RWSC	Revised World Soil Charter
RCP	Representative concentration pathways
RQ	Research questions
SCD	Sustainable community development
SDG	Sustainable development goal
SAW	Simple additive weighting
SEI	Stockholm Environment Institute
SIDA	Swedish International Development Cooperation Agency
SNB	Soil nutrient balances
SOC	Soil organic carbon
SOM	Soil organic matter
SSA	Sub-Saharan Africa
SSSA	Soil Science Society of America
STAN	*SubSTance flow ANalysis*, name of a software
SuSanA	Sustainable Sanitation Alliance
SWIM	Soil and Water Integrated Model
SWSR	Status of the World's Soil Resource
TDBP	Tanzanian Domestic Biogas Program
TLUD	Top-Lit UpDraft
TOC	Total organic carbon
TU	*Technische Universität*, or Technical University
TZ	Tanzania
TZS	Tanzanian Shilling
UBA	*Umweltbundesamt*, or German Environment Agency
UDDT	Urine-diverting dry toilet
UDSM	University of Dar Es Salaam
UH	Universität Hohenheim
UN	United Nations
UNEP	United Nations Environment Programme
UNU	United Nations University
USD	United States Dollar
WB	World Bank
WBT	Water boiling test
WHO	World Health Organization

Chemical elements

Sign	Description
C	Carbon
C_{tot}	Total C
Ca	Calcium
CAL	Calcium acetate lactate
CaO	Calcium oxide
$CaCO_3$	Lime
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
K	Potassium
Mg	Magnesium
Mn	Manganese
N	Nitrogen
N_{min}	Mineral N
N_{org}	Organic N
N_{tot}	Total N
N_2O	Nitrous oxide
NH_3	Ammonia
NH_4^+	Ammonium
NO_3^-	Nitrate
P	Phosphorus
P_{CAL}	CAL soluble P
P_{lab}	Labile P
P_{tot}	Total P
PO_4^{3-}	Phosphate
Zn	Zinc

Chapter 1

Introduction

Resume of the rational of the present thesis.

Smallholders[1] cultivate at least 50 % of the world's food crops (Graeub et al., 2016). Paying attention to their needs, and managing soils appropriately, are, therefore, preconditions for long-term global food production. Essential human needs and rights include, among others, access to food, water, energy, and sanitation.

Biomass is still the most important energy carrier for cooking in many regions of the world, including sub-Saharan Africa (SSA) (Parikka, 2004). To avoid exhausting natural resources, it is necessary to manage biomass resources effectively, both in terms of collection, and efficiency of use. The former is realized through 'sustainable' resource management techniques, such as forestry management, or cascading the use of resources, while the latter is achieved largely through employing well-designed technology. The simplest and most prominent application of *bioenergy*[2] for cooking is likely to be the three-stone fire. There are, however, more technologically sophisticated, and presumably more 'environmentally friendly', bioenergy alternatives available. These have been designed with the aim of reducing, or even substituting, the use of firewood, and include *improved cook stoves* (ICS), such as microgasifier stoves, or biogas systems. Bioenergy can also be applied to sanitation processes in order to destroy or deactivate pathogens from human excreta. When managing human excreta, preventing the transmission of disease is an essential element of *ecological sanitation* (EcoSan). Sanitation, therefore, needs to take place at as early a stage as possible during the process (WHO, 2006). Technological sanitation alternatives that allow for considering human excreta as a *resource*, rather than as *waste*, include the urine-diverting dry toilet (UDDT) for collecting human excreta, as well as thermal sanitation via pasteurization and composting for properly treating the matter collected.

[1] Here, the term *smallholders* is used as a synonym for *small-scale farmers* or *subsistence farmers*. In spite of this generic term, smallholders do not form a homogeneous group. In my work, I refer in particular to 'households engaged in agricultural production on a relatively small scale' (Cousins, 2011), and to subsistence and semi-subsistence, or semi-commercial, smallholders, which means that 'farming meets most of their social reproduction requirements' (*ibid.*). I chose the term *smallholders* as it is the most common self-designation for farmers in the case study region of the present work. The socio-economic and agroecological living conditions of those smallholdings are introduced in Section 1.4. For further 'class-analytic perspectives on small-scale farming' see, for example, Cousins (2011).

[2] In this context, *bioenergy* refers to the technical recovery of energy from biomass.

Managing soils 'appropriately' involves replacing elements that have previously been taken from the soil (von Liebig, 1841). Many smallholders in SSA, however, lack the resources to sufficiently replenish soil nutrients and soil organic matter (SOM) in soils depleted by agricultural activity (Buresh et al., 1997; Markwei et al., 2008). The International Assessment of Agricultural Knowledge, Science and Technology for Development[3] (IAASTD) sees 'agriculture at a crossroads', and calls for focusing on efficient, small-scale agroecosystems with nutrient cycles that are as closed as practicably possible (McIntyre et al., 2009a). *Agroecology*, and material cycling within the agroecosystem, represent the agreed prerequisites for soil conservation and amelioration. As such, agroecology fosters local and small-scale food production (La Via Campesina, 2015) and long-term food supply (FAO, 2014; Lal, 2006; Lal, 2009; Tittonell, 2016; De Schutter, 2011). Kiers et al. (2008) further promote the use of locally available resources in particular. As an example, residues from cooking and from sanitation can be employed in recycling-driven soil fertility management. Residues from cooking that can be recovered as resources for agriculture include ashes, biochar (i.e. char particles), and biogas slurry. *Biochar* in particular is rich in carbon (C), and its recovery can therefore contribute to restoring SOM, while *biogas slurry* is valued as nutrient-rich fertilizer. In addition, once sanitation has been completed, *urine* and *faeces* constitute a valuable resource for recycling plant nutrients, including nitrogen (N), phosphorus (P), potassium (K), and micro nutrients (Esrey et al., 2001). Creating such integrated systems for resource management, allows, as a consequence, existing fertilizer gaps to be filled.

Focus of the present work.

In my research, I theoretically and empirically open up a wider research field with investigations into so-called *microenergy systems* (MES)[4]: understanding and quantifying how energy, sanitation, and agriculture are interlinked in smallholder systems in SSA. I have examined this nexus using the example of organic smallholder farming systems in Karagwe, Tanzania (TZ). I have also followed three pilot projects that act as case studies to the present research. Two Karagwe farmer's initiatives have recently developed locally-adapted technologies with the aim of providing clean cooking energy and safe EcoSan to the local community. A further objective of the farming projects is to sustain local food production and food sovereignty through the use of locally available residues. In my research, I have applied an integrated system analysis to jointly investigate (i) cooking and sanitation technologies that are locally available to smallholders in Karagwe, and (ii) recycling-driven approaches to soil fertility management. I studied such 'intersectional resource management' with respect to the potentials for:

- Meeting the needs of farmers for decentralized cooking energy supplies and sanitation services;
- Sustaining local food production through soil improvement;
- Protecting local resources and reducing key negative environmental impacts.

[3] Also known as the World Agriculture Report.

[4] During my PhD studies, I was part of a research group that studied decentralised energy technologies, mainly in the Global South, as an embedded system within the technological, economic, cultural, political, and social systems (cf. Section 1.6). According to Schäfer and Philipp (2009), a MES defines a decentralized energy system that is based on small-scale energy technologies, and in which the provision and demand of energy are locally linked.

Outline of this thesis.

The following sections of Chapter 1 elaborate on the scientific rationale of my work. I provide short reviews on contemporary knowledge concerning bioenergy (Section 1.1), sanitation (Section 1.2), and soil management (Section 1.3), each tailored to the specific regional research context of TZ. I then introduce the study site and case studies (Section 1.4). Thereafter, I describe the scope of the present research, including research objectives, research questions, and then go on to present the structure of my thesis as a cumulative dissertation (Section 1.5). To conclude the first chapter, I attempt a short reflection and critique of my work in a wider social, scientific, and political context (Section 1.6). Chapters 2 - 6 present the five scientific publications that constitute the essential elements of my cumulative dissertation. In final Chapter 7, I formulate the synthesis of my work. For this purpose I first summarize the main results of my research (Section 7.1). Thereafter, I discuss the practical relevance of my work (Section 7.2) as well as opportunities and challenges identified for real-world application (Section 7.3). After a short critique of my methodology (Section 7.4) I finally formulate future research demands identified, and close with the overall conclusions (Section 7.6).

Conventions.

Some commonly used conventions are adopted in this thesis:

- *Italic* letters indicate discipline-specific definitions, established terms upon initial use, terms applied from languages other than English, and quotations covering more than two lines.
- Names of institutions and other established terms are capitalized.
- Literature references in the text are listed in alphabetical order.
- Footnotes are used to include additional information for interested readers; this information, however, is not necessary to follow the thesis.
- Supplements and appendices to this thesis (including those belonging to the publications) are found in the General Annex, which is provided as a separate document for convenience.

1.1 Bioenergy provision and utilization of residues

In this section, I first provide a brief summary of the current situation in regard to biomass use for energy provision in TZ. I then go on to introduce those bioenergy technologies that are locally available in the study area of Karagwe. Against this background, I elaborate on the current state of scientific knowledge in regard to residue use from bioenergy provision as soil fertility improvers in agriculture. This section closes with a summary of my research interests in the field of bioenergy technologies and the use of residues.

Conventional use of bioenergy in Tanzania.

In general, bioenergy technologies convert biomass either (i) to thermal energy, or heat, or (ii) to a secondary energy carrier (Kaltschmitt et al., 2009). With respect to the first, examples are the (direct) combustion or oxidation of firewood or other fuels, and the thermo-chemical or bio-chemical gasification of organic matter, and the subsequent oxidation of this gas (*ibid.*). The resulting heat can be used for electricity generation (e.g. in a power plant with turbine and generator, Stirling engine, etc.), for productive processes (e.g. bakery, green-house heating, etc.), or for consumption in households or institutions (e.g. cooking, heating, etc.). The second biomass conversion path includes producing charcoal from fuelwood, which is commonly realized through thermo-chemical *pyrolysis* (Chaposa, 1998)[5]. The present work focuses on using bioenergy technologies for cooking at a household level.

The prime source of energy in TZ is wood, either used directly as firewood, or in the form of processed charcoal (Msuya et al., 2011). In the case of farming households in rural TZ, a variety of different biomasses are used as cooking fuel, though firewood still clearly dominates (Grimsby et al., 2016). Msuya et al. (2011) have estimated that by 2030, TZ will have lost approximately 8.5 % of its national forests when compared to 2010. This loss is largely accounted for by forest removal to provide sufficient wood as fuel for charcoal production. About 20 % of the country's forests had already been lost in the decades between 1990 and 2010[6] (WB, 2016a) to provide firewood and charcoal. Msuya et al. (2011) have further estimated that greenhouse gas (GHG) emissions over the same period, such as methane (CH_4), carbon monoxide (CO), and carbon dioxide (CO_2), from charcoal production alone will increase to approximately $420 \cdot 10^6$ t CO_2-eq. by 2030[7].

Locally available, small-scale bioenergy alternatives.

There are, however, small-scale and decentralized bioenergy alternatives available which would enable smallholders in TZ to reduce or substitute their use of wood fuel. Such bioenergy technologies can be classified according to the organic materials utilized:

(A) Organic matter with comparatively *high moisture content*[8], such as cow dung, kitchen residues, fresh harvest residues, etc., can be anaerobically fermented in small-scale biogas digesters (e.g. Rajendran et al., 2012; Tumwesige et al., 2011; Vögeli et al., 2014) (Fig. 1.1). The biogas produced is first collected directly inside the digester, or in a separate tank, for intermediate storage. Biogas is then burned in a biogas burner (e.g. Tumwesige and Amaguru-Togboa, 2013). The predominantly liquid[9] and organo-mineral rich residue from the fermentation process is called biogas slurry, bio-slurry, or digestate. Biogas technology was introduced to TZ in the early 1970s (Rupf et al., 2015). Economic and political motivations aside, imple-

[5] See Section 1.3 for further information on applied technologies for charcoal production in TZ.

[6] According to the World Bank (WB, 2016a), 415.000 km^2 of TZ was covered with forest in 1990, compared to just 334.300 km^2 in 2010.

[7] In comparison, total GHG emissions in 2012 amounted to approximately $235 \cdot 10^6$ t CO_2-eq. in TZ (WB, 2016b) and to $951 \cdot 10^6$ t CO_2-e in Germany (WB, 2016c).

[8] According to Ward et al. (2008), *wet fermentation* works with biomass with a moisture content of > 84 % of fresh matter (FM), while *dry fermentation* calls for substrates with a moisture content of 60 to 78 % of the FM.

[9] The moisture content of biogas slurry is approximately 96 % of FM (Table A.12 in Appendix A1).

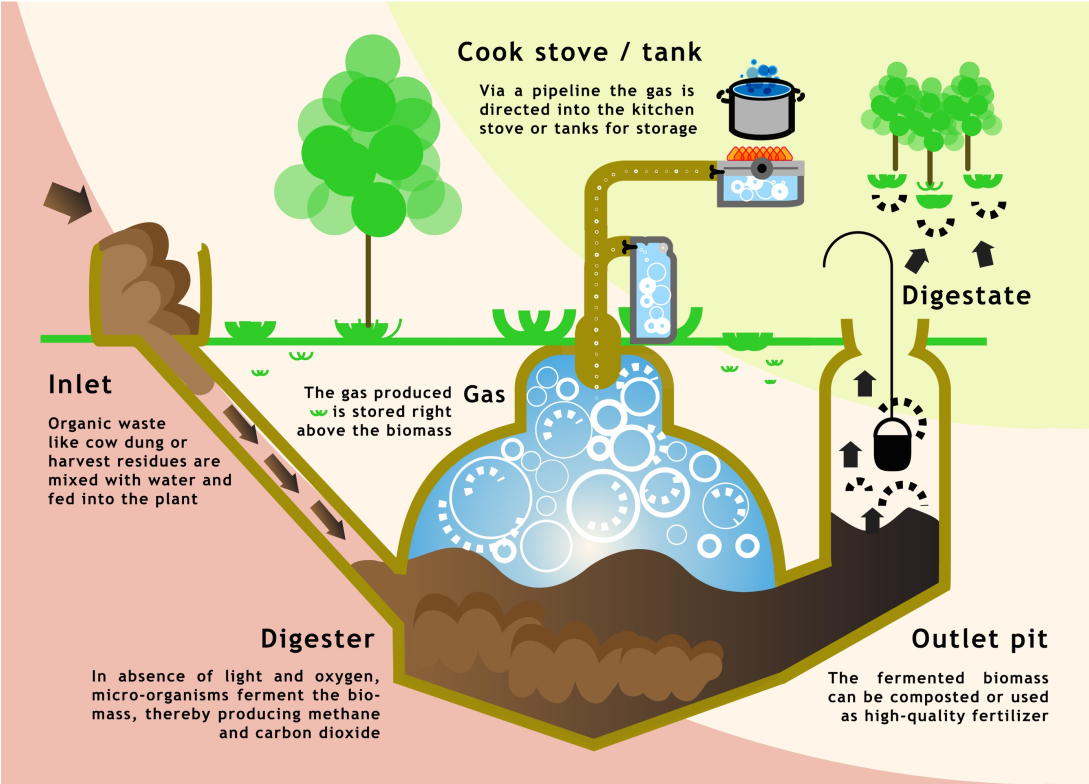

Figure 1.1: *Working principle of a small-scale biogas digester including subsequent use of the biogas for cooking and of the biogas slurry/digestate for fertilization. [Infographic under creative commons license (CC) by Lusi Ajonjoli.]*

mentation was also encouraged by practical considerations, such as (i) the year-round elevated temperatures, and (ii) the widespread agricultural activities providing various potential feedstocks (*ibid.*). A small-scale biogas digester for Karagwe, requiring only locally available materials for construction and operation, has recently been developed by Tanzanian and German partner initiatives. It uses cow dung, banana stems, and kitchen 'waste' as its feeding material (Becker and Krause, 2011; Fig. 1.11, p. 33).

(B) Organic matter with comparatively *low moisture content*[10], such as sawdust, maize cobs, rice husks, etc., can be utilized for cooking with microgasifier stoves (e.g. Anderson and Schoner, 2016; Lotter et al., 2015; Mukunda et al., 2010; Roth, 2013). Microgasifier stoves are characterized by the fact that they separate, both spatially and temporally, the process of converting biomass to heat into two distinct phases. The first involves the gasification of biomass into combustible gases ('wood-gas') and char, which is followed by oxidation, or combustion, of the wood-gas[11] (Roth, 2013). The former process takes place within the bottom part of the stove, the latter in the stove's top part, the so-called 'combuster' (Anderson et al., 2007). Microgasifiers are more efficient, and produce less smoke and GHG emissions, when compared to three-stone fires (Jetter and Kariher, 2009; Rajabu and Ndilanha, 2013). For these reasons they are consid-

[10] According to Englund et al. (2016), the moisture content in the biomass used for gasification should preferably be, at most, 12 % of FM, with lower moisture contents providing better results.

[11] This two-step conversion of biomass to heat is facilitated by the specific design of the microgasifier, and by its so-called 'primary' and 'secondary' air flows (Fig. 1.2).

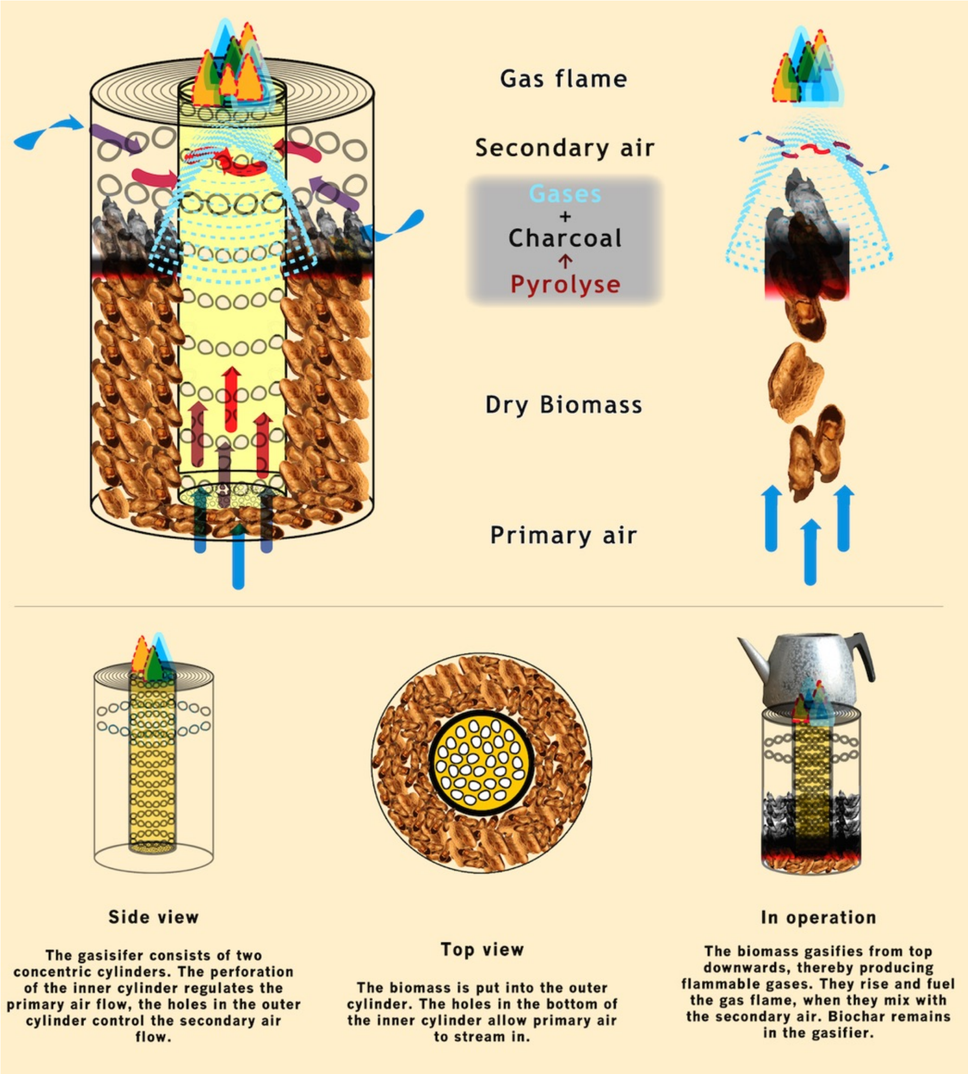

Figure 1.2: *Working principle of a microgasifier used for cooking, including co-production of biochar. The example given is of a stove operating with biomass in small pieces, such as groundnut shells. [Infographic (CC) by Lusi Ajonjoli.]*

ered an example of 'advanced design' for an ICS (Roth, 2013). The resulting char particles, a predominantly powdery by-product, can be used (i) to continue cooking, as is realised in the 'TChar' microgasifier stove (Anderson et al., 2011), (ii) to produce carbonised briquettes (Mwampamba et al., 2012), or (iii) to improve soil quality in concordance with traditional soil management practices (see following paragraph as well as Section 1.3). Various models of micro-gasifier stove have been recently tested in Karagwe with the aim of adapting designs to locally available production materials and feedstocks, such as powdery sawdust and coffee husks, or chunky firewood and maize cobs (Ndibalema and Berten, 2015; Fig. 1.10, p. 33).

Linking bioenergy and agriculture.

Organic matters that can be recycled to smallholder agriculture for fertilization and soil improvement include (A) biogas slurry from anaerobic fermentation and (B) powdery biochar from micro-gasification.

(A) According to Möller and Müller (2012), biogas slurry, is *inter alia* characterized by a high content of ammonium (NH_4^+) compared to undigested matter. As a consequence, it is considered particularly suitable for cropping systems that require 'quick-release' fertilizers, such as organic vegetable cultivation. Studies observing plant response to biogas slurry have often revealed positive results in terms of stimulated crop productivity (e.g. Baba et al., 2013; Clements et al., 2012; Garfí et al., 2011; Komakech et al., 2015), improved aggregate stability (Häfner, 2017), and improved activity in terms of soil microbiology (Möller, 2015). Other studies, however, have revealed neutral effects (e.g. Svensson et al., 2004) or even depressed crop yields (e.g. Sieling et al., 2013) and phytotoxicity related to NH_4^+ (Möller and Müller, 2012). To the best of my knowledge, plant responses to biogas slurry have rarely been studied in the SSA context. One example is Komakech et al. (2015), who conducted field experiments in Kampala, Uganda. They observed that biogas slurry from fermented animal manure tripled the yield of maize grains in comparison to the control.

(B) The benefit of charcoal particles in the soil has been well documented since the 'discovery' of exceptionally fertile *Terra Preta* soils in the Amazon Basin (see Section 1.3). In this context, 'biochar' is the collective term for C-rich, pyrolyzed organic materials used as soil amendment (Lehmann and Joseph, 2009). In the soil, biochar can improve the availability of both nutrients and water by effecting the chemical and hydraulic characteristics of the soil (Glaser and Birk, 2012; Lehmann and Joseph, 2009). Moreover, biochar can positively affect the activity of microbial communities in the soil (McCormack et al., 2013), as well as root symbionts such as *arbuscular mycorrhizal* (AM) fungi (Hammer et al., 2014 and 2015). However, biochar alone does not offer sufficient nutrients for plant growth (Lehmann and Joseph, 2009), and so needs to be mixed with other organic, nutrient-rich 'waste' material, such as kitchen and harvest residues[12]. Kammann et al. (2015) demonstrated that using biochar as a compost-additive is the most promising approach for soil improvement. During composting (i.e. degradation and conversion of the matter), biochar is 'loaded' with nutrients (*ibid*). It has been demonstrated that biochar particles adsorb nitrate (NO_3^-) and phosphate (PO_4^{3-}) through their surfaces and pores (Agyarko-Mintah et al., 2016; Gronwald et al., 2015; Kammann et al., 2015). Numerous pot and field experiments (e.g. Herath et al., 2013; Kammann et al., 2011; Liu et al., 2012; Major et al., 2010; Nehls, 2002; Petter et al., 2012; Schmidt et al., 2015; Schulz et al., 2013) and several meta-analyses (e.g. Biederman and Harpole, 2013; Jefferey et al., 2011; Liu et al., 2013) have repeatedly demonstrated that amendments of (composted) biochar enhance plant growth. One major effect observed is rising soil pH. This makes biochar application particularly interesting for soils in SSA which often suffer from acidity (see Section 1.3), and, as a consequence, limited P-availability. According to Mukherjee and Lal (2014), it is fact, however, that the effects of biochar amendments are highly site-specific, which is compounded by a lack of scientific field-scale information on crop responses and soil quality for various soil-type and biochar combinations. Experiments with biochar, and in particular with composted biochar, are to the best of my knowledge still rare for the SSA context. In one of the few available examples,

[12] Kammann et al. (2015) pointedly summarized practical guidance in respect to this by saying that 'compost the organic (nutrient-rich) best, and pyrolyze the woody (nutrient-poor) rest'.

Kimetu et al. (2008) used uncomposted biochar on highly degraded soils in Kenya and doubled maize grain yields in comparison to the growth on untreated soils.

The 'way forward' from bioenergy analysis and the use of its by-products.
From information compiled from the state of knowledge explained above, I hypothesize that using small-scale biogas digesters, or microgasifiers for cooking, has a clear potential (i) to reduce the use of wood as a fuel resource for cooking and (ii) to recover resources for soil fertility management. Adequate or even exceptional fertilizing potentials have frequently been attributed to biogas slurry or composted biochar. Studies on the fertilizing effect of biogas slurry or biochar are, however, generally lacking for SSA. Against this background, I reason that on-site testing of using biogas slurry as fertilizer, and biochar as a compost additive and soil amendment, is necessary before recommending the practice to smallholders in Karagwe.

With this in mind, my overall scientific interest in the field of bioenergy is as follows:

1. To quantify changes in resource consumption, resource recovery, and environmental emissions depending on the technology used for cooking in farming households; and
2. To conduct field experiments in order to study agroecological effects of using biogas slurry and co-composted biochar as soil amendments.

1.2 Conventional versus ecological sanitation

At the beginning of this section, I contrast conventional sanitation systems, based on a waste-approach, to recycling-driven EcoSan approaches. Against this background, I further elaborate the state of knowledge of inactivating pathogens in human excreta, which allows for their subsequent use in agriculture. I further present and explain an 'innovative' practical example of applied EcoSan, which is based on the principles of *Terra Preta* soil enrichment and has been developed as a Tanzanian-German partnership project in Karagwe. Thereafter, I briefly explain the state of knowledge of the energetic use of human excreta as another potential alternative to EcoSan. Finally, I close the section with a summary of my research interests in the field of EcoSan and the agricultural use of human excreta.

Conventional sanitation systems.
Widely implemented sanitation technologies are mainly based on one of the following two systems:
(A) 'Drop-and-store' designates systems in which human excreta is stored in a pit in the soil after dropping down from the toilet (Esrey et al., 2001). The pit latrine is the most common and lowest-cost example of this system worldwide (*ibid.*). The more solid portions of the 'toilet sludge' are either retained in the soil or are removed. This is often carried out manually with buckets, for example. The liquid portion of the 'waste' infiltrates into the soil and may, therefore, eventually reach the groundwater table. Major problems with this decentralized sanitation sys-

tem are itemized below (Doorn et al., 2006; Dzwairo et al., 2006; Graham and Polizzotto, 2012; Jacks et al., 1999; Montangero, 2006; Ngumba et al., 2016; Pathak, 1991):

- Manual emptying of latrines is an 'inhuman' practice[13];
- Methane emissions from anaerobic decomposition of excreta[14];
- Potential downstream contamination of groundwater with faecal microorganisms[15];
- Potential eutrophication of rivers and lakes caused by nutrient leaching[16].

(B) In systems following the principle of 'flush-and-discharge', human excreta is flushed from the toilet with either fresh or rain water[17] (Esrey et al., 2001). Subsequently, the wastewater from toilets, called *blackwater*, is collected in a decentralized septic tank, or transported to a central sewage system[18]. Problems with this water-based and more centralised sanitation approach include (Chaggu et al., 2002; Doorn et al., 2006; Otterpohl et al., 1997; Wilsenach et al., 2003; Winblad et al., 2004):

- Waste of (drinking) water used for flushing;
- Contamination of sewage sludge with heavy metals and other chemical pollutants from industrial wastewater;
- Eutrophication of aquifers through leaching from open sanitation systems, or discharge of wastewater or sewage sludge;
- GHG emissions from sludge treatment;
- High operation and rehabilitation costs of central sewer system;
- High energy demand for nutrient removal from sewage sludge;
- Restricted flexibility due to scale of implemented sewer systems;
- Restricted access for poor communities due to cost and complexity.

Both conventional sanitation systems are, basically, linear-operating systems, which consider human excreta as 'waste', or wastewater, rather than as a resource for agriculture[19]. The nutrients contained in human excreta are transferred either (i) to the air, for example, in the form of ammonia (NH_3) or nitrous oxide (N_2O), (ii) to the soil, for example, in the form of PO_4^{3-} or NH_4^+, or (iii) to subsurface aquifers, as NO_3^-. Meinzinger (2010), as an example, crit-

[13] Pathak (1991) refers to this practice as 'manual scavenging'.

[14] Reid et al. (2014) estimated that the worldwide emissions from pit latrines contribute approximately 1 % to global anthropogenic CH_4 emissions.

[15] Consequently, a lateral distance of minimum 25 m is required between pit latrines and water sources for human consumption (Graham and Polizzotto, 2012).

[16] Eutrophication and pollution of lakes, rivers, and groundwater is a problem in many countries in SSA (Dzwairo et al., 2006; Ngumba et al., 2016; Nyenje et al., 2010). In TZ, direct discharge of sewage as well as of domestic and industrial wastewater to Lake Victoria has led to critical concentrations of nutrients and organic matter, leading in turn to eutrophication and the invasive growth of hyacinths (Cheruiyot and Muhandiki, 2014; Juma et al., 2014; Scheren et al., 2000; Zhou et al., 2014).

[17] Chaggu (2004) calls this principle 'flush-and-forget'.

[18] In a central sewage system, blackwater is mixed with industrial wastewater from trade, commerce, and industry (Meinzinger, 2010). The treatment of mixed wastewater is commonly realized through anaerobic digestion, dewatering, drying, and incineration of sewage sludge (*ibid.*).

[19] In principle, sewage sludge can be used as fertilizer. This practice is decreasing in Europe, however. In Germany, for example, only about one quarter of total sewage sludge was used for agriculture in 2014, whilst approximately 60 % of sewage sludge was thermally disposed of through incineration (Destatis, 2015). Thereafter, only a small proportion of the available ashes, containing, for example, P, are used in agriculture; some are recycled back to industry; while others are disposed of (Meinzinger, 2010).

icized conventional sanitation systems for breaking the 'historic link' between sanitation and the agroecosystem. Anthropogenic nutrient cycles were, however, common in Karagwe before early development cooperations implemented the widespread installation of pit latrines in the area in the 1940s (Rugalema et al., 1994; cf. Section 1.4, p. 28). With respect to the potential implementation or dissemination of sewage-based systems in TZ, Chaggu (2004) expresses the problem in a nutshell. She described that '*[...] the increased demand for water normally causes problems of conflict and unending tensions in society and so, advocating using the sewerage system is a 'dream or wishful thinking' that will never be fulfilled in the lifetime of many Tanzanians. [...] Nonetheless, the desire of providing sanitation to the majority of the people of the developing world through sewerage system has practically failed (Mgana, 2003). Practically, decentralized sanitation and reuse options [...] of 'human waste' are the only possible sustainable concepts.*'

Ecological systems as sanitation alternatives.

Considering human excreta as a valuable resource is crucial for 'closing the loop' of essential nutrients[20]. The historic integration of human excreta and applied soil management is known from the Asian context[21] (Guha, 2011; King, 1911), from South America (Factura et al., 2010; Kammann et al., 2015) (cf. Section 1.3, p. 20), from East (Rugalema et al., 1994) and West Africa (Frausin et al., 2014), and also from northern Europe and around the Mediterranean (Bond et al., 2013; De Decker, 2010; Londong, 2015). In order to design resource-efficient sanitation systems for contemporary societies, the position of agriculture within these systems must be reinstated as an essential element of sanitation, and therefore included in system analyses (Meinzinger, 2010)[22]. In practice, resource-oriented, and 'sustainable' sanitation approaches should achieve the following goals (DWA, 2008; Esrey et al., 2001; Londong, 2015; Meinzinger, 2010; Otterpohl et al., 1997; SuSanA, n.d.; WHO, 2006; Winblad et al., 2004):

- To protect human health by
  - providing a clean environment through hygiene, and
  - breaking the cycle of disease through sanitation barriers and inactivation of pathogens;

[20] Meinzinger (2010) estimated that, theoretically, about 25 % of N, 20 % of P, and 33 % of K applied to the soil with fertilizers worldwide, could be substituted through utilizing the excreta of the world population.

[21] Appropriate sanitation was of highest importance to Gandhi (1919), who once said that 'sanitation is more important than independence'. Gandhi (1937) defined that: '*An ideal Indian village will be so constructed as to lend itself to perfect sanitation. [...] The very first problem the village worker will solve is its sanitation. [...] If the worker became a voluntary bhangi 'sweeper', he would begin by collecting night-soil and turning it into manure and sweeping village streets. He will tell people how and where they should perform daily functions and speak to them on the value of sanitation and the great injury caused by the neglect.*' (Gandhi, 1937; Guha, 2011). King (1911) observed that in permanent agriculture in China, Korea and Japan 'sustainability is mainly based on closed nutrient cycles through the use of night soil'.

[22] Meinzinger (2010) emphasized that 'the time has come to challenge the current systems, to move away from 'process-thinking' and to shift towards 'system-thinking'. This could eventually lead to re-establishing the link between sanitation and agriculture'. With '*process-thinking*', Meinzinger (2010) refers to the second part of the 19th century, when the main focus was on developing requirements, processes, and technologies for treating waste, rather than on resource efficiency or recycling (Larsen et al., 2007).

- To protect the environment by
  - reducing or avoiding emissions of nutrients, ecotoxic substances, oxygen depleting substances, and matter suspended in freshwater resources or the marine environment,
  - reducing or avoiding GHG emissions, and
  - promoting resource recovery within the anthroposphere, through processes such as water recycling and recovery of C, N, P, etc.;
- To protect natural resources, especially through efficient resource management, which includes considering human excreta as a resource for fertilization;
- To meet global need for sanitation[23];
- To adapt to socio-economic and geographic conditions on-site in order to be economically viable, socially acceptable, and technically, as well as institutionally, ‘appropriate’;
- To involve local people in the development of strategic sanitation plans and project planning;
- To start implementation at the minimum practical size, namely, at the household and/or community level.

One of the most prominent recycling-oriented approaches to sanitation is *EcoSan*. Applied examples of EcoSan-projects exist all over the world with diversity in specific approaches and technologies used for collecting and treating human excreta (DWA, 2008; SuSanA, n.d.). Commonly, EcoSan is realized through decentralized systems, and is based on household and community management. In this way, bigger investments in large-scale infrastructure are avoided (Esrey et al., 2001). Furthermore, EcoSan is particularly appropriate for areas with water shortages or irregular water supplies, as no, or only very little water, is required. UDDTs often form a part of EcoSan-installations (Fig. 1.3). In a UDDT, faeces and urine are collected separately. This facilitates the discreet treatment of collected matters and, therefore, allows for unrestricted use of human excreta in agriculture (Morgan, 2007). The potential of resource-focused sanitation in SSA has been analyzed by several studies[24]. For example, Belevi et al. (2002) found that composting of human excreta and those municipal solid wastes (MSW) that are usually disposed of could cover about 30 % of the N and P demanded for urban and peri-urban agriculture in Kumasi, Ghana. Also in the city of Arba Minch in southern Ethiopia, about 16 % of synthetic fertilizers used could be substituted by resources from source-separating toilets, as estimated by Meinzinger (2010). Lederer et al. (2015) concluded that the recovery of human excreta had a greater potential to reduce existing soil nutrient deficits in Busia District, Uganda, than recycling hitherto unused MSW. Finally, analyzing sanitation systematically can support the formulation and implementation of a strategic sanitation plan, as demonstrated by Yiougo et al. (2011) for the case of Pouytenga in Burkina Faso.

Linking sanitation with agriculture.

Using residues from EcoSan for fertilization and soil improvement requires adequate sanitation of urine and faeces. Using urine as liquid mineral fertilizer is relatively easy and safe. The World

[23] As a reaction to this need, Sustainable Development Goal (SDG) No. 6 has been formulated: ‘Ensure availability and sustainable management of water and sanitation for all’ (UN, 2015).

[24] All of the studies mentioned, applied material flow analysis (MFA).

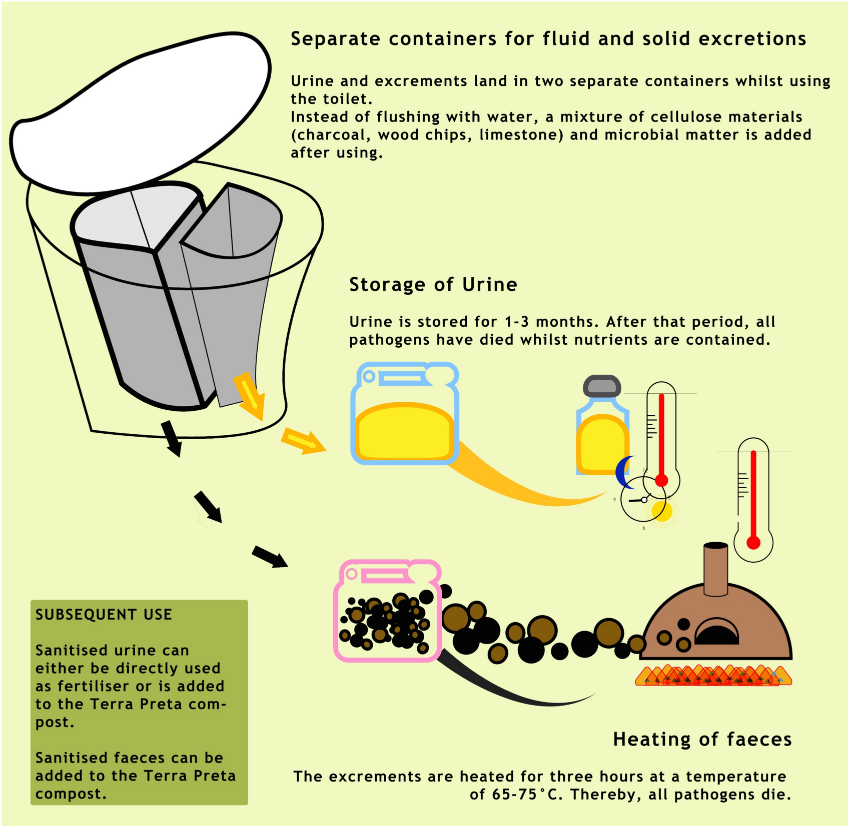

Figure 1.3: *Working principle of a urine-diverting dry toilet (UDDT) including possible paths for the subsequent treatment of urine and faeces, comparable to those analyzed in the present study. [Infographic (CC) by Lusi Ajonjoli.]*

Health Organization (WHO, 2006) recommends to simply store urine, which leads to a rise in pH that consequently inactivates potential pathogens present in the urine, such as schistosomiasis/bilharzia, hepatitis, etc. The recommended duration of storage is either (i) one to three months, depending on the surrounding temperature and if the urine is clean/uncontaminated and neat/undiluted, or (ii) six months, if the urine is cross-contaminated with faecal particles (*ibid.*). When experimenting with urine storage in Uganda, Niwagaba et al. (2009) demonstrated that at fluctuating temperatures of $24 \pm 7\,^{\circ}$C, a storage period of two months was sufficient to reach non-detection levels for all pathogens studied including *Escherichia coli* (*E. coli*), *Salmonella*, *Ascaris*, and *Salmonella* Typhimurium. Looking at the practitioner's perspective, Andersson (2015) reports that farmers in eastern Uganda perceived fertilization with stored urine as an 'efficient, low-cost, and low-risk practice'.

Processes to inactivate pathogens contained in human faeces are manifold and include drying (Richert et al., 2010), composting (Niwagaba et al., 2009; Ogwang et al., 2012), lacto-acid fermentation (Factura et al., 2010), pasteurization (Feachem et al., 1983; Schönning and Stenström, 2004), co-pelletizing with subsequent gasification (Englund et al., 2016), and direct incineration (Niwagaba et al., 2009) of faeces. Composting of human excreta in particular has been tested thoroughly, including in the SSA context (e.g. Niwagaba et al., 2009; Ogwang et al., 2012). To completely assure successful sanitation of faecal compost, the WHO (2006) recommends a treatment at 55 to 60 °C over several days, and up to one month, depending on conditions. Longer periods are recommended, for example, when constant monitoring of the temperature is not possible. National regulations specifically dealing with the treatment of human excreta are rare, and do not exist in either TZ or in Germany[25]. Niwagaba et al. (2009) demonstrated practically that faecal compost was effectively sanitized after being exposed to temperatures > 50 °C for at least two weeks in Uganda. Nevertheless, to sufficiently inactivate pathogens during composting, it is important to reach the required temperature throughout the entire compost pile. Vinnerås (2007) found that, therefore, both, insulating the compost and turning the material at least three times during the high temperature period, is crucial. This practice, however, involves the risk of transmitting diseases to workers who handle the compost (*ibid.*).

Locally available approaches to EcoSan.

In a pilot project in Karagwe (Section 1.4, p. 29), an 'innovative' EcoSan approach designed after the principles of *Terra Preta* was tested (Fig. 1.4). Initially, a UDDT was used to collect urine and faeces. Urine was simply stored in closed containers for one month, while faeces were thermally sanitized via pasteurization. The concept follows Feachem et al. (1983), who described the linear relationship between temperature and time required to inactivate certain pathogens (Fig. 1 in P1).

Pasteurization took place in a loam oven, with the faeces inside a container. The loam oven was employed for storing heat provided by a microgasifier, comparable to the stove introduced in Section 1.1. For appropriate treatment, faeces needed to be exposed to 65 to 75 °C for a duration of 30 to 120 minutes (*ibid.*). The approach described is called 'Carbonization and Sanitation' (CaSa), since it combines (i) the production of biochar through *carbonization* and (ii) the thermal *sanitation* of faeces. Subsequently, sanitized faeces were composted together with other household and farming residues, such as kitchen 'waste', ashes or biochar, harvest residues, terracotta/brick particles, etc. Finally, arable crops were fertilized by using the resulting biochar-faecal-compost as an organic soil amender in combination with urine as a liquid, mineral input. If additional treatment of urine and faeces is not possible, or not desired, resources collected in the UDDT can also be used for reforestation (cf. discussion in Section 7.3.2, p. 184).

The energetic use of human excreta as a sanitation alternative.

The direct connection of toilets with anaerobic biogas digesters has often been promoted in order to make energetic use of human excreta. However, after fermentation and biogas production, additional care and further treatment of the biogas slurry is required if the slurry is to be used as fertilizer (Vögeli et al., 2014). After fermenting human excreta mixed with kitchen 'waste' under *mesophilic conditions*[26], biogas slurry possibly still contains pathogens, namely *E. coli* and Helminth eggs, as found by Wendland (2009) as well as Lohri et al. (2010). According to

[25] In Germany, existing guidelines for composting generic organic waste, the Biowaste Ordinance (BO), can be transferred for legal application (Lettow, 2015). For animal excreta, the German BO (2013) prescribes a thermophilic treatment at 55 °C for two weeks, 60 °C for six days, or 65 °C for three days.

[26] *Mesophilic fermentation* takes place at a temperature range of 20 to 40 °C. It is the predominant operation regime in anaerobic fermentation to reach adequate process stability, as these conditions are favourable for a large variety of species of robust mesophilic bacteria (Wendland, 2009).

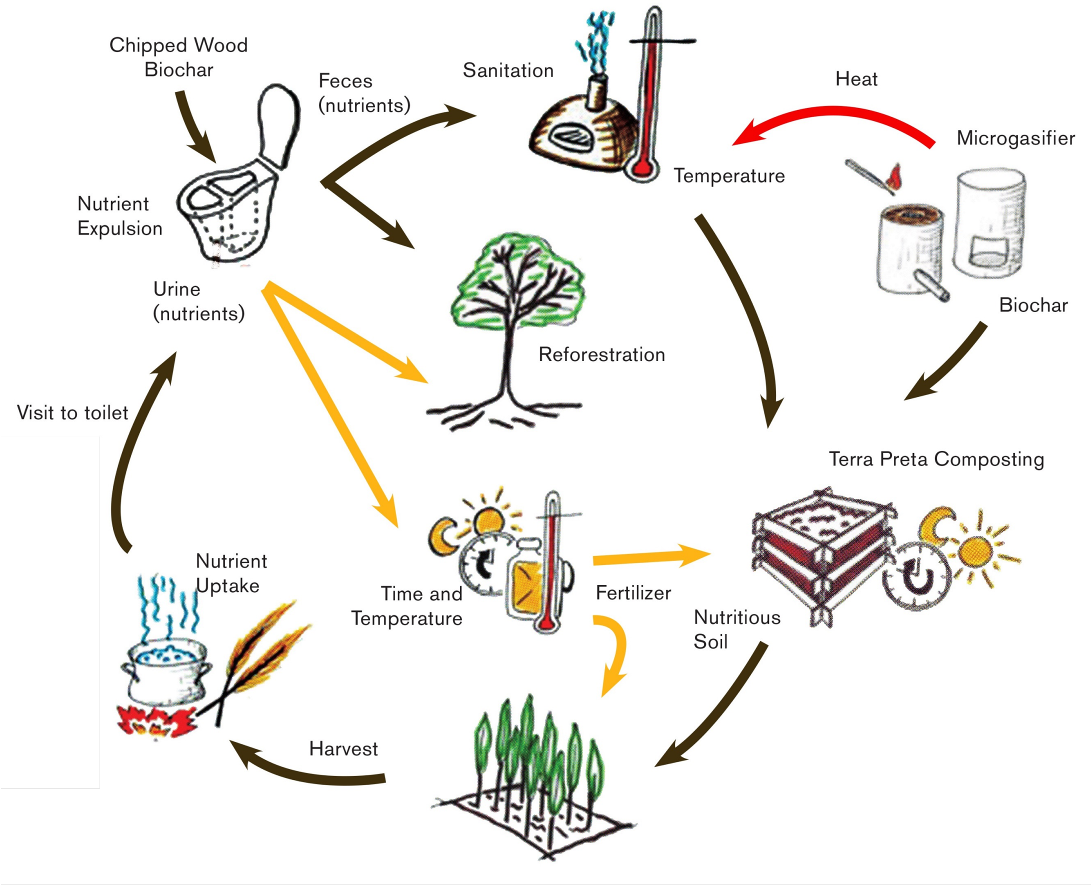

Figure 1.4: The 'CaSa' approach, as an 'innovative' EcoSan approach to close natural cycles has been tested in Karagwe and includes: a UDDT, a sanitation oven heated with a microgasifier stove, urine storage, co-composting of faeces, urine, biochar, and other residues, and, finally, the subsequent use of the compost in combination with urine for crop production. Black, yellow, and red arrows indicate material flows of organic matter, urine, and energy/heat, respectively. [Infographic (CC) designed by Ariane Krause and illustrated by Daniel Mutz and Lusi Anjonjoli.]

WHO (2006), such slurry is thus not safe enough for use in agriculture. I further argue that possible energy yields from fresh matter (FM) differ significantly, with 1,600 kJ, 600 kJ, or only 80 kJ in 100 g of wood, human faeces, or untreated faecal sludge collected from pit latrines or septic tanks, respectively. Even though the net calorific values in dry matter (DM) of faeces or faecal sludge are, in general, comparable to dry wood fuel, it is the FM that needs to be handled in daily life, and the moisture contents of those matters differ significantly[27]. Moreover, in practice, biogas slurry needs to be removed from the digester, which is, according to Lohri et al. (2010), an activity comparable to the manual emptying, or 'scavenging', of pit latrines.

The 'way forward' from the analysis of sanitation systems.

In summing up, my scientific interest in the field of EcoSan has been to study CaSa processes involving pasteurization and the subsequent composting of faeces and biochar. I reason that, in general, faeces should be sanitized and then recycled to the agroecosystem instead of being en-

[27] The net calorific value in DM of wood, fresh faeces, or faecal sludge is approximately 18, 23, or 16 MJ kg^{-1} , respectively (Kaltschmitt et al., 2009; Murphy et al., 1993; Muspratt et al., 2014). The moisture content in wood is approximately 12, 75, or 95 % of FM, respectively (Chaggu, 2004; Jetter and Kariher, 2009; Muspratt et al., 2014).

ergetically used, as the latter path is still associated with a high risk of pathogen contamination. I hold that CaSa is a promising approach to EcoSan due to the fact that health risks for farmers are reduced as sanitation takes place at a very early stage, namely, directly after the UDDT and before composting. Furthermore, sanitation of human faeces is achieved in a comparably short time as treatment is realized at elevated temperatures in comparison to standard composting methods. Meanwhile, pasteurization avoids the high losses of C and N associated with the gasification or incineration of (dry) faeces. If microgasifier stoves are employed for thermal sanitation, the process additionally provides charcoal powder as a by-product that can be added to composting as biochar (i.e. 'cascade use' of wood). Finally, an integration of sanitation and agriculture supports soil improvement through the combined recovery of C, N, P, etc.

With this in mind, my overall scientific interest in the field of EcoSan has been as follows:

1. To quantify changes in resource consumption, resource recovery, and environmental emissions depending on the technology used for sanitation in farming households; and
2. To experimentally study the agroecological effects of using biochar-faeces-compost produced in CaSa pilot project as a soil amendment.

1.3 Sustaining soil fertility through appropriate management

I begin this section by taking a brief glance at current insights into contemporary soil management, and how it affects soil fertility. I then present and discuss those agricultural practices considered suitable for 'sustainable' soil management. I also introduce *Terra Preta*, a traditional example of soil management from South America, which has served as a role model for my work, and discuss different methods of using biochar. I close the section with a summary of my research interests in the field of 'sustainable' soil fertility management.

Researching contemporary soil management.

Appropriate soil management sustains soil function (Horn et al., 2010), and, thus, secures food production. However, predominantly human-induced worldwide soil degradation has been identified repeatedly as a serious threat over the past decades (e.g. FAO, 1982; Lal et al., 1989). According to the Status of the World's Soil Resource (SWSR), a report prepared by the Food and Agriculture Organisation (FAO) of the United Nations (UN), and the Intergovernmental Technical Panel on Soils (ITPS), the current status of most soils ranges from fair, to poor and very poor, which has negative impacts on crop yields (FAO and ITPS, 2015). Many soils worldwide suffer from soil erosion, changes in soil organic carbon (SOC)[28], especially depletion of soil humus, and nutrient imbalances (Fig. 7.1)[29] (*ibid.*). With regard to the latter threat, FAO and

[28] Concentrations of SOC and SOM are in proportion to one other. Converting SOC to SOM is possible by applying a conversion factor ranging from 1.4 to 2.5, or traditionally with a factor of 1.7 (Pribyl, 2010).

[29] It should be noted that such global trends, as visualized by Montanarella et al. (2016) in Fig. 7.1, are in reality neither as explicit, nor as clearly associated with national or regional borders. Taking a global perspective simplifies the real situation, which is more contradictory. For example, even on a local level, the soil status of two neighbouring farms may differ significantly with regard to nutrient access, or depletion or content of SOC/SOM. All these factors depend on individually applied soil management practices.

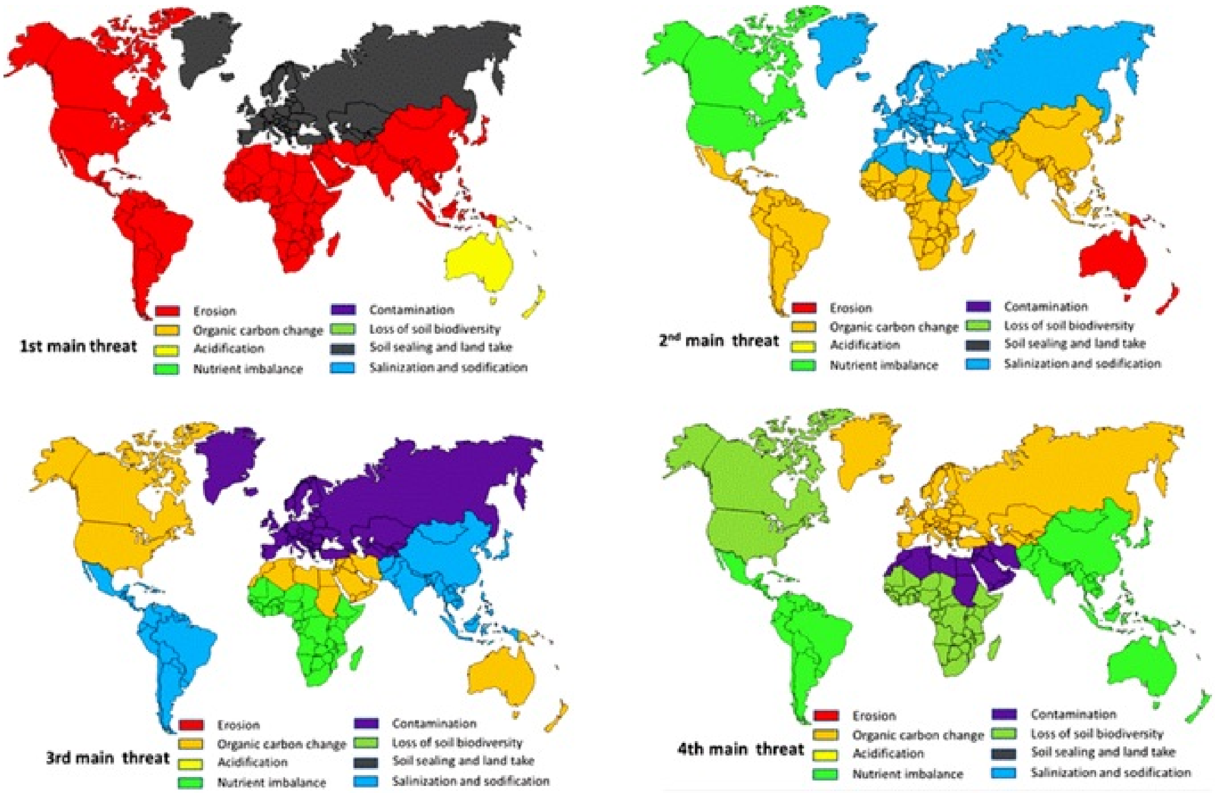

Figure 1.5: *Mapping the four main threats to global soils, by FAO regions and according to the global assessment of Montanarella et al. (2016).*

ITPS (2015) note that, on the one hand, the nutrients in many soils are continuously depleted, for example in SSA. On the other, soils are detrimentally over-fertilized in other regions of the world, such as Europe and North America (*ibid.*), down to the fact that an adequate input of elements, such as C, N, P, K, etc., is often neglected (Lal, 2009).

'Sustainable'[30] land-use and food security are, thus, clearly related to soil fertility management. Success, however, also depends on political factors such as access to land, land tenure rights, and social security, etc., which all influence the capacity for long-term thinking and planning. Tittonell (2016) encapsulated it neatly when he stated: '*Feeding the world, [. . .], requires much more than soil science and it certainly exceeds agricultural research. Yet it helps to be aware of the role we can play in this puzzle, a role that is not minor*'. Tittonell stressed, for example, the need for 'innovative' design and locally-adapted concepts for soil amelioration and soil conservation. According to Tittonell, the design of 'sustainable' soil management strategies is based on understanding the complex reality of socio-ecological systems. Applied research, therefore, should focus on analyzing the network of resource flows at farm-level, as well as the natural and human induced spatial heterogeneity of soil at field scale. The aim of this is to identify hotspots

[30] In this context, sustainability can be defined in accordance with Gliessman (1997) who wrote: '*the greater the structural and functional similarity of an agroecosystem to the natural ecosystems in its biogeographic region, the greater the likelihood that the agroecosystem will be sustainable.*' Also McIntyre et al. (2009b) emphasize the importance of 'systems [. . .] that enhance sustainability while maintaining productivity in ways that protect the natural resource base and ecological provisioning of agricultural systems.'

which require direct soil management. Sources, sinks, direction, magnitudes, connections, and dependencies of material flows can be analyzed by applying material flow analysis (MFA), as in the present work (Section 1.5). In addition, social relations and social networks, such as village organizations, links between villagers and district governments, etc., need to be identified. The latter is required for the involvement and participation of both the local community and the authorities in any strategic project at the planning and implementation stages. Methodologies that can contribute are manifold, and include, among others, participatory rural appraisal (PRA), multi-criteria decision analysis (MCDA), and constellation analysis. As concrete measures of 'sustainable' soil fertility management in the context of SSA, the IAASTD and FAO promote agroecology and integrated plant nutrient management (IPNM) (FAO, 2014; FAO, 2016; Markwei et al., 2008), two comparable concepts which are further explained in the next but one paragraph. Finally, Tittonell (2016) underlines the importance of applied soil science, and demands a focus on soil management strategies from analysis (i.e. '*How does it work?*') to the design (i.e. '*How to make it work?*').

Towards 'sustainable' agriculture and soil management.

This table 1.1 outlines specific strategies and actions for practitioners as well as tasks for researchers, which have been identified for strengthening smallholder agriculture, and for maintaining and restoring the productivity of soils. The recommendations and requests presented in table 1.1 have been formulated within the last decade by scientists and practitioners and include the perspectives of the following groups and individuals:

1. Representatives of international organizations and movements representing small-scale food producers, under the umbrella of La Via Campesina (2015), who demand a transformation of food production towards *food sovereignty*;
2. The FAO (2015a) provides 'Guidelines for Action' to restore and to rehabilitate global soil quality in the Revised World Soil Charter (RWSC)[31];
3. Montanarella et al. (2016) summarize the results of the SWSR, and suggest most important following actions as a consequence of the SWSR;
4. The IAASTD, namely McIntyre et al. (2009a) and Kiers et al. (2008), consider agriculture to be 'at a crossroads', and emphasize the importance of small-scale farming in order to take advantage of its high water, nutrient, and energy-use efficiencies, and its potential to conserve resources and biodiversity;
5. Lal (2009), as an environmental and soil scientist, has observed and underlined the significance of ongoing global soil degradation, as well as the need for soil fertility management for more than four decades;

[31] Most actions recommended in the RWSC, however, refer either to promoting 'sustainable' soil management or to developing soil information and monitoring systems alongside soil policies; only few suggestions are more precise about how to reach 'sustainable' soil management. For example, Principle no. 5 of the RWSC reads: '*Soil management is sustainable if the supporting, provisioning, regulating, and cultural services provided by soil are maintained or enhanced without significantly impairing either the soil functions that enable those services or biodiversity. The balance between the supporting and provisioning services for plant production and the regulating services the soil provides for water quality and availability and for atmospheric greenhouse gas composition is a particular concern.*'

6. Tittonell (2016), as an agronomist, summarizes insights, findings, and understandings from recent soil science in order to support knowledge implementation, and to contribute to food security.

In addition, I point out how I myself have addressed issues of soil fertility management in the analysis of smallholder farming systems in Karagwe in my work.

Applied concepts of soil fertility management.

Agroecology[32] and IPNM are widely agreed prerequisites in order to improve soil conservation and amelioration (Camacho and Krämer, 2016; FAO, 2014; Lal, 2006; Lal, 2009; La Via Campesina, 2015; Tittonell, 2016; De Schutter, 2011). Material cycling within the agroecosystem represents an essential element of both concepts[33]. When tailored to a particular cropping system, IPNM aims to provide a solution to the triple challenge of (i) improving land productivity, (ii) sustaining soil fertility, and (iii) reducing environmental degradation (FAO, 2016). Applied IPNM, as well as agroecology, combine (i) the use of organic amendments, such as compost, farmyard manure, mulch, etc., with (ii) the use of mineral fertilizers, alongside (iii) practices including intercropping, crop rotation, biological N-fixation (BNF), agroforestry, liming, low or no tillage, erosion control, water management, etc.[34]. Such practices, concepts, and technologies have often been applied in practice, and were proven to be successful for soil fertility management (Batjes and Sombroek, 1997; Blanco-Canqui and Lal, 2008; Buresh et al., 1997; Lal, 2009; La Via Campesina, 2015; Roy et al., 2006; Sanchez et al., 1997).

Composting, for example, is a widespread and common method, whereby various organic residues mixed with mineral components, are aerobically and bio-chemically decomposed by macro- and microorganisms. Access to synthetic fertilizers or to lime, however, is often financially and/or logistically restricted to subsistence farmers in large areas of SSA (Markwei et al., 2008). For this reason, the IAASTD promotes the use of locally available resources (Kiers et al., 2008) in particular. Pursuant to Buresh et al. (1997), however, on-farm availability of organic matter is also restricted in the case of many smallholders in SSA, due to poor land productivity. Moreover, existing organic materials tend to be characterized by comparatively low P content (Sanginga and Woomer, 2009). Pig and poultry manure, which constitutes a possible P-rich resource, is often not sufficiently available, especially to structurally poor farming households in SSA (Nziguheba et al., 2016). For these reasons, a lack of P is a very common factor in limiting plant growth in SSA (Buresh et al., 1997). Consequently, many smallholders face being locked into a vicious circle of low soil P, resulting in low production of food crops, and thereafter, a limited supply of organic material for soil fertility management via mulching or composting.

[32] Agroecology can also simply be described as ‘farming with nature’ (Scherr and McNeely, 2008; Tittonell, 2016).

[33] For this reason, Tittonell (2016) compared agroecology to the approach of ‘cradle-to-cradle’ (C2C), which became popular within the last decade in the industrial design sector.

[34] *BNF* refers to including legumes in crop rotation; *agroforestry* refers to growing trees on or around fields used for crop production; *liming* is applied for acidity management; *erosion control* comprises methods for reducing soil erosion, such as planting cover crops, mulching with crop residues, manuring, and stabilizing slopes and terraces with contour hedgerow systems or slow forming terraces; *water management* includes water harvesting and recycling, efficient irrigation systems, using drought resistant or tolerant crops, and *in-situ* water conservation in the root-zone.

Table 1.1: *Overview of suggested strategies towards 'sustainable' agriculture and soil fertility management.*

Work of:	Strategies to foster local agriculture and regional economies:	Strategies for applied and appropriate soil management:
1. La Via Campesina (2015)	Building local food systems; collective self-organization and solidarity; linking rural and urban populations.	Small-scale agriculture based on agroecological principles such as building life in the soil, recycling nutrients, managing biodiversity and energy conservation in a dynamic way and at all scales, resource efficiency, synergies; production practices promoted include intercropping, manuring, compost, integrating crops, trees, livestock and fish, etc.
2. FAO (2015a)	Locally-adapted, for example to socio-economic context, to local and indigenous knowledge, etc., and fostering the rights of smallholders, for example through land tenure, financial services, educational programmes, etc.	Measures adapted by local decision-makers and developed by multi-level and interdisciplinary stakeholders.
3. Montanarella et al. (2016)	Primary focus on those regions where people are most vulnerable, especially in tropical regions with depleted soils and food insecurity.	Locally appropriate management practices, such as for realizing circles of elements, water and energy and for stabilizing and restoring stocks of SOC/SOM.
4. McIntyre et al. (2009a); Kiers et al. (2008)	Optimised rural supply chains, for example with small seed companies, improved infrastructure, such as paved streets, etc.; increased local addition of value; empowering local communities.	Protecting natural resource base; ecological provisioning of agricultural systems; small-scale agroecosystems.
5. Lal (2009)	Improving land tenure; addressing gender and social equality; offering micro-finance for purchasing inputs; paying farmers for ecosystem services.	Enhancing SOM; improving soil structure and biology; conserving water in the root zone.
6. Tittonell (2016)	Production should follow the need, i.e. produce the food where it is needed.	Restoring degraded soils; apply recycling and utilize locally available resources; providing ecosystem services to ameliorate environmental destruction.
My contribution	Increasing fertilization and soil improvement through circular economy on a farm-level and subsistence production of fertilizers in order to ultimately raise local food production.	Intersectional resource management based on the principles of agroecology, circular economy, IPNM, and *Terra Preta*.

As explained earlier in Section 1.2, human excreta constitutes a valuable and locally available resource for plant nutrients, especially for P and N. Recovering these nutrients while avoiding risking human health is, therefore, of utmost importance. Taking into account the fact that mineral P fertilizer is not a long-term option due to the fact that we are expected to reach global '*peak phosphorus*' as early as 2030 (Cordell and White, 2011), this option is also of global relevance. In addition, residues from cooking can further contribute to recycling nutrients, for example, from ash or biogas slurry, or to recovering C from biochar (Section 1.1).

Table 1.1: *(continued) Overview of suggested actions for 'sustainable' agriculture and soil fertility management.*

Work of:	Concluded actions on how to manage materials:	Proposed focus for science and technology:
1. La Via Campesina (2015)	Material recycling; using local seeds and animal breeds; ban on using agro-toxics, artificial hormones, genetically modified organism (GMO), etc.; drastic reduction of external and industrial inputs.	Inclusion of peasants in research, for example, to control research agenda, to define objectives, to choose methodologies, etc.; identify, document, and share good experiences of local initiatives, especially those addressing climate change.
2. FAO (2015a)	Limiting the accumulation of contaminants through regulations.	Supporting 'sustainable' soil management relevant to end users.
3. Montanarella et al. (2016)	Reducing and stabilizing global fertilizer use in general; *but* increasing N- and P-inputs in regions with nutrient deficient soils, such as in many areas in SSA.	Improving and actualizing existing databases on global soils.
4. McIntyre et al. (2009a); Kiers et al. (2008)	Using locally available resources for realizing almost-closed natural cycles, while using industrial mineral fertilizers is no option for subsistence farming.	Orienting on IPNM; developing technologies with lower environmental impacts; up-scaling the principles of small-scale farming systems to larger-scale farming.
5. Lal (2009)	Creating positive C budgets; strengthening nutrient cycling.	Making fertilizers available to farming community through developing local sources of fertilizer.
6. Tittonell (2016)	Promote decoupling and reduce the use of non-renewable resources.	Knowledge-based reduction of risks for farmers implementing soil management practices; being creative and innovative to design 'sustainable' soil management strategies.
My contribution	Using resource-efficient technologies and recycling locally available residues from cooking and sanitation for soil fertility management.	Action research based on an interdisciplinary scientific approach; catching up with locally identified research demand, and communicating and discussing results with representatives of the community.

One prominent and proven example of soil management with a long-lasting positive effect on soil fertility is know as *Terra Preta*[35]. These human-made soils are found in the Amazon Basin (Sombroek, 1966). *Terra Preta* production evolved centuries ago, and it is most probably the product of managing 'wastes' and soil jointly. Such integrated and, obviously, sustainable resource management has also included the use of residues recovered from cooking and from sanitation (cf. Glaser et al., 2002). Kammann et al. (2015) report that for the creation of *Terra Preta*, biochar (Section 1.1) was 'used in mixtures of manures, human faeces, food waste and agricultural residues'. Historically, biochar was an essential element of soil fertility management and has been applied all over the world (Wiedner and Glaser, 2015). *Anthrosols* similar to *Terra Preta* are also found, for example, in Australia and New Zealand (*ibid.*), or in West-Africa, where they are called 'African Dark Earth' (Frausin et al., 2014).

[35] *Terra preta* is Portuguese for 'black earth'.

Compared to surrounding soils (e.g. Ferralsol, Acrisol, or Arenosol), *Terra Preta* soils often show a significantly higher availability of important plant nutrients, especially P, but also of calcium (Ca), manganese (Mn), zinc (Zn), etc., and a moderate pH, which provides suitable conditions for plant growth (Falcão et al., 2009; Lehmann et al., 2003). Other characteristics of the soil include adequate water retention capacity and adequate effective cation exchange capacity (CEC_{eff}) (Lehmann et al., 2003). Biochar plays a major role in the specific properties of *Terra Preta* (cf. Section 1.1, p. 7). Depending on soil and climate conditions, charred matter is not decomposed as rapidly as other organic materials and can build up a recalcitrant stock of SOM[36] (Lehmann et al., 2015). Biochar amendments are thus potentially important in order to realize C-sinks to combat climate change (i.e. 'C-sequestration'). In view of the latter, and the outstanding fertility observed, *Terra Preta* is nowadays often seen as a role model for 'sustainable' soil management. There is reasonable doubt, however, that the application of biochar is recommended in all situations, and on all soils. Mukherjee and Lal (2014) pointed out that field-scale data on crop response and soil quality in particular are lacking for various soil-biochar combinations.

Against this backdrop, I asked myself the following question:

> *How* can we transpose the principles of *Terra Preta* genesis to the present day, and, based on this, realize 'sustainable' soil fertility management (i) in an effective, efficient and creative way, (ii) adapted to local socio-economic and *agro-eco-logic* systems, and (iii) by using locally available materials?

A corollary of applying *Terra Preta* principles to contemporary practice is the need to answer the following question: *How do we acquire biochar*?

Producing charcoal and using it as a soil amendment!?

The 'appropriateness' of any biochar-approach highly depends, for example, on the biomass used for carbonization, on a possible utilization of biochar in cascades, or on the carbonization processes and technologies applied (cf. Kammann et al., 2015; Smebye et al., 2017; Sparrevik et al., 2014). For producing biochar, various bioenergy technologies can be implemented (cf. Boateng et al., 2015; Joseph et al., n.d; Lohri et al., 2015 and 2016; Taylor, 2010).

Biochar is most often produced via *pyrolysis*[37] (e.g. Boateng et al., 2015; Brown et al., 2015; Taylor, 2010). The most common pyrolysis technologies applied in SSA are either aboveground or underground *earth kilns* (Girard, 2002; Malimbwi and Zahabu, 2009). Despite the advantages of low-cost and simple construction, the main problem with these kilns is emissions of synthesis gases and smoke (Kaltschmitt et al., 2009). These emissions are a nuisance for people in the immediate surroundings and are associated with negative environmental impacts (Sme-

[36] Lehmann and Kleber (2015) recently criticized the traditional model of 'labile and stable organic compounds', and their role in the genesis of long-term 'stable' SOM. Lehmann and Kleber argue that the degradation of SOM and other organic matter in the soil is rather a continuum, and depends on many factors, including accessibility of matter, microbial ecology, energy transportation processes, and prevailing temperatures affecting enzymes, etc.

[37] Pyrolysis takes place at temperatures between 400 and 700 °C, at ambient or elevated pressure, and in the absence of oxygen (Antal and Grønli, 2003).

bye et al., 2017). Another disadvantage is that firewood is the main resource for pyrolysis in many regions of SSA, including TZ (Ellegård et al., 2003; Msuya et al., 2011). The average efficiency of earth kilns is relatively low, and yields of DM of charcoal range from approximately 9.5 % (Malimbwi and Zahabu, 2009) to around 30 % (Pennise et al., 2001) per DM of firewood. More efficient alternatives for low-cost carbonization are available (Lohri et al., 2015), however. For example, an improved, low-cost, and supposedly more 'environmentally friendly' pyrolysis system was developed by Adam (2009), known as the 'Adam Retort Kiln'. Another simple pyrolysis kiln technology was recently presented by Schmidt and Taylor (2014), called the 'Kon-Tiki'. This latter can be produced at reasonable costs, operates without smoke, and is therefore especially feasible for smallholder systems (*ibid.*).

Biochar can additionally be produced via *hydro-thermal carbonization* (HTC)[38] (e.g. Funke and Ziegler, 2010; Titirici et al., 2015). The product of HTC is a coal-like substance contained in a liquid. The solid product is called 'hydrochar', following Wagner (2014). Positive effects on soil quality and plant growth by amending the soil with hydrochars are, however, still questionable[39]. Busch et al. (2012) demonstrated certain bio-toxic characteristics of hydrochars[40]. Furthermore, the construction of a HTC-reactor requires high-quality material and is cost-intensive (Krause, 2010; Lohri et al., 2016).

Finally, utilizing residues from micro-gasification as biochar is a particularly promising approach for generating environmental benefits in rural tropical conditions (Smebye et al., 2017). This is, to the best of my knowledge, yet to be thoroughly researched.

The 'way forward' from an analysis of possible means of soil fertility management in Karagwe.

In summing up, implementing circular economies, while considering 'waste' as a resource, are connecting elements in the concepts of agroecology, IPNM, *Terra Preta*, EcoSan, and also of my work. My research interest has been to study 'innovative' and recycling-based soil management practices on the example of Karagwe in TZ. I focus particularly on researching (i) the co-composting of human excreta with biochar produced in microgasifier stoves, and (ii) using locally available biogas slurry as fertilizer. This Fig. 1.6 visualizes the connection of bioenergy alternatives potentially applied for cooking, and introduced in Section 1.1 (left side), with the CaSa approach to EcoSan introduced in Section 1.2 (top-right side), and the recovery of residues from both, cooking and sanitation, for either composting or direct soil amendment (bottom-right side).

[38] The HTC-process is a technical reproduction of the natural coalification process, which takes places under elevated pressure and high temperatures, while the biomass is enclosed in liquid water or water vapour.

[39] For example, Gajić and Koch (2012) as well as Bargmann et al. (2014) reported that amending hydrochar to the soil decreased the plant-available N, and attributed this observation to its immobilization. Moreover, depressed plant growth was reported *inter alia* from Gajić and Koch (2012) and Wagner (2014). Steinbeiss et al. (2009) found that the stability of C in the soil is lower for hydrochars when compared to pyrochars.

[40] Titirici et al. (2008) showed that toxic substances, including various furfurals, are intermediate products of the HTC-process. At the end of the process, they can possibly still be present on the surface of the hydrochar or remain in the process water.

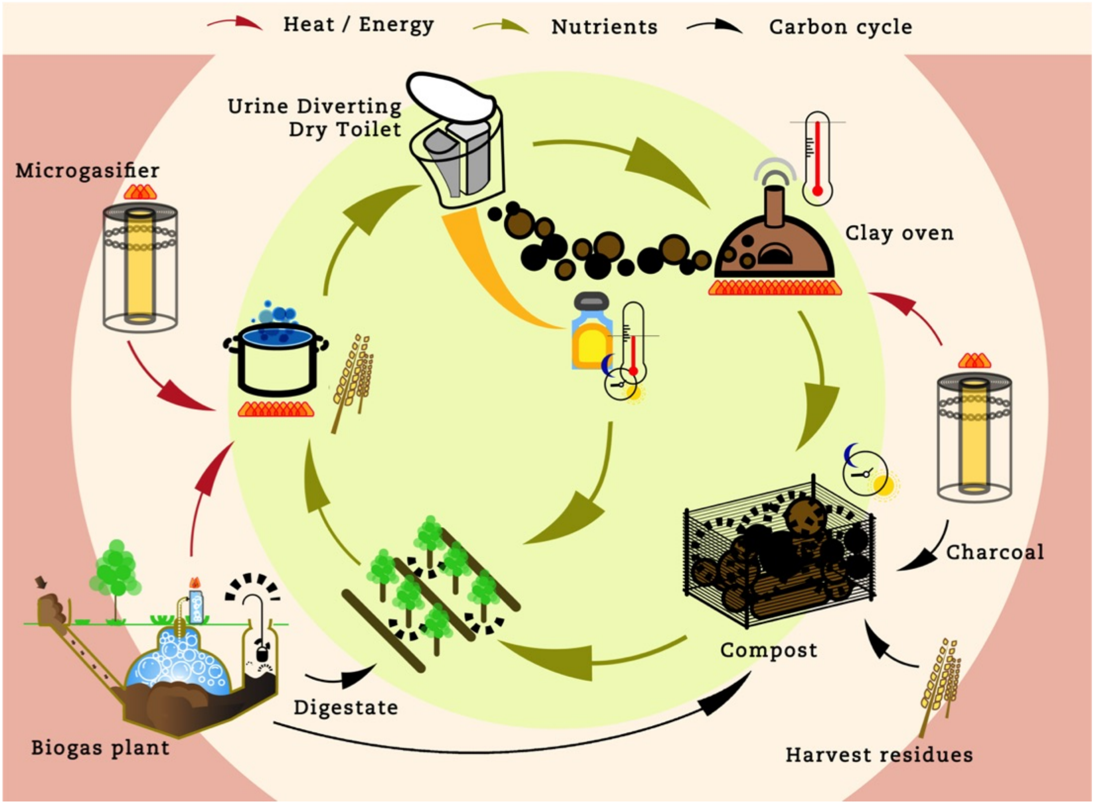

Figure 1.6: *Intersectional resource management using residues from cooking and EcoSan for soil improvement in the context of smallholder farming in Karagwe. [Infographic (CC) designed by Ariane Krause and Lusi Ajonjoli.]*

My overall scientific interest in the field of soil fertility management can be summed up as follows:

1. To study the use of locally available biochar co-composted with human excreta, as well as biogas slurry, in regard to short-term effects on crop productivity and fertility-related soil characteristics;
2. To estimate the extent to which residues from cooking and sanitation can serve to cover the demand of organic and mineral inputs to the local soil in smallholder farming systems in Karagwe; and
3. To analyze the effect of possible integrated fertilization strategies on local soil humus and nutrient balances.

1.4 Study area and case studies

In this section, I first introduce the study area of my work with the emphasis on local smallholder agroecosystems. I then elucidate the specific characteristics of local soils, and locally applied means of soil fertility management. Thereafter, I introduce the case study projects, and explain how my work relates to them.

Study area: Karagwe District.

The study area of the present work is the rural area of Karagwe District (lat. 01°33' S; long. 31°07' E; alt. 1500 - 1600 m.a.s.l.). Karagwe is one of eight districts in Kagera Region in northwest TZ (Fig. 1.7). Kagera is part of the Lake Victoria Basin, and is located near to the volcanic areas of the East African Rift Zone. The biggest city of Kagera is Bukoba, which is situated on the shore of Lake Victoria. The administrative and economic centres of Karagwe are the towns of Kayanga and Omurushaka respectively. The typical terrain of Karagwe District consists of hills and valleys[41] (Fig. 1.8). According to the last national census, approximately 2.4 million people live in Kagera Region - about 6 % of TZ's population (Tanzania, 2012). Kagera is, in general, moderately densely populated with approximately 85 inhabitants per square kilometre[42]. About one quarter of Kagera's population is situated in Karagwe.

The regional economy is dominated by smallholder agriculture with about 90 % of households selling agricultural products grown on their farms (Tanzania, 2012). The majority of households in Kagera region (> 71 %) are involved only in the cultivation of crops (*ibid.*), in contrast to rearing livestock, or a combination of the two. Banana is the most prominent perennial crop, while beans and maize dominate annual cropping. Within Kagera, Karagwe is the main producer of onions, and has the second largest area cultivated with cabbage. Crops are usually sold at local markets, or distributed to national markets through locally operating intermediaries (Mavuno, 2015). Rainfall is bimodal (March-May and October-November), and varies between 500 and 2,000 mm yr^{-1}, while mean temperatures range from 20 to 28 °C during the day (Tanzania, 2012). This semi-arid and tropical savanna climate (according to the Köppen-Geiger climate classification in Peel et al., 2007) allows twice-yearly harvests for most annual crops.

The agroecosystem in Karagwe

Specific characteristics of agriculture in Kagera and Karagwe have been described, *inter alia*, by Baijukya et al. (1998), Rugalema et al. (1994), and Tittonell et al. (2010). The following paragraph is based on these references and supplemented by statistics presented in Tanzania (2012):

Typically, farms are located individually and scattered in the vicinity of town or village centres. Dwellings are located at the centre of the farm and are concentrically surrounded by agricultural land. A farm usually comprises of *shamba* and *msiri*[43]. *Shamba* typically features a multi-layer design with diverse crops: high-growing, shady perennial crops, such as banana plants or fruit and coffee trees, are intercropped with low-growing, annual crops as cover crops, such as beans, cassava, wild varieties of African egg-plant, etc. As the *shamba* most commonly consists of the land directly surrounding the house, it is also translated as a 'banana-based home garden'

[41] As visible in Fig. 1.8, hills are often eroded and coloured red from the exposed soil. The valleys, meanwhile, are damper and green with vegetation.

[42] My own calculation from a population count of 2.4 million inhabitants (Tanzania, 2012) and a geographical land coverage of 28,500 km^2 (Kagera, 1997). In comparison, TZ as a whole, Germany, and Bangladesh have population densities of approximately 60, 230, and 1,240 inhabitants per square kilometre, respectively (WBI, 2016d; WBI, 2016e; WBI, 2016f).

[43] In Swahili, 'shamba' means *field*; *shamba* and *msiri* are locally also called *kibanja* and *kikamba*, respectively; see Figs S.1 and S.2 in Supplements S2 in the General Annex.

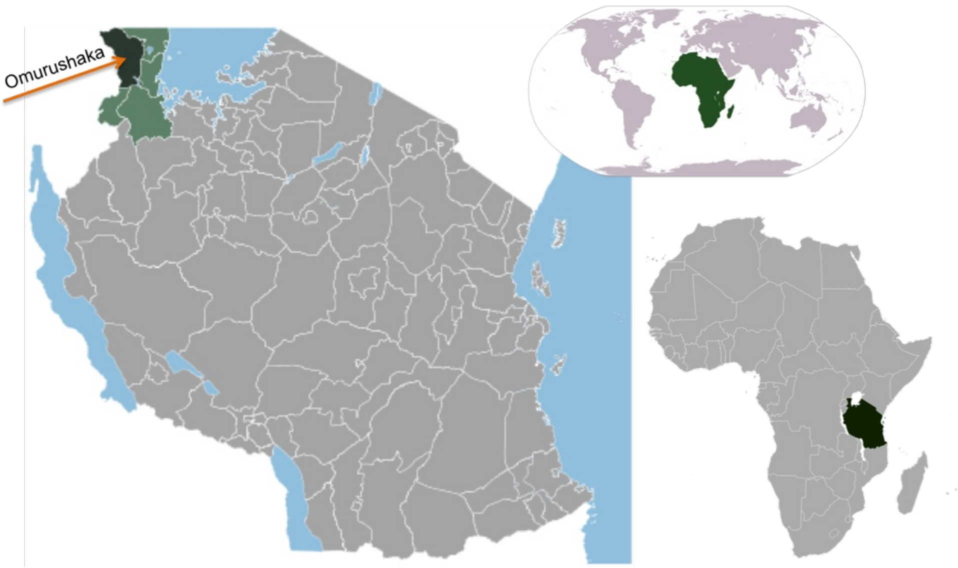

Figure 1.7: *Map indicating the location of Karagwe District (dark-green, to the left) in Kagera Region (green, to the left) in northwest Tanzania (dark-green, bottom-right) in Africa (green, centre-top) (Wikimedia Commons, 2016).*

into English. The *msiri* is used for intercropping annual crops, such as maize, beans, cassava, vegetables, etc. Most commonly, the *msiri* is found on fields close to the farm itself and is often on land that was formerly grassland. The *shamba* is the most important type of land use for agriculture in Kagera, accounting for >40 % of total agricultural land. *Msiri* cultivation, meanwhile, is implemented on about one fifth of the farmland. The third-most important land use is mono-cropping of annual crops, which is practiced on about 15 % of total agricultural land[44]. In addition, kitchen gardens for vegetable cultivation, locally called *bustani*, have recently been promoted to farmers by local initiatives. The aim is to increase the production of nutrient and vitamin rich crops in order to supplement a diet based mainly on starchy banana as its staple food and supplemented with beans for protein. Providing a more diverse and healthier diet would contribute to food security for subsistence farmers, and strengthen their immune systems for the fight against diseases such as malaria.

Rural livelihoods in Karagwe District.

On average, a Karagwe household comprises six individuals (Tanzania, 2012). Sanitation facilities in Karagwe are mainly pit latrines: 88 % of households use standard pit latrines, compared to just 4 % of households using improved pit latrines; only 1 % of households possess a system of flush or pour toilets in combination with septic tanks, and 6 % do not have any toilet facilities at all[45] (*ibid.*). The main resource for cooking is biomass: 96 % of households use firewood, while about 3 % use charcoal[46] (*ibid.*). These patterns, alongside population growth, have increased pressure on natural resources, including soil, open and running water, forests, etc., over the last three decades (Ogola, 2013; Rugalema et al., 1994).

[44] The remaining 25 % of farm land is used for tree planting, left fallow, or set aside for animal husbandry (Tanzania, 2012).

[45] The remaining 1 % was not further specified, and categorized as 'other types' (*ibid.*).

[46] The remaining 1 % use 'other sources' (*ibid.*).

Figure 1.8: *The characteristic landscape of Karagwe with hilly terrain [picture (CC) by Ariane Krause, 2012].*

The average household income in Kagera ranges from about 0.5 to 1.5 million Tanzanian Shilling (TZS) per year (IFAD, 2003; Kirchberger and Mishili, 2011; Lwelamira et al., 2010). Farming households access, on average, 0.75 ha of usable land, of which, about 0.63 ha is planted land per farm (Tanzania, 2012). This classifies them as smallholders, pursuant to Dixon et al. (2004)[47]. Crop farming is the main occupation and sustains the livelihoods of approximately 84 % of Karagwe households (*ibid.*). About one tenth of agricultural income derives from selling cash crops; mainly coffee. In addition, business incomes, wage salaries, and other casual earnings contribute to cash income for approximately 16 % of Karagwe households (*ibid.*).

In Karagwe, there are, in general, two types of smallholder farms (Baijukya et al., 1998; Rugalema et al., 1994; Tanzania, 2012; Tittonell et al., 2010):

- Fully subsistent farms:
  - Mainly without animal husbandry, some keep small animals, such as chickens, rabbits, guinea pigs, etc.;
  - With little inputs to agriculture, mainly through recycling of residues for mulching and carpeting with grasses; and
  - Some practice of shifting cultivation.

[47] According to Dixon et al. (2004), smallholders ‘often cultivate less than one ha of land, whereas they may cultivate 10 ha or more in semi-arid areas’.

- Partially subsistent farms:
  - Farmers work only part-time and gain additional income from off-farm work;
  - With livestock, including 'zero-grazing' – or intensive indoor rearing cows; and
  - More intensive agricultural inputs through purchasing mulching material, (synthetic) fertilizers, and seeds, as well as hired labour.

Farmers of the partner organizations of this research mainly belong to the first group of fully subsistence farmers[48] and practice *organic farming*. Smallholder farms are not located on 'private land'. National land policy and existing land tenure systems in TZ imply that all land is public land (Ogola, 2013). Following the Land Act and the Village Land Act of 1999, the president of TZ is officially assigned as a trustee for all citizens, whilst district and village councils manage land tenure locally. Access to land is provided to citizens either through 'unwritten customary rights of occupancy', or through 'certified granted rights of occupancy'[49] (*ibid.*). Customary and granted rights of occupancy are both usually valid for 99 years, and can be passed on to children and grandchildren. Although policies, laws, regulations, and by-laws on 'sustainable' land and agroecosystem management exist, institutions do not enforce them (*ibid.*). As a consequence, effective resource management is not supported sufficiently by the government, and resource-related conflicts in Kagera grow steadily worse (*ibid.*). Increasing fragmentation of farmland land, due to population growth, also places ever-higher demands on the land for sustaining food security and farm incomes (Rugalema et al., 1994). As a consequence, a strong demand for an increase in agricultural productivity is generated. With regard to the regional economy, the local soil is among the most important production factors for local communities, consequently assigning significant importance to conservation and amelioration of agricultural soils.

Soil pre-conditions in Karagwe.

Local soil in Karagwe and Kagera may be classified as an *Andosol*[50] (Batjes, 2011). Worldwide, Andosols are present on just 1 - 2 % of the land surface area, most commonly in areas with dense population where these soils are used for arable cultivation (Chesworth, 2008). Andosols are often located at higher altitudes and/or in volcanic areas, such as the East African Rift Zone, and originate from the weathering of volcanic materials, especially glasses (*ibid.*; Perret, 1999). In hilly areas, Andosols are mainly found at the top of slopes, in combination with Cambisols or Luvisols on hillsides, and Acrisols or Vertisols on valley floors (Driessen et al., 2001).

[48] According to Mavuno (2014), members of the partner organizations '*are largely responsible for their own economic and social sustainability given that the land provides almost all their immediate requirements including food (bananas, beans, maize and cassava), firewood for fuel, and cash crops (coffee) for money for other uses*'.

[49] Granted rights of occupancy can also be 'bought' by non-Tanzanian citizens from the government, which has been criticized for this practice (e.g. FIAN, 2010; Kachika, 2010; Roosa, 2017; or farmlandgrab.org, africaland-grab.com, etc.). Such post-colonial behaviour, called '*land grabbing*', has, to the best of my knowledge, not yet been an issue in Karagwe in the way it has in other regions of TZ (FIAN, 2010; Kachika, 2010). For example, the company Agrica Limited has accessed land rights for >5,000 ha in the fertile Kilombero Valley, where the company produces mono-culture maize. In the closing statements of the *Tropentag* Conference in Berlin, 2015, Cater Coleman, founder and chief executive officer of Agrica, referred to himself as a 'land grabber'. Agrica Limited declares itself as the 'leading rice producer in East Africa' and its board of directors consists entirely of non-Tanzanian men of European origin. Assuring access to land and land rights for farmers is, however, a prerequisite for motivating farmers to manage the land appropriately. Despite its impact on local agriculture in the SSA context, a more in-depth discussion of such socio-political aspects remains out of scope of my study.

[50] The name *Andosol* derives from the Japanese word *an do* meaning 'black soil' (Zech et al., 2014).

Andosols display unique properties and high fertility, making them especially suitable for growing crops such as coffee, tobacco, banana, etc. The greatest challenge is the tendency of Andosols to retain P (Zech et al., 2014). According to Perret and Dorel (1999), shifting cultivation has typically been practiced on Andosols. When Andosols are cultivated under fixed systems, loss of soil fertility through depletion of soil nutrients becomes a problem when cultivation is practiced without sufficient nutrient replacements (Perret and Dorel, 1999; Dorel et al., 2000). Intensive, mechanized production, meanwhile, causes further detrimental mechanical stress and destroys soil structure (*ibid.*). In order to sustainably cultivate Andosols, and to guarantee (high) crop production, necessary fertility amelioration measures include regular use of manure and/or other organic material, P-fertilization, liming, etc. (Driessen et al., 2001; Tonfack et al., 2009). Non-tillage techniques are further recommended, while it is advisable to abandon the use of heavy machinery in order to reduce the frequent and heavy disturbance of the soil (Perret and Dorel, 1999; Abera and Wolde-Meskel, 2013). Andosols can act CO_2 sinks, even under acid soil conditions, due to the fact that they tend to accumulate organic C through the formation of metal-humus-complexes and allophanes (Chesworth, 2008; Driessen et al., 2001). Abera and Wolde-Meskel (2013) conclude that more research should be conducted into Andosols, particularly in the East African Rift Zone. They further emphasize the investigation of appropriate management practices for enhancing soil fertility, agricultural use, and sequestering C for the 'sustainable' use of Andosols.

Soil management applied in Karagwe.

Numerous surveys and rural appraisals have indicated that declining soil fertility is the principal obstacle for farmers in Karagwe (Baijukya et al., 1998). As is the case for many smallholders in SSA, farmers in Karagwe are especially challenged by soil constraints, including erosion due to hilly landscapes, soil acidity with pH < 4.0, nutrient deficiencies in general, and, in particular, the scarcity of potentially plant-available P in the soil[51]. The latter is promoted by low pH and also by the specific properties of the local Andosol type (Zech et al., 2014). According to Rugalema et al. (1994), the growth of the market economy within the last decades, especially in regard to cash-crops such as coffee and banana, has increased the export of nutrients from the region. Despite *current* N-uptakes of crops often exceeding N-inputs to the soil with mineral and organic fertilization (Baijukya et al., 2006; UNEP, 2007), in the past, nutrient input and output flows have apparently been more balanced in the region. According to Baijukya et al. (1998) and Rugalema et al. (1994), appropriate inputs of nutrients were realised by the following means:

- Effective recycling of all residues back to agricultural land;
- Importing nutrients from the surrounding grasslands in the form of fodder for livestock;
- Recovering nutrients by applying human excreta to holes dug in the *shamba* for planting new banana trees[52].

[51] Identified in pre-studies conducted by myself in Karagwe in 2010, based on soil sampling, laboratory analysis, and questionnaires.

[52] Rugalema et al. (1994) reported that '*in the past it was common for farmers to deposit human excreta on each stool of banana on rotation basis, a practice locally known as omushote. The practice was largely abandoned*

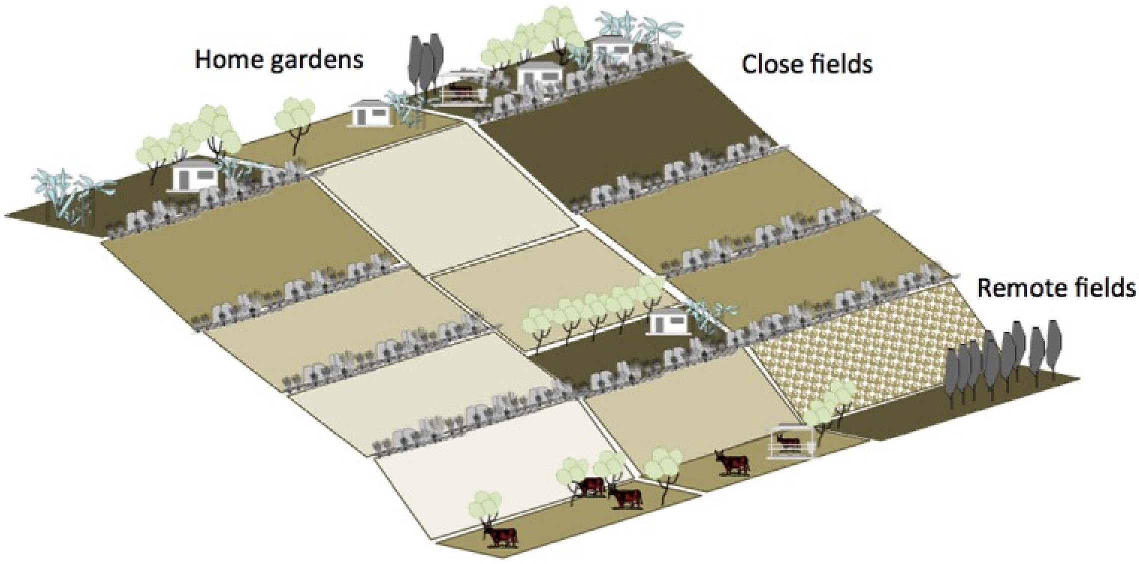

Figure 1.9: *Soil fertility on smallholder farms in East Africa typically shows a discrete patterning and spatial heterogeneity. Fertility is thus characterized by 'discrete soil gradients', after Tittonell (2016).*

According to Tittonell (2016), farmers in East Africa often pay special attention to a certain portion of their land where specific, highly-valued crops are cultivated (Fig. 1.9). This may result in that which Tittonell described as 'islands of soil fertility'. Many farmers in Kagera are proud of their typically well-managed banana-based home gardens (Rugalema et al., 1994). The *shamba* commonly receives sufficient inputs of agricultural and domestic 'waste' as it directly surrounds the farm. The *msiri*, situated on close fields, often receives fewer inputs and is, therefore, typically more adversely affected by nutrient depletion. Grasses for feeding livestock tend to be collected from fields further away, while dung is used in the home gardens. This practice actively imports nutrients to the home gardens, while worsening nutrient depletion on the remote fields. According to Tittonell (2016), soil fertility in Karagwe is characterized by such 'discrete patterns of spatial heterogeneity'. This means that soil fertility declines with distance from the farm houses (Fig. 1.9). In regard to balancing inputs and outputs of soil nutrients for the *shamba*, Baijukya et al. (1998) showed that structurally poor households without cattle are most affected by declining soil fertility. As countermeasures, Baijukya et al. made recommendations including the increased use of compost and effective recycling of all household refuse, including human excreta. Standard compost in Karagwe contains a mixture of fresh and dried grasses, ash, kitchen waste, and depending on the availability, animal manure or leftovers from brewery processes. In addition, water is added (if available) to improve moisture content. Composting is carried out in batches, and usually takes around three to six months. Compost heaps are often placed in shallow pits under the shade of trees, and covered with soil and grasses to mitigate evaporation[53].

as pit latrines became widespread from the 1940s. Abandoning omushote has most likely contributed to a decline in soil fertility on the shamba'.

[53] Based on learning from a local agricultural technician, and on my own observations during pre-studies conducted in 2010.

Case studies supporting the present work.

There are three projects in Karagwe that are closely associated with this research work, acting as case studies to support it (Table 1.2). The three local projects are, namely[54]:

1. Biogas Support for Tanzania (BiogaST) aims at providing cooking energy from a biogas system comprising of a small-scale biogas digester with a plug-flow fermenter[55] using harvest and kitchen residues, and a 'LOTUS' biogas burner (Fig. 1.11);
2. Efficient Cooking in Tanzania (EfCoiTa) works with ICSs, such as Top-Lit UpDraft (TLUD) microgasifier stoves that operate with pieces of firewood or maize cobs (Fig. 1.10, right) and an improved sawdust microgasifier stove that utilises sawdust or coffee shells (Fig. 1.10, left);
3. Carbonization and Sanitation (CaSa) deals with EcoSan, including a squat-type UDDT (Fig. 1.12) and a clay oven for thermal sanitation of excreta via pasteurization, heated with a microgasifier (Fig. 1.12).

Two local farmers associations facilitate projects at a grass-roots level, namely MAVUNO[56] (Project for Improvement for Community Relief and Services) and CHEMA (The Programme for Community Habitat Environmental Management). Further information on both MAVUNO and CHEMA is summarized in the last paragraph of this section. The initiation of these projects followed demand from local communities, which had previously been identified by MAVUNO and CHEMA. The general motivations of the facilitating initiatives have been as follows:

- To meet the demand of local smallholder communities for 'sustainable' cooking and sanitation technologies;
- To reduce negative environmental impacts including deforestation through excessive use of firewood and soil degradation through nutrient depletion; and
- To sustain and, if possible, improve crop production for ensuring food security and increasing income generation.

More specifically, the primary objectives of the case study projects are as follows:

- Promoting 'sustainable' (ecological, reliable, and affordable) cooking in the region, with the approach of a diversification in the technologies applied, and, thus, in the resources used, in order to guarantee bioenergy supply for smallholders and to protect local resources;
- Implementing EcoSan in the region, with a barrier approach to sanitation and appropriate treatment of human excreta in order to allow for a switch in practices back to the use of human excreta as a soil amendment without risking human health;
- Implementing a circular resource economy, through increased recycling of nutrients and improved soil humus content, in order to improve local soil fertility and productivity.

[54] For further information on these projects, please visit (i) websites of MAVUNO (English) for BiogaST and for CaSa, of CHEMA (English) for EfCoiTa, and of EWB (German) for BiogaST, for CaSa, and for EfCoiTa or (ii) see articles by J. Schell (English) for BiogaST, for CaSa, and for EfCoiTa; and (German) for all three projects, for BiogaST, for CaSa, and for EfCoiTa (Please click on the projects' names in the soft copy of this thesis).

[55] Note: during the course of the present research, the design of the applied biogas technology changed. BiogaST now works with a small-scale biogas digester of the fixed dome digester type.

[56] *Mavuno*; 'harvest' in Swahili.

In order to meet the objectives, the following activities have been chosen:

- Implementing improved cooking facilities, including biogas systems and ICSs;
- Establishing EcoSan, including UDDTs, thermal sanitation, urine storage, and composting;
- Recovering biogas slurry, biochar from microgasifiers, and human excreta from EcoSan for CaSa-composting and soil amendment.

Table 1.2: *Characteristics of the three case study projects: overview of objectives, contents, applied technologies, and facilitating as well as partner organisations.*

Projects	CaSa	BiogaST	EfCoiTa
Contents	EcoSan with pasteurization of faeces and co-composting of human excreta and biochar (i.e. residues from using microgasifiers for thermal sanitation or for cooking) after the principles of Terra Preta.	Provision of cooking energy through small-scale biogas digesters using organic residues from farming for anaerobic fermentation.	Resource protection and 'sustainable' cooking through advanced microgasifier stove design.
Technologies	UDDT, sanitation loam oven, microgasifier stove, batch composting	Small-scale biogas digesters and biogas burner	Two kinds of domestic microgasifier stoves; also institutional ICS[a]
Facilitators	MAVUNO	MAVUNO	CHEMA
Partners[b]	TU, IGZ	CAMARTEC, EWB, TU, UH	EWB, TU

[a] *Not part of the present work.*
[b] Technische Universität (TU) Berlin, Germany; Leibniz Institute of Vegetable and Ornamental Crops (IGZ) Großbeeren, Germany; Centre for Agricultural Mechanisation and Rural Technology (CAMARTEC) Arusha, TZ; Engineers Without Borders (EWB) Berlin, Germany; Universität Hohenheim (UH), Germany

The perspective for implementation has been on a household as well as an institutional level. All projects are 'development cooperations' of Tanzanian and German partner organisations[57], and have been mainly funded by German donors with additional contributions from MAVUNO, CHEMA, and the local community. Several research activities, such as Bachelors, Masters, and PhD theses, have accompanied the projects since 2008. During the initial phases of 'technology development', new technologies and concepts were 'invented', and existing technological designs were adapted to local conditions. Framework conditions considered included local availability of materials for construction and operation, local skills, knowledge, awareness, etc. Then, technologies were tested in pilot projects in order to test them in the field, collect further data, and to demonstrate them to the community. Dissemination of these technologies began in 2015/2016. Each of the three projects follows a different approach: CaSa first focused on the institutional level and initially implemented its technologies at a girls' secondary boarding school run by MAVUNO. As yet, no detailed plans exist for implementation in households. BiogaST, meanwhile, has already installed three biogas digesters at a school, and eight domestic biogas digesters. EfCoiTa focused on selling stoves at the CHEMA workshop, at local markets, and

[57] A deeper analysis of motivations of and power relations between German and Tanzanian project partners has been studied by B. Barthel, a fellow PhD student from my research group, who has taken a 'post-colonial perspective on decentralized energies' and has analyzed, as one example case study, BiogaST.

through local shops. Their first marketing campaign and advertisement events in local markets began in 2016.

The 'way forward' from studying local challenges and potential opportunities in the study area.
In summing up, there is, for multiple reasons, a strong demand for soil fertility management and appropriate soil amenders in Karagwe. *Msiri* cultivation, typical for Karagwe, has not yet been fully researched. For this reason, I focus on an analysis of nutrient demands and potential coverages in such systems, and on researching realistic options for managing the local Andosol through the use of cooking and sanitation residues available from case study projects.

Facilitating organizations in the case study projects and partners of the present research.
MAVUNO was established in 1993 as a non-profit NGO and is based in Ihanda village, near Omurushaka. MAVUNO is an association of organic smallholder farmers and is run by the sons of one of the founders. The NGO aims to foster 'self-determined development and rural empowerment' through working in close collaboration with community members (Mavuno, n.d.). MAVUNO's activities extend to 10 villages in Karagwe and the neighbouring Kyerwa District, with more than 400 smallholder households organized under its umbrella. In total, nearly 10,000 people benefit from MAVUNO's services and workshops (Mavuno, 2015). MAVUNO facilitates BiogaST and CaSa. MAVUNO also operates a girls' secondary boarding school, where technologies have been implemented to contribute to the school's infrastructure.

CHEMA was established as an NGO in 1991, and is based in Omurushaka town. The legal owner of CHEMA is the Roman Catholic diocese in Kayanga. Most members of CHEMA are organic smallholder farmers. CHEMA aims to 'improving rural livelihoods through comprehensive village based natural resource management and sustainable agriculture' (Chema, n.d.). In addition, CHEMA's activities focus on 'intersectional issues' including gender, HIV, basic hygiene, and environmental education. CHEMA's work extends to 12 villages in Karagwe and Kyerwa districts. More than 560 smallholder households, 10 primary schools, and 13 groups of beekeepers participate regularly in seminars and workshops conducted by CHEMA in the villages and at its office in Omurushaka (Chema, 2016). CHEMA is actively engaged in developing and promoting the use of energy saving stoves and facilitates the EfCoiTa project. Stove technicians produce microgasifier stoves alongside rocket stoves in a workshop at CHEMA's premises.

Figure 1.10: *Microgasifier stoves analyzed in the present work comprise an improved sawdust stove (left) and a TLUD stove (right). Sketches (with cutaways) and photographs by D. Fröhlich.*

Figure 1.11: *The biogas system analyzed in the present work comprises a small-scale biogas digester (left and center) and a LOTUS biogas burner (right). Sketches and photographs of the digester from BiogaST (n.d.) and of biogas burner by Schrecker (2014).*

Figure 1.12: *The CaSa approach to EcoSan analyzed in the present work comprises a UDDT (left) and sanitation oven (right). Photographs by A. Krause, sketches from CaSa (n.d.).*

1.5 The scope of this research

In this section, I first recap the relationship between my research and the case studies. I then present the research objectives and questions, and explain the structure of my research approach. Overall, I classify my work as applied science based on environmental science, and with a strong interdisciplinary and transdisciplinary character.

Research interests and motivations from a practitioner's perspective.

My dissertation had as its starting point the intention to implement those cooking and sanitation technologies developed in the case study projects in Karagwe. Increased dissemination of these technologies leads to potentially higher availability of residues, such as biogas slurry from anaerobic digestion, powdery biochar from microgasifiers, and sanitised human excreta from EcoSan, all of which can be used for on-farm material cycling. As part of a team comprising local farmers and staff members of MAVUNO and CHEMA, I further jointly identified the need for transparent and 'holistic' systems analysis. Together we agreed that my work should include the following elements relevant for answering practitioners' questions (PQ) :

1. Estimation of the potentials for smallholders to reduce firewood consumption through changes in cooking technologies in households;
2. Estimation of resources required for managing toilet 'waste' in smallholder households through thermal sanitation as per the innovative CaSa approach;
3. Estimation of the potentials for smallholders, depending on the technologies applied, to capture household cooking and sanitation residues, and to recycle N, P, and C to farmland;
4. Assessment of whether the benefit of 'safe' recycling of nutrients and C through pasteurization is 'worth' the fuel consumption involved;
5. Assessment of potential to ameliorate local soil and to increase local food production from intercropping on *msiri* land;
6. Analyses of possible benefits and burdens for the environment through (adapted) environmental impact assessment (EIA);
7. Further sustainability assessment of the technologies analyzed in order to support regional strategic planning and local decision-making processes around implementation.

Research interests and objectives from a scientific perspective.

In previous sections, I have outlined my general scientific interests stemming from my analysis of decentralized, small-scale bioenergy provision (Section 1.1, p. 8), of domestic EcoSan (Section 1.2, p. 14), of agreed means for soil fertility management in SSA (Section 1.3, p. 22), and of the agroecosystem of the study area (Section 1.4, p. 32). With a focus on Karagwe, my overall aim has been to study potentials for circular economies in local smallholder farming systems and to include locally available technologies and the recovery of residues as resources. I have also been interested in identifying weak points in the system, especially from an ecological perspective. From an agronomic perspective, my interest has been to quantify the potential to increase agricultural productivity and, thus, the 'consumptive use' and the 'productive use' of soil management practices that utilize resources recovered from cooking and sanitation.

In detail, my primary research objectives have been as follows:

1. Laboratory-based quantification of the nutrient contents of locally available substrates, such as biogas slurry, CaSa-compost (i.e. co-composted human excreta and biochar), standard compost, plant residues, ashes, etc., in order to characterize the substrates and to determine their respective potential for fertilizing and ameliorating the soil of Karagwe;
2. Exploratory studies to collect initial evidence on whether locally available substrates used as soil amenders can increase (i) water and nutrients available in the soil under the given conditions, and (ii) crop biomass, while simultaneously maintaining or improving the nutrient content of food crops;
3. Model-based comparison of those cooking and sanitation technologies most commonly used in Karagwe against locally developed alternatives, with respect to (i) resource consumption, (ii) potential to recover resources, and (iii) environmental emissions assessed with global warming potential (GWP) and eutrophication potential (EP);
4. Model-based *ex-ante* assessment of residue integration from household bioenergy and EcoSan alternatives into soil fertility management through systematic comparison of specific IPNM approaches, including the use of biogas slurry, CaSa-compost, and urine on a farm level;
5. Identification of criteria and applicable methods to evaluate locally available technologies from multiple perspectives relating to sustainability and 'sustainable community development' (SCD), including the development and pre-testing of a tailored assessment tool; and
6. Estimation and evaluation of how different fertilization strategies based on locally available substrates affect (i) the production of crops for own consumption in the household ('consumptive use'), (ii) the production of crops to generate farm income ('productive use'), and (iii) the quality of local soils in the mid and long-term ('ecological use').

Research questions.
The overarching research questions has been as follows:

> *Does a combination of the implementation of locally developed cooking technologies and innovative EcoSan constitute an appropriate means to provide sustainable energy supplies and sanitation services, and, simultaneously, improve the quality of local soil as the major resource for food production and income generation for smallholders living in Karagwe?*

Against this background, I formulated several more detailed research questions (RQ) that built my framework for achieving my research objectives:

1. What is the nutrient concentration in locally available biogas slurry, standard compost, and CaSa-compost, and how can the amendment of these substrates potentially contribute to the availability of nutrients in the soil?

2. What effects of amending the local Andosol with biogas slurry, standard compost, and CaSa-compost can be observed on (i) soil physicochemical properties, (ii) biomass growth and crop productivity, and (iii) plant nutrient status?
3. How do locally available bioenergy alternatives, such as rocket stoves, microgasifiers, and biogas systems, compare to more widespread technologies, such as three-stone fires and charcoal burners, in terms of input, output, and potential recycling flows?
4. How does a locally available EcoSan facility, namely a UDDT, with or without additional thermal treatment of faeces, compare to septic tank systems with flush toilets, and the current practice of favouring pit latrines, in terms of input, output, and potential recycling flows?
5. How do identified modifications[58] in the farming system affect (i) soil nutrient balances, (ii) availability of resources for subsistence production of compost, and (iii) environmental emissions assessed with GWP and EP?
6. How do identified modifications in the farming system affect the availability of food crops for smallholders in Karagwe?
7. What are the most relevant criteria and applicable methods for assessing sustainability of small-scale cooking and sanitation technologies that are locally available in Karagwe?
8. How did the stakeholders involved in pre-testing rated the technologies at hand with regard to different relevant criteria and to overall sustainability?
9. Which common opinion do different stakeholders of the project have about the technologies analyzed and what characteristics can be found with respect to diversity or similarity in perceptions of stakeholder groups?

Research approach.

In order to answer these RQs effectively, I chose an interdisciplinary research approach and applied a broad set of methodologies. The interdisciplinary nature of my research was based on:

- Engineering science and bioenergy technologies for cooking and thermal sanitation,
- Recycling economies and recycling-oriented resource management,
- Soil science and soil fertility management of tropical soils,
- Agricultural science and crop nutrition,
- Environmental planning and a combination of multi-objective optimisation with technology assessment and EIA.

Cross-cutting issues included, for example, organic farming, agroecology, IPNM, sustainability assessments, the basics of mathematical modelling, action research, and science communication.

[58] System modifications refer to a shift in household cooking and sanitation technologies, alongside improvements in the recovery of residues as resources, and the subsequent use of this material according to the principles of IPNM.

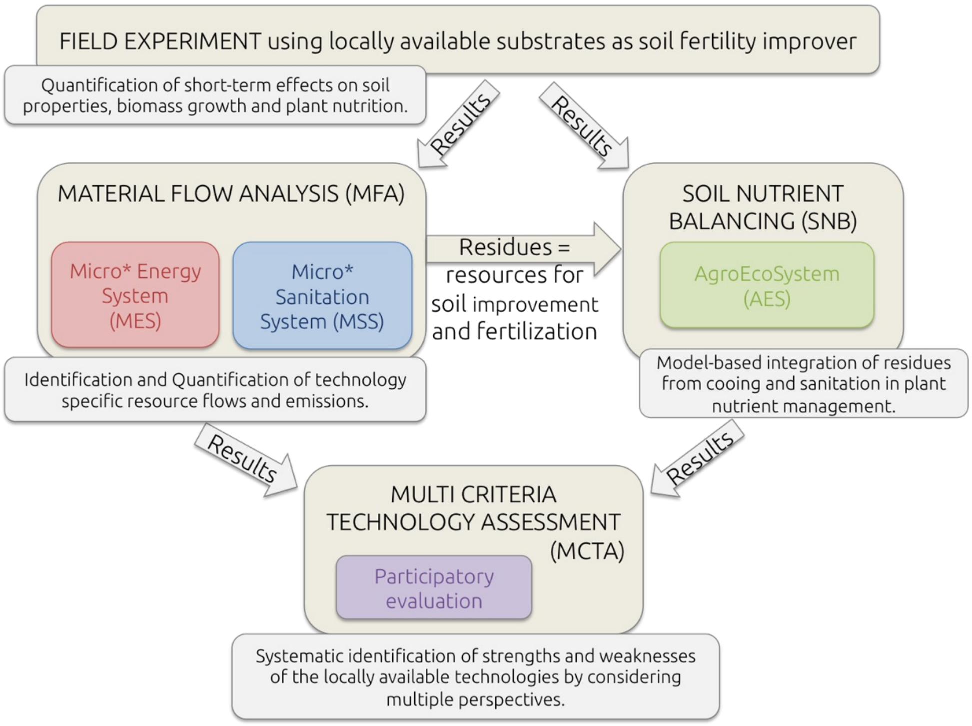

Figure 1.13: *Conceptual design of the present research projects, and links between the different research steps and applied methodologies. (* 'Micro' refers to the micro-economic perspective, i.e. 'on household-level'.)*

Applied methodologies include:

1. A comprehensive literature review,
2. Collecting (i.e. measuring, accessing, or calculating) and evaluating technology-specific data from case study projects,
3. Laboratory analyses of locally available substrates,
4. Practice-oriented short-term field experiment,
5. MFA,
6. Soil nutrient balances (SNB),
7. Multi-criteria analysis (MCA) as a decision support with participatory elements.

Publication strategy.
My research project is a cumulative work that comprises, in total, five scientific articles. Table 1.3 gives an overview of how the previously explained research objectives, questions, and methods relate to each of the five publications (P1-P5). The first publication (P1) served as an introduction paper. The co-authors, E. George, M. Kaupenjohann, and J. Köppel, and I provided a short review on bioenergy, EcoSan, and integrated resource management based on *Terra Preta* principles. In P1, we also introduced the three case studies from Karagwe and assessed substrates derived from the case studies' pilot projects for agricultural use. The second publication (P2) examines the short-term and practice-oriented field experiment I carried out in Karagwe in 2014. I used locally available substrates as soil amenders for the intercropping of locally grown and nutritionally desirable crop species. In P2, the co-authors, T. Nehls,

E. George, and M. Kaupenjohann, and I discussed differences observed in plant growth and crop nutrition in relation to nutrients and water availability in the soil. In the third publication (P3), co-author, S. Rotter, and I compared locally available cooking and sanitation technologies by quantifying and assessing technology-related material flows. As part of this research, I developed a computational model pursuant to the MFA-method. Based on this model, we discussed material flows, depending on the technology applied for cooking or sanitation, between the farming system and the natural environment, including relevant factors such as resources used, emissions caused, etc. We further quantified potentially available residues for on-farm nutrient cycling and SOM-restoration. In the fourth publication (P4), S. Rotter and I discussed the results of an *ex-ante* system analysis aimed at integrating locally available substrates into on-farm IPNM practices. In doing so, we estimated material flows between each smallholder household and its respective agricultural land. This research step was based on a computational model in which I combined MFA and SNB. Finally, I performed an MCA for widening the perspective from ecological impacts of the analyzed technologies towards the multiple factors related to sustainability. Stakeholders from all case study projects and colleagues from academia participated in this sustainability assessment. Hence, the fifth publication (P5) by J. Köppel and myself presented this assessment tool, as well as conclusions from the participatory pre-testing.

Table 1.3: *Publications within the cumulative dissertation project, with connection to research objectives, research questions, and research methods applied* [60].

Manuscript No.	Research Objectives	Research Question	Applied Method	Status	Chapter
P1	No. 1	No. 1	No. 1, 3	published	2
P2	No. 2	No. 2	No. 3, 4	published	3
P3	No. 3	No. 3, 4	No. 1, 2, 3, 5	published	4
P4	No. 4	No. 5	No. 1, 2, 3, 5, 6	published	5
P5	No. 5	No. 7, 8, 9	No. 1, 2, 7	published	6

Relevance and limitations of my work

To ultimately justify the relevance of my work, I summarize the most important outcomes expected of this study as follows:

- To advance the practical application of known principles, including EcoSan-composting, fertilizing with biogas slurry, and amending the soil with biochar through practical experiences and scientific evidence;
- To increase multi-perspective knowledge of recently developed technologies and to justify their prescribed 'appropriateness';
- To reduce risks for farmers who adopt the technologies and make use of the substrates as soil amenders in their agricultural practice;
- To enhance the implementation of alternative sanitation systems, bioenergy technologies, and the use of biochar as a soil amendment in Karagwe.

Finally, my work also has its limitations. For example, objectives that are often related to research on bioenergy, or EcoSan technologies, such as indoor air-pollution or hygiene, have been mentioned in my introduction and discussion, but were not researched. Also economic considerations have only been touched upon. Furthermore, for simplification, smallholders have been considered as a largely homogeneous group (cf. footnote no. 1, p. 1). This does not, however, reflect the reality. Smallholders have widely varying access to resources such as land, education, money, transport, affiliation to the community and community associations, etc.

1.6 Reflection and critique of the research approach

In this final section of the introduction, I will first provide my view in regard to the relationship of my research to social, scientific, and practitioner's systems. On this basis, I then explain why and how my work is related to action research. In addition, I briefly explain the position of my work within the wider political context. My motivation to write this section has been to enable my work to be more transparent, and to offer self-positioning in order to concretize and contextualize my work. Therefore, I provide interested readers with further information around the wider context of my work, which may be of help in order to better understand my research perspective and approach.

Science as an embedded system.
According to Friedrichs (1990), there is a mutual interaction between researchers, research, and society, because scientific work is always influenced by the social system and the epistemological system of the researcher(s). For example, research is more likely to be undertaken and published by representatives of certain social groups with access to the necessary resources[61]. This, ultimately, leads to particular, socially-defined points of views being statistically more often represented in research publications (Kapoor, 2004). The reverse, for underrepresented social groups is, of course, also the case. Accordingly, in the present section, it is my desire to explain the scientific nature of my work as I perceived it. I first briefly disclose my personal position in the social system, the scientific system, and the practitioner's system from my perspective. This may help the interested reader understand why and how my research has been facilitated and which resources (and privileges) I had access to.

Interrelationship of my work and the social system.
I was born in West Germany, in a *white*, middle to upper middle-class family, and enjoyed financial stability in my childhood. As a *white*, able-bodied, cis-gendered woman (assigned, identified, and socialized as a female person) with German citizenship, I enjoy many privileges and have access to the state social security system, including occasional benefits such as health insurance, housing allowance, and so on. I attended a state-run school, and after high school graduation, I pursued a higher education at university.

[61] The dominance of Eurocentric self-perception in 'Western' science, and its claim that it defines 'standard' science and has no bias, is only one example of this effect.

Interrelationship of my work with the scientific system.

At university, I studied industrial engineering[62], which is a combination of mechanical engineering and economics. During my studies, I was most interested in energy engineering (especially bioenergy technologies) and resource economics. My diploma thesis, written in 2009/2010, constituted a lateral entry into environmental sciences in general, and soil science in particular. Overall, my academic education was highly interdisciplinary. Although I enjoyed being educated as a kind of 'universal expert', I believe there are problems in so far as the education system is largely oriented towards serving the demands of industry and businesses in the particular field of study I selected.

Even though, in my experience, it is still not common for industrial engineers to undertake doctoral studies, I decided to undertake further research. I was invited to apply for an interdisciplinary PhD programme, which proved a valuable option for me to combine (i) my personal interest in extending my knowledge with (ii) my activism in the case study projects, whilst also (iii) being financially sustained for at least three years. My application was successful and I joined the MES research group, which focuses on decentralized energy supply in the Global South from an interdisciplinary, micro perspective[63]. Within the MES research program, I was one of eight PhD students, and enjoyed a constructive atmosphere with my colleagues within the group. I was, furthermore, very well supported by my supervisors J. Köppel, S. Rotter, M. Kaupenjohann, E. George, and also M. Schäfer.

The Hans-Böckler Stiftung (HBS - a foundation of the *Deutscher Gewerkschaftsbund*, or Federation of German Trade Unions) supported my research financially over three years from 2012 until 2015 in the form of a monthly living allowance. Since 2012, I have shared an office with my fellow PhD students in the building of the Centre for Science and Technology at *Technische Universität* (TU) Berlin. There, we have reliable access to printers, internet, online libraries, including an electronic knowledge portal, various software, etc. The HBS provided funding for three journeys to TZ for field research (2012, 2013/2014, 2015) and two journeys to participate in intensive methodological training, once to Denmark, and once to TZ. Laboratory analysis and technical equipment were supported by the HBS, by the department of soil science at TU Berlin, by the Leibniz Institute of Vegetable and Ornamental Crops (IGZ), and also by own funds. Fees for the editing and publication of the manuscripts have mainly been covered by the academic departments of the respective co-authors (E. George, M. Kaupenjohann, J. Köppel, S. Rotter). Proof-reading of this final thesis was financed by myself with the generous support of my father, P. Krause.

Interrelationship of my work with the practitioner's system.

During my PhD, I was very active as a volunteer within all three of the case study projects. From 2008 to 2013, I was a member of Engineers Without Borders (EWB) Berlin, which is a partner organisation to MAVUNO and CHEMA. In 2008/2009, I was active in the BiogaST project

[62] This study program is called '*Wirtschaftsingenieurwesen*' in German, which is also often translated into English as 'business engineering'.

[63] Click here to visit website of MES research group.

and participated in the construction of the first prototype adapted biogas digester in Berlin. In 2010, I took an 'investigative journey' to Karagwe. I organized the journey myself, with the support of M. Kaupenjohann and J. Köppel, and travelled in the official capacity of an EWB volunteer. Before I went to Karagwe, my initial plan had been to carbonize biogas slurry via HTC for subsequent use as soil amender. During my time in Karagwe, however, the agricultural technician at MAVUNO, I. Bamuhiga, emphasized EcoSan instead. We decided to work together in order to investigate how nutrients that had earlier been removed from agricultural land could be recycled from human excreta without creating health risks for farmers. Together we decided to implement a project for (i) designing a concept to combine EcoSan with bioenergy in order to make use of heat for sanitation, (ii) adapting the approach to conditions in Karagwe, and (iii) developing the respective technologies required. I was assigned responsibility for conducting a 'feasibility study', including further research and planning. Once back in Germany, I conducted an intensive literature review on EcoSan and the technical means for sanitizing human excreta, both in combination with bioenergy technologies and in isolation [64]. In early 2011, Bamuhiga was invited to Berlin, and so we had the chance to meet again, to discuss in person, and exchange ideas, thoughts, and doubts. As a result of our conversations, together we decided to continue the experiment with a UDDT and loam oven for sanitation in combination with a microgasifier. We conceptualized this blend of technologies and processes as a possible EcoSan approach for Karagwe, namely, the 'CaSa concept'. In 2012, I returned to Karagwe to support and coordinate the implementation of a 'pilot project' for CaSa together with my colleague A. Bitakwate (biogas technician at MAVUNO). In total, I was project coordinator for CaSa from 2010 until 2013. In 2012, I further participated in initiating the EfCoiTa project[65] but soon withdrew from the project team due to other commitments. In 2014, I ended my EWB membership due to personal conflicts with the management board and the administrative office. Shortly after, EWB decided to drop out of the CaSa project. Since then, the project has been run solely by MAVUNO and is still funded by the German donor (The *Heidehof* Foundation).

Due to my position, I was involved to a certain extent, therefore, in the development of all the technologies analyzed in the present thesis. I further supervised a series of Bachelor and Master theses that were related to the projects as well as to my research (Friedrich, 2013; Grapentin, 2014; Häfner, 2012; Hausmann, 2015; Meyer, 2013; Schmid, 2013; Schrecker, 2014). During my time in TZ, I followed the activities and progress of all projects on-site. The collaboration and information sharing between me and the project team members was mostly very good, despite some personal and structural conflicts associated with the context of 'development cooperations' (see next but one paragraph). After putting much effort in the development of

[64] I still pursued HTC during my 'feasibility study' with laboratory experiments on carbonizing biogas slurry. During Bamuhiga's stay in Berlin, we decided together against HTC for various reasons, including the risk for people in the direct surrounding of a HTC pressure vessel, possible environmental pollution through potential toxic substances, etc..

[65] While I was in Karagwe for the CaSa pilot project, I needed to find a local expert who could help me construct a microgasifier stove for firing the loam oven. I was told that I could find one at CHEMA and went there. Before I had the chance to explain the intention of my visit to the stove technician, A. Ndibalema, he told me about his idea of building a microgasifier stove. He explained that he had not yet worked out the construction details, and didn't have plans or material lists. In a great example of serendipity, I had those very plans with me (thanks to Dr. TLUD for his consequent open source practice!) and we started working on microgasifiers immediately.

technologies and initiation of projects, I was personally invested in supporting these projects and the technology implementation with my own research. It was also important to me, to conduct research to provide a 'proof-of-concept' regarding the technologies' capacity to fulfil the expected objectives and to answer PQs (described on page 30).

Identification of my work as action research.

According to Checkland and Holwell (1998), action research is when 'the researcher enters a real-world situation and aims both to improve it and to acquire knowledge'. Hence, due to the close association of my work with the case study projects, I identify my work as action research. Furthermore, I perceive my work as a cyclical process with several feedback-loops between me, as the researcher, and the local community. Practical examples from my research that are elements of action research include:

- Declining soil fertility had been observed by smallholders and MAVUNO for many years. The problem was communicated to me during my 'investigative journey' to Karagwe in 2010. By this time, I was already working in close cooperation with I. Bamuhiga, who was responsible for supervising me. I had the chance to accompany Bamuhiga in his daily field work for a period of four weeks. During this time, I learned a considerable amount about local agriculture and we discussed in depth the challenges and opportunities for soil fertility management in regard to Karagwe smallholdings.
- Exchanging information, sharing updates, and supporting one other with advice and feedback was part of the frequent communications between Bamuhiga, Bitakwate (both MAVUNO), Ndibalema (stove technician at CHEMA), and myself. This communication has endured from 2010 until the time of writing (2017).
- In order to learn from other peoples knowledge and experiences, I interviewed many people in person, including scientists and practitioners in Germany, who are recognized as experts in EcoSan and bioenergy technologies during the 'feasibility study' for CaSa in 2010/2011. I documented everything I had learned about the technologies and processes to be able to share documents with others[66].
- In order to meet East African scientists and practitioners from the fields of bioenergy, soil science, resource management, etc., I travelled around TZ and neighbouring Uganda in 2013/2014, and visited five universities and three research centres. My intention was (i) to learn more about those research topics currently tackled at East African universities, and (ii) to present my research approach to them and collect their feedback.
- Learning Swahili was essential for me to communicate and interact with local farmers in person. These language skills allowed me to learn about farmers' concerns and ideas and to include these issues in my research.
- Being able to speak Swahili, and also some of the local language *Kinyambo*, made it possible for me communicate with Karagwe women, who carry out most of the field work at smallholder farms, but rarely speak English. It was very important for me to be able

[66] For example, together with S. Jacobsen, I wrote a short review paper on the 'important aspects of sanitation', see web link. Other documents, such as photo documentaries of construction during the CaSa pilot project, or final project reports are also available in the web.

to speak to these women directly in order to understand their opinions, as my respected colleagues at MAVUNO, who do speak English, are exclusively male.

- While staying in Karagwe, I organized several seminars with farmers, including group discussions and field visits to the pilot projects. I also attended many meetings at MAVUNO, such as weekly plenary sessions for staff members, monthly group meetings of farmers, and biannual plenary assemblies of board members. I also conducted experiments to collect data. Most experiments were performed together with the project workers and were thus as transparent as possible.
- Participating or observing technology developments in the case study projects, which took place mainly before and at an early stage of my research, enabled me to gain a thorough understanding of the technologies, the underlying processes, and opportunities and challenges that their application presented for the daily life of smallholders.
- The design of the 2014 field experiment was inspired by local farming practices. My motivation was to gain scientific data about certain soil amenders that can be integrated into local practices in order to make agriculture more productive, whilst ensuring farmers' interests were taken into account in regard to the everyday suitability of the processes proposed. To my delight, I was often visited by farmers when working in the fields. They were interested in following the progress of the experiment[67]. These meetings allowed group discussions on the observed effects, potential benefits, and burdens. Important issues that were stressed by farmers were taken into consideration in the scientific discussions of the results[68].
- After the field experiment, some of my harvest was needed for laboratory analysis. In addition, I shared some of my harvest with colleagues from MAVUNO and also sold some to a local canteen in order to get to know local prices better.
- In order to receive colleagues from TZ as guests in Berlin, or other locations in Germany, I was engaged in fundraising for my colleagues in 2011, 2013 and 2015. These reverse visits strengthened our cooperation and gave us additional opportunities to share our ideas and thoughts.
- In order to ensure, that results of my research were also brought back to the community, I conducted local 'research feedback workshops' with MAVUNO and CHEMA staff members towards the end of my research in 2015. I presented my (by then preliminary) results and conclusions, and put them up for discussion.

Overall, the close cooperation with MAVUNO, CHEMA, EWB, and local farmers, present throughout this work, has allowed me to learn a considerable amount about local agriculture and, as a consequence, to tailor my research approach to the given context of Karagwe. I also iteratively defined and shaped my research questions and hypotheses based on the ongoing experiences of working with these collaborations guiding my research. The case studies have further

[67] In addition, farmers were also interested in seeing a white person working the fields. At first, local people doubted that I would really do the experiment by myself.

[68] For example, I analyzed the nutrient content of maize grains to reassure farmers that not only were larger and heavier maize cobs an improvement in terms of the quantity of the harvest, but that in terms of quality, the individual grains from these larger cobs have comparable (or even better) nutritional value.

been an important source of data. Personal engagement in these projects allowed me to study manufacturing processes of the technologies (e.g. material demand, production costs, time consumption, appropriateness for local tools, means of transportation, etc.), and to collect hands-on experiences when using the technologies during laboratory and field testing as well as at my own home (e.g. emptying the UDDT, operating a CaSa sanitation oven, cooking with biogas and microgasifier stoves, feeding the biogas plant, etc.).

Context of post-colonial studies and post-development theory.

As described above, the case study projects are 'development cooperations' between Tanzanian and German partners. Thus, in my activism, as well as in my research, I was involved in a 'development' context, which is negatively criticized in the context of post-colonial studies, as well as in post-development theory[69]. Ziai (2016) abstractly described 'development' as 'a bundle of interconnected and normatively positively charged processes that took place in some regions and in others not'. Such processes leading to progress and industrialisation are not only attributed positively but also set as a 'historic and ideal norm' even though there are also clearly existing drawbacks (*ibid.*)[70]. As a consequence, other communities, such as those in African, Latin American, or Asian contexts, are defined as 'deficient' or 'underdeveloped'. The 'need of development' was somehow manifested by US-President Truman in 1949, when he defined, or better constructed, Africa, Asia, and Latin America as 'underdeveloped areas' and by this, legitimised 'development' and any 'development intervention' (Ziai, 2007). However, 'development policy programs' already existed during colonial times (*ibid.*). Likewise, 'development cooperations' in TZ are historically shaped, unequal 'partnerships', as stated by Eriksson Baaz (2005)[71].

Against this background, I attempted to be aware of the inherent structures that I am involved in when working in 'development cooperations' but tried to be as self-critical and self-reflective as I could. The close collaboration and ongoing discussions with my colleague B. Barthel (sociologist and political scientist) were therefore very beneficial and valuable. Nonetheless, I was personally confronted with intrinsic and *inherited* structures of white supremacy and post-colonial privilege. Some of the examples described in the last preceding paragraph on action research can serve to explain how I handled post-colonial aspects in my research practice. For example, I stayed in Karagwe for extended periods[72], was really interested in the people and their way of living and farming, and highly appreciated what I could learn from them. This is in contrast to

[69] According to Ziai (2016), post-colonial studies presents a particular epistemological interest in uncovering and questioning continuities and similarities to colonialism in the contemporary world. Ziai further defined post-development theory by claiming 'that it is time to think about alternatives to development instead of alternative ways of reaching development in the Third World'. Ziai further stresses that 'local alternatives to the Western ways of looking at politics, economics and science are not only possible, but existent'. These 'alternatives to development', refer to the practices of social movements and local communities in Latin America and Asia, according to Ziai (2006).

[70] In my opinion, examples of the drawbacks mentioned are social inequality and environmental destruction.

[71] Tangible examples from the everyday practice of 'unequal development cooperations' include the fact that it is usually the 'Western' or European partners, who set the basic agenda of the projects; it is mainly or solely *white* people who are responsible for planning, management, accounting, etc. within the 'cooperation' projects; project trips are usually one-way and, *of course*, it is the *white* people who travel to the Global South, while bilateral journeys and evenly distributed allocation of travel funds for both directions are scarcely implemented.

[72] Between 2010 and 2015, I stayed in Tanzania a total of 15 months over five separate trips.

the common pattern of many very short visits, telling local farmers what to do, rather than listening to them, etc.[73]. In addition, before terminating my research, I conducted 'research feedback workshops' in Karagwe. I considered this step highly important as an essential critique in post-colonial studies is that research in a 'development' context, is often performed largely for the benefit of the *white* researchers. After collecting data, there is not enough emphasis on communicating the gained knowledge, or its consequences, back to local communities. Despite, the often negative expectations in such a context, my work in Karagwe was mostly pleasant. It also made me aware about those privileges I have access to as a *white* academic. The unpleasant situations I experienced can mainly be assigned to structural problems. For example, I repeatedly experienced, in TZ as well as in Germany, that I was often perceived as *the* person who wants to implement EcoSan in the region. Nonetheless, as explained above, it was the agricultural technician at MAVUNO who put the focus on EcoSan, and the initiation of CaSa was a common decision of, among others, MAVUNO staff members and myself. I also experienced that the managements teams of EWB and MAVUNO put (too) much responsibility on my shoulders, as the *white* person intended to carry out project coordination. I was still very much researching and learning, so it also felt inappropriate when, for example my Tanzanian colleagues, referred to me as an 'expert'. In summing up, I sometimes felt caught up in stereotypes related to characteristic structures of 'development cooperations'; stereotypes that both 'sides' of the equation have, to some degree, internalized. Nonetheless, the cooperation with individuals from the project teams was a very educational, important, and valuable experience for me. I also received a great deal of enjoyment from the experience of team-working with my colleagues at MAVUNO, partners at CHEMA, and volunteers with EWB.

The political context of food sovereignty.

As part of the reflection of my work, I also want to emphasize that I do not believe that soil management alone appropriately solves the global problem of hunger[74]. Reaching food security, and especially food sovereignty, should go beyond the application of fertilizers or soil improvement. In this regard, the FAO (2015b) recognized that 'even though the world produces enough food to feed everyone, hunger remains a problem'. Also Tittonell (2016) emphasized that 'hunger is not the result of insufficient agricultural production' and added that 'hunger is the result of [. . .] inequality'. Radically expressed, the problems can mainly be analyzed as a result of the distribution and allocation of resources and power based on imperialism, capitalism, and post-colonialism (Bush, 2010). La Via Campesina, therefore, advocate for the concept of '*food sovereignty*' and set political demands including: (i) exempting food and agriculture from inter-

[73] The Swahili word *mzungu* refers to 'someone constantly on the move' (UD, 2017). *Mzungu* is nowadays commonly 'applied to all white people in East Africa, as most were encountered as traders, visiting colonial officials or tourists' (*ibid.*). During my time in TZ, I was also often called a *mzungu*. But after some months staying in Karagwe, people who were closer to me, such as workers and farmers of MAVUNO, changed to calling me *mzungu-mafrica*, which could be translated to 'African *white* person'. It also happened that people called me *mkulima*, meaning 'farmer'.

[74] In total, 868 million people are undernourished worldwide (FAO, 2013) and hunger still mainly concerns poorer people in the Global South (FAO, 2015b). In contrast, obesity is a severe problem not only for many wealthier people in the Global North, but also for many in the Global South (FAO, 2013). Worldwide, 500 million people are obese and an additional 900 million are overweight (*ibid.*).

national trade agreements, (ii) easing access to local markets for local farmers, and (iii) solidarity between producers and consumers (La Via Campesina, 2015; Rosset, 2003). Fundamental political preconditions for food sovereignty are, for example, access to land and social security.

The political context of vegan organic farming.

Finally, I would like to explain why I concentrated on using 'humanure' (Jenkins, 1994) as a fertilizer to substitute 'animal manure', and on the agricultural production of plant food crops. Refusing the production and consumption of meat and dairy products and, as a consequence, also refusing fertilizing with animal dung, are important elements of 'vegan organic farming', or stock-free organic farming[75] (e.g. Bonzheim, 2015). In my opinion, a vegan diet is first of all necessary to prevent the exploitation of animals and to respect animal rights. There are, however, further reasons for vegan food production. For example, the UN Environment Programme (UNEP) showed that the production of meat and dairy products requires more resources and causes higher emissions than plant-based alternatives (Hertwich et al., 2010)[76]. The UNEP concludes that '*impacts from agriculture are expected to increase substantially due to population growth, increasing consumption of animal products. Unlike fossil fuels, it is difficult to look for alternatives: people have to eat. A substantial reduction of impacts would only be possible with a substantial worldwide diet change, away from animal products*' (*ibid.*). Simply spoken: a mainly vegetarian and vegan diet contributes to, for example, lower GHG emissions, decreased water consumption, and a reduction in land use and competition for arable land, etc. For these reasons, I was interested in investigating the fertilizer potential of human excreta as one prospective perspective in 'vegan organic farming'[77].

[75] For further information, see website of the vegan organic network.

[76] In total, agricultural production accounts for 70 % of the global freshwater consumption, 38 % of the total land use, 19 % of the global GHG emissions, 60 % of the eutrophication caused by P and N emissions, and 30 % of toxic pollution in Europe (UNEP, 2010). However, 'more than half of the world's crops are used to feed animals, not people', according to the Hertwich et al. (2010).

[77] As an exception, I considered cow dung as a feeding substrate to the biogas digester in order to be in accordance with local practices in regard to BiogaST.

Chapter 2

Publication no. 1

Nutrient recycling from sanitation and energy systems to the agroecosystem - Ecological research on case studies in Karagwe, Tanzania

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Comment:

The equation no. 1 on page 4047 in the publication must read as follows:

$$E = (1.0 \cdot CaO + 1.4 \cdot MgO + 0.6 \cdot K_2O) - (0.4 \cdot P_2O_5 + 0.7 \cdot SO_3 + n \cdot N)$$

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Nutrient recycling from sanitation and energy systems to the agroecosystem- Ecological research on case studies in Karagwe, Tanzania

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Open cycles of organic carbon and nutrients cause soil degradation. Procedures such as ecological sanitation (EcoSan), bioenergy and Terra Preta practice (TPP) can contribute to closing nutrient cycles and may, in addition, sequester carbon. This paper introduces three projects in Karagwe, Tanzania, and their applied approach of integrated resource management to capture carbon and nutrients from different waste flows. Substrates derived from these case studies, biogas slurry, compost and CaSa-compost (containing biochar and sanitized human excreta), were assessed for their nutrient content by analysis of the total element composition. Evaluation focused on potential impacts of the tested amendments on the nutrient availability in the soil as well as on the local soil nutrient balance. Results revealed that all substrates show appropriate fertilizing potential compared to literature, especially for phosphorus (P). CaSa-compost was outstanding, with a total P concentration of 1.7 g dm^{-3} compared to 0.5 and 0.3 g dm^{-3} in compost and biogas slurry respectively. Furthermore, these soil amendments may reduce acidity of the soil, with a calculated liming effect of 3.4, 2.6 and 7.8 kg CaO for each kg of nitrogen added for biogas slurry, compost and CaSa-compost respectively. To offset negative P balances in Karagwe, about 8100, 6000 and 1600 dm^3 ha^{-1} are required for biogas slurry, compost and CaSa-compost respectively. We conclude that especially CaSa-compost might offer immediate positive effects to crop production and nutrient availability in the soil.

Key words: Ecological sanitation, bioenergy, Terra Preta practice, biochar, biogas slurry, compost, soil amendments, soil improvement, waste as resource.

INTRODUCTION

Open cycles cause agronomic problems

Since more nutrients are taken out of the agroecosystem than are put back, anthropogenic activities create open cycles of mineral nutrients and carbon (C) (Lal, 2006). Such activities comprise among others: Excessive

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deforestation for firewood, exploitation of phosphate rocks for fertilizer production, and energy consumption for production of synthetic fertilizers. Furthermore, most current sanitation systems waste nutrients from human excreta (especially nitrogen (N), phosphorus (P) and potassium (K) as well as micronutrients) since they are either disposed in the ground (pit latrine, ashes of incinerated sewage sludge) or enter the aquatic system (pit latrine, flush toilet), where they cause eutrophication and lead to contamination of the groundwater with fecal microorganisms(Esrey et al., 2001;Graham and Polizzott o, 2012; Meinzinger, 2010). In general, open cycles can cause soil degradation and loss of soil fertility since cultivated soils become increasingly deficient in essential plant nutrients when long term cropping takes place without replacement of nutrients (Hartemink and Bridges, 1995). In addition, soil organic matter (SOM), which is the major building block of a fertile soil, might be depleted by continuous cropping if the plant residues are not put back into the soil after harvesting (Batjes and Sombroek, 1997). Consequently, the soil might show declining water and nutrient retention capacity and an increasing tendency to soil erosion (Horn et al., 2010). Tropical climate conditions aggravate such soil degradation; with year-round elevated temperature, SOM is lost due to fast microbial decomposition of organic matter; heavy rains during the rainy season in turn cause leaching of mineral nutrients (Lal, 2009). It is widely agreed that in order to secure sustainable food supply for everyone, soil degradation must be reversed and soil productivity enhanced.

Problems of using synthetic fertilizers in Sub-Saharan Africa

Agricultural practices using synthetic fertilizers often add too much N to the soil and sometimes neglect input of P, K and micronutrients, which can result in imbalanced plant nutrition (Lal, 2009). Furthermore, nutrients added by synthetic fertilizers often are immediately available and thus can be subject to high losses via leaching and volatilization (Finck, 2007; Savci, 2012). Moreover, the *International Assessment of Agricultural Knowledge, Science and Technology for Development* (IAASTD) showed that in some parts of Sub-Saharan Africa (SSA), especially poor farmers do not have access to synthetic fertilizers (Markwei et al., 2008). Those who have access often lack adequate information on their appropriate use (*ibid.).* Inappropriate use of synthetic fertilizers, however, may result in soil acidification, pollution of water bodies, and emissions with global warming potential to the atmosphere (Markwei et al., 2008; Savci, 2012). Furthermore, the production of synthetic fertilizers requires energy; for example about one third of the total energy input to crop production of the United States of America is required to produce, to package, to transport and to apply synthetic fertilizers (Gellings and Parmenter, 2004).

Solutions based on using locally available organic fertilizers

Kiers et al. (2008) concluded that in African countries reversing soil infertility might be achieved “through the use of locally available resources”, because the use of synthetic fertilizers is not a feasible option for many subsistence farmers. In “Agriculture at a crossroads“ McIntyre et al. (2009) called for a focus on efficient, small-scale agroecosystems with almost closed nutrient cycles. In addition, the IAASTD demanded that research in a SSA context should reorient “towards integrated nutrient management approaches” (Markwei et al., 2008). Kimetu et al. (2004) demonstrated in Western Kenya that “inorganic N additions can be fully substituted by organic N additions if the appropriate source of organic matter is applied”. Furthermore, the intensified use of organic fertilizer can reduce the cost of fertilization in crop production in SSA (Markwei et al., 2008).

In order to create positive C and nutrient budgets, SOM can be enhanced through addition of organic amendments, as Lal (2009) pointed out. He further suggested that both organic residues, such as compost and animal manures, and biological N-fixation should be included in the nutrient management (*ibid.*). Stoorvogel (1993) particularly emphasized the efficient use of organic household waste as a means to supply nutrients. Beardsley (2011) pointed out that human excreta “is an abundant but often ignored source of P available for recycling worldwide”. Another important soil management practice to strengthen the nutrient cycling process in SSA is acidity management through liming, as described, for example, by Batjes and Sombroek (1997).

Approaches towards closing the loop

In our research, we focus on the following practices for local nutrient and C recycling: (1) Composting in general, as well as co-composting of human excreta and ecological sanitation (EcoSan); (2) Provision of bioenergy combined with agricultural use of residues; (3) Terra Preta practices (TPP) – using biochar as a soil amendment.

Composting and ecological sanitation

Composting is a globally common method in agriculture whereby organic residues are mixed with mineral components and subsequently aerobically decomposed by macro- and microorganisms (for East-Africa see work of e.g. Amoding et al. (2005), Karungi et al. (2010) and

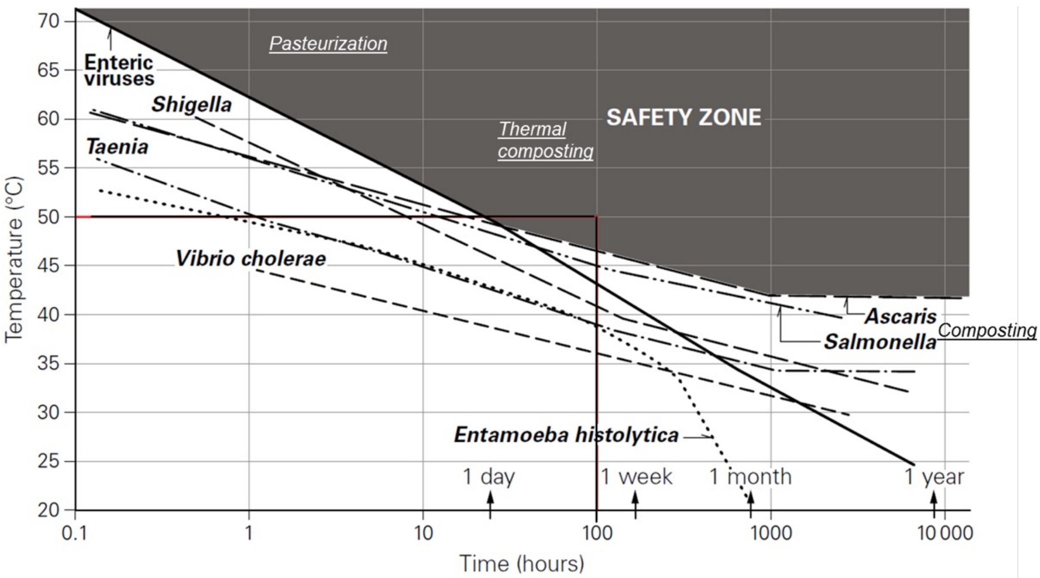

Figure 1. Relationship between temperature and time required to inactivate certain pathogens (according to Feachem et al., 1983, graphic adopted from Vögeli et al., 2014; corresponding combinations of time and temperature for the described possible treatments are indicated)

Tumuhairwe et al. (2009). EcoSan facilitates co-composting of human excreta as an alternative to conventional sanitation systems. EcoSan aims at (i) "closing the loop" by recycling nutrients from humanexcreta in order to improve soil fertility; (ii) avoiding potential human health risks by sanitizing urine and feces; (iii) preventing the pollution of freshwater and marine environments by avoiding waste water discharge into natural water bodies (Winblad et al., 2004). Further benefits of EcoSan, according to Esrey et al. (2001), are that it is: (i) A decentralized system based on household and community management and, thus, omits investment in large-scale infrastructure; (ii) Particularly appropriate in areas with water shortages or irregular water supply since no or very little water is required; (iii) Feasible in both rural and urban areas as well as for rich and poor people alike. Usually, urine and feces are stored and processed on-site. A number of different types of composting toilets are in use in EcoSan, e.g. the urine diverting dry toilet (UDDT), which collects human excreta separately (see Morgan, 2007, for further description and discussion of "Toilets That Make Compost - Low-cost, sanitary toilets that produce valuable compost for crops in an African context"). According to the World Health Organization (WHO, 2006) urine is safe for use as a fertilizer, untreated or after short storage. However, feces mostly contain pathogens (such as viruses, bacteria and worm eggs) and require treatment (*ibid*.). Techniques for sanitation include: dehydration or drying, e.g. through UDDT with a separation of the solid parts and the liquid fraction of the excreta and improved ventilation system (Winblad et al., 2004); disinfection by using additives, e.g. urea (Vinnerås, 2002) or lactic acid bacteria (Factura et al., 2010); disinfection through exposure to elevated temperatures over time, e.g. mesophilic or thermophilic composting (Niwagaba et al., 2009; Ogwang et al., 2012) or pasteurization (RKI, 2013; Schönning and Stenström, 2004). In general, thermal sanitation relies on a temperature/time relationship to inactivate certain pathogens, as described by Feachem et al. (1983) (Figure 1).

Currently, there are no national regulations for the treatment of human excreta, in neither Tanzania nor Germany, but different guidelines for thermophilic composting exist. The WHO (2006) recommended a treatment at 55 to 60°C over several days up to one month depending on the conditions (e.g. constant control of the temperature). In Germany, the following thermal treatments are required for organic waste in general: 55°C for two weeks, 60°C for six days or 65°C for three days (German BO, 2013).

Bioenergy and the agricultural use of its residues

Bioenergy technologies focus on energy recovery from biomass. Also, by-products and residues from bioenergy provision can be recycled back into the agroecosystem. The main principle is the conversion of biomass to heat for either the consecutive production of electricity or direct provision for productive processes (e.g. for a bakery, green-house heating) and consumption in households or institutions (e.g. for cooking and heating) (Kaltschmitt et al., 2009). In this study, our focus is onprovision of cooking energy at household level and the applied technologies include: three stone fire, charcoal burner, microgasifier and a system using a biogas digester and biogas burner. The use of firewood, three stone fires and charcoal burners is currently most common in many countries of SSA. Ash is the main residue from these bioenergy applications and contains mineral nutrients such as P and K as well as calcium (Ca) and magnesium (Mg), but hardly any C, N or sulphur (S) since these elements volatilize during the oxidation process. Ash is therefore often used as a soil amendment or addition to compost. Another small-scale technology is the biogas digester, which is used for cooking both in households and institutions, such as schools or hospitals (Vögeli et al., 2014). Organic wastes are anaerobically digested via microbiological activity in a closed fermenter, resulting in a methane-rich combustible gas as the main product and biogas slurry as a liquid residue (*ibid.*). Small-scale and low-tech biogas digesters usually operate in a mesophilic range of about 30 to 40°C and a retention time of around 40 days (Kossmann *et al.*, undated). Biogas is accumulated inside the digester or in a separate storage tank and is usually combusted in a biogas burner. Biogas slurry can be used as a fertilizer since it contains most of the mineral nutrients from the digested organic waste in an already plant-available form (Vögeli et al., 2014). Caution and additional treatment of the biogas slurry is required, however, in case human excreta is also digested since pathogens are not inactivated under the mesophilic conditions mentioned above (Figure 1). In Nepal, for example, Lohri et al. (2010) showed that the biogas slurry from mixed fermentation of human excreta and kitchen waste contained pathogens such as helminth eggs. Moreover, inappropriate use of the liquid biogas slurry can cause eutrophication if it is applied in excess or discharged directly to a receiving body of water (Kossmann et al., undated). Finally, households can meet their energy demand by using microgasifiers, which are improved cooking stoves that use dry biomass and spatially separate the transformation of biomass into combustible wood-gas from the subsequent oxidation of the gas (Mukunda et al., 2010; Roth, 2013). One particularly prominent stove design is called the TLUD ("Top-Lit Up Draft"), which is licensed as an open source technology (Anderson and Reed, 2007). Apart from heat, the stove provides charcoal of about 10 to 30% of the fuel fresh weight as a by-product (Roth, 2013). As for ash, charcoal preserves mineral nutrients. It also contains C in a concentration of about 60 to 75% of its dry matter (DM) (McLaughlin et al., 2009). The charcoal can be used for further provision of energy by directly pouring the hot charcoal onto a conventional charcoal burner, to continue cooking immediately, or by making charcoal briquettes in a separate process with an accumulated amount of charcoal. Charcoal can also be used as a soil amendment, which is then termed biochar (Taylor, 2010). Altogether, residues from bioenergy processes have a potential for use as soil amendments; however, their quality depends on the composition of the feedstock used and the application practice. There is a need for field experiments to evaluate the impact of biogas slurry on the local carbon balance as well as on soil characteristics and productivity (Bogdanski and di Caracalla, 2011). The positive effects of pyrolitic charcoal as a soil amendment are historically evident in findings of Terra Preta soils, which we will introduce in the following section. However, there is still a lack of scientifically rigorous field experiments using biochar derived from microgasifiers on tropical soils.

Terra Preta practices (TPP) - using biochar as a soil amendment

One particularly interesting and promising holistic approach for improving or remediating degraded soils is the principle of "Terra Preta" (Portuguese for "Black Soil" = "Udongo Meusi" in Swahili), as practiced by people in the Amazon basin in Brazil, South America, centuries ago (Sombroek, 1966; Glaser et al., 2002). Lehmann et al. (2003b) classified Terra Preta as Anthrosol, a human-made, fertile, black soil. Glaser and Birk (2012) found that it mainly contains charcoal, animal and human excreta as well as other organic and inorganic wastes. Compared to surrounding soils, including Ferralsol, Acrisol or Arenosol, the Terra Preta soils show significantly higher availability of P, Ca, manganese (Mn), and zinc (Zn) (Lehmann et al., 2003a). For example, Falcão et al. (2009) found up to 40 times larger concentrations of plant-available P in Terra Preta than in surrounding natural soils. Other characteristics include high water and nutrient retention capacity as well as a pH of around 5.7, adequate for plant growth (Lehmann et al., 2003a; Horn et al., 2010). Biochar plays a major role for the specific properties of Terra Preta because it builds up a stable stock of SOM. Biochar shows an aromatic C structure with many micro pores, large surface, high adsorption capacity and a C-concentration of about 70 to 80% of DM (Lehmann and Joseph, 2009). In some soils, biochar can significantly improve the availability of both nutrients and water by effecting chemical and hydraulic characteristics of the soil. It can also positively affect the activities of soil microbial communities (Lehmann and Joseph, 2009; Glaser and Birk, 2012). According to Taylor (2010), biochar works as a catalyst in the soil, because it "facilitates reaction beneficial to soil dynamics without being consumed in the process". This means that much of the biochar persists in the soil and is not decomposed in the way many other organic materials are (*ibid.*). Therefore, biochar amendments may enhance plant growth in some cases, although nutrient inputs from biochar are low (Lehmann and Joseph, 2009).

Consequently, its application was tested in combination with mineral fertilizers (Kimetu et al., 2004; Jeffery et al., 2011), in combination with compost that releases nutrients over time (Liu et al., 2012; Schulz et al., 2013), and as compost-additive to be enriched and loaded with nutrients during the composting process (Kammann et al., 2015).

Recently, Frausin et al. (2014) revealed the presence of so-called African Dark Earth at more than 134 locations in several West-African countries including Liberia, Sierra Leone, Guinea and Ghana. This Terra Preta-like African Anthrosol is preferably located in the vicinity of towns and mainly is the product of women doing appropriate management of wastes from housing and farming (*ibid.*). Altogether, TPP - using biochar as compost-additive and soil amendment - is seen as a "suitable technique helping to refine farm-scale nutrient cycles" (Schulz et al., 2013).

Research objectives

Based on the context described in the introduction, we hypothesize that new approaches which combine EcoSan, bioenergy and TPP can contribute to soil improvement and resource protection by recycling of nutrients and C, if sanitation is taken into account and integrated appropriately. Especially the use of biogas slurry from fermentation of organic waste as a fertilizer and the combined composting of residues from microgasification and sanitized human excreta are promising methods. However, there is need for practice-oriented experiments and assessment of the local ecological impacts under the specific conditions of tropical regions. Hence, the objectives of this paper were (i) to introduce three case studies from Karagwe, Tanzania, and their applied approach of integrated resource management; (ii) to assess the substrates derived from these projects with respect to their nutrient concentrations; and (iii) to evaluate potential impacts of the tested amendments on the nutrient availability in the soil as well as on the local soil nutrient balance.

MATERIALS AND METHODS

Farming activities in Karagwe, Tanzania

Karagwe district is located in Kagera region in northwest Tanzania, a hilly area situated at an altitude of about 1200 m up to 1800 m.a.s.l., semi-arid with equatorial-tropical climate (Baijuka and de Steenhuijsen Piters, 1998). The average daily temperature is about 21°C, with a range from 10°C at night to > 40°C during the daytime (Blösch, 2008). Rainfall is bimodal with rainy seasons from March to May (long rainy season) and October to November (short rainy season), with crop cultivation taking place during both seasons (Tanzania, 2012). Precipitation ranges between 1000 and 2100 mm $a^{-1,}$ with annual and regional differences (Blösch, 2008).

According to the national sample census of agriculture 2007/2008 for Kagera region, most families in Karagwe districtsubsist on farming activities (Tanzania, 2012): about 45% of the population work full-time on their farms and more than 86% of the households sell agricultural products grown on their farms. On average, around 0.75 ha usable land is available per household out of which around 83% is planted. The most important permanent crops are banana and coffee, while beans, sorghum and maize dominate annual cropping. Most of the planted land is used multiply in mixed cropping systems and only some 16% of the land is used for temporary mono-cultural cultivation. A majority of approximately 78% of the farmers in Kagera region who apply fertilizers on their land, use organic fertilizers which are according to Baijukya and de Steenhuijsen Piters (1998) mainly grasses (mulch) and farmyard manure. However, the supplied amount only suffices for roughly 5% of the planted land (distributed to 0.7 and 4.3 %. of the planted land in the long and short rainy season respectively). Synthetic fertilizers are used on less than 1% of the planted land in Kagera region. In 2010 we conducted a preliminary study in Karagwe district including a survey on 10 households and soil sampling at three different farms. We found that small-scale farmers in Karagwe live on an average with six people in one household. In addition, we found that some major problems of local agriculture are a very low soil pH of 3.8 to 4.2, low nutrient availability (especially P) and soil erosion due to a hilly landscape. Concerning sanitation services, a majority of more than 90% of the rural population of Karagwe district use pit latrines, around 6% do not have any toilet so use bushes and only 1% uses flush toilets in combination with septic tanks (Tanzania, 2012). Hence, for 91% of rural households in Karagwe district, excreta are disposed in a pit or tank after dropping without any treatment or use. Concerning energy supply, the most common source of energy for cooking is biomass, with about 96% of the rural households using firewood and 3% using charcoal (Tanzania, 2012). It is common in Karagwe to add ashes from three stone fires to the compost.

Grassroots projects in Karagwe realizing integrated resource management

Since 2008, two local non-governmental organizations, namely MAVUNO Project Improvement for Community Relief and Services (MAVUNO; meaning "harvest" in Swahili) and CHEMA Programme for Community Habitat Environmental Management (CHEMA), have initiated projects in cooperation with the German association Ingenieure ohne Grenzen e.V. (Engineers Without Borders, EWB) and Technische Universität (TU) Berlin. These projects follow a community-participatory approach to appropriate development of technologies and aim at resource protection, autonomous energy supply and safe sanitation services. Together, these projects present an integrated approach to resource management as well as recycling of nutrients and C (Figure 2). Their process combines three systems: The energy system, whereby cooking energy is provided as heat by either burning biogas from a small-scale biogas digester or by microgasifiers; the sanitation system based on EcoSan; finally, the recycling of by-products from both systems, namely biogas slurry, biochar and sanitized human excreta, back into the agroecosystem. In the latter, composting and the principles of TPP are applied to capture nutrients and C from different waste flows.

One of the expected results is soil improvement, to ensure long-term food security and income generation for the rural population. The respective technologies were developed and tested in Karagwe within three pilot projects:

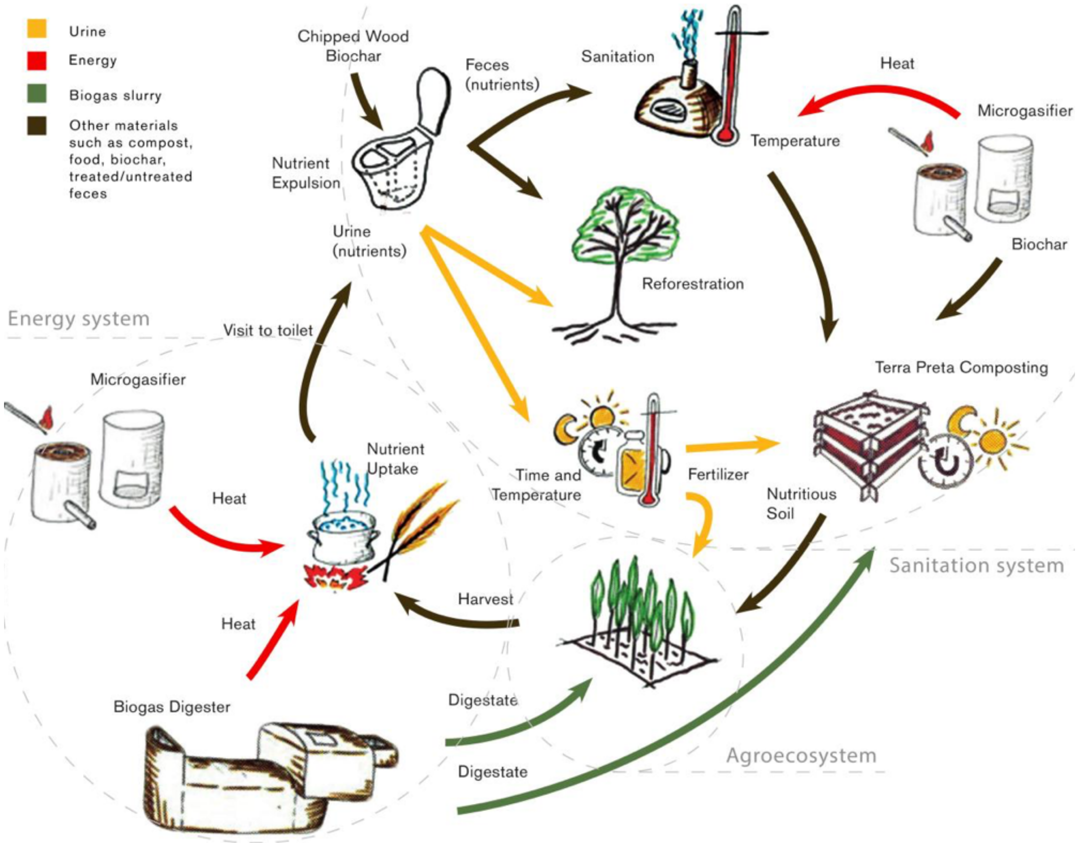

Figure 2. Illustrated concept of the integrated approach of bioenergy, EcoSan, TPP for sustainable food production where waste is considered a resource, as realized by three projects in Karagwe, Tanzania (own picture; with graphical assistance of Daniel Mutz and Lusi Ajonjoli).

(1) The project "Carbonization and Sanitation" (CaSa) aims at closing the cycle of nutrients on a local scale by recycling human excreta without health hazards. This project is a cooperation of MAVUNO, EWB and TU (CaSa, 2011). The approach is called CaSa because the heat of the carbonization process is used for thermal sanitation (Figure 2). The process starts in a UDDT, where a mixture of dry materials like biochar, sawdust, loam soil and ash is added after defecation to improve and accelerate drying of the feces. All solid parts including toilet paper are collected in aluminum pots and remain inside the UDDT for two to four weeks in order to dry. Afterwards, the pot is brought to a loam oven for thermal sanitation via the process of pasteurization, where microgasifiers are used to provide the required heat. Finally, the co-produced biochar, sanitized human feces and stored urine are composted together with other organic and mineral residues. The pilot project for testing the technologies started in 2012 and finished in 2014; since then the implementation has begun with the construction of eight toilets, a sanitation area and a composting area in a boarding school in Karagwe.

(2) The project "Biogas Support for Tanzania" (BiogaST) focuses on the sustainable provision of cooking energy through small-scale biogas digesters, which use organic residues from farming. It is a cooperation of MAVUNO, EWB and the University of Hohenheim in Stuttgart, Germany. The technology follows the design of a plug flow reactor and uses mainly cut pieces of banana tree stump, mixed with cow dung and kitchen waste. Water, together with the anaerobic microorganisms, is recycled and nutrient-rich biogas slurry is produced (Becker and Krause, 2011). Since 2010, two pilot digesters have been in operation to study (i) the effect of using different organic wastes in different mixtures and (ii) the design of a heating system to raise the temperature inside the fermenter and consequently increase biogas production. In 2015, implementation will start with the construction of a larger digester to provide a school canteen with cooking energy.

(3) The project "Efficient Cooking in Tanzania" (EfCoiTa) conducts research on advanced designs of microgasifiers including TLUD and improved sawdust stove (Ndibalema and Berten, 2015). In this project, CHEMA and EWB work in close cooperation with the Center for Research in Energy and Energy Conservation (CREEC) based at Makerere University and Awamu Biomass Energy Ltd, both located in Kampala, Uganda. In 2014, a series of so-called water boiling tests were performed to assess the resource efficiency and currently, in 2015, so-called controlled cooking tests are in progress together with kitchen performance tests to evaluate the practical use of the stoves in local households (Ndibalema and Berten, 2015).

Technically, these projects are connected through the use of microgasifiers for thermal cooking energy in the EfCoiTa-project as well as for the sanitation process in the CaSa-project. Furthermore, they collectively consider waste as a resource and exercise the use of by-products as soil amendments according to the principles of TPP. Hence, the assessment of these substrates regarding their fertilizing effect and the evaluation of potential impacts on the local soil's nutrient budget was among the first tasks of the accompanied ecological research.

Substrates tested as soil amendment.

The following substrates derived from the CaSa- and BiogaST-projects were tested:

1. Urine collected in UDDT and stored for two months in closed jerry cans for sanitation.
2. Biogas slurry from the first pilot digester using banana tree stump mixed with cow dung for fermentation (mixture 1:1 by volume).
3. Grass is included in the assessment because, according to local practice, plots where biogas slurry is applied are covered with grasses.
4. Compost prepared by local farmers containing a mixture of fresh and dried grasses (91 vol%), ash (3 vol%) and kitchen waste (6 vol%). In addition, water was added to improve the moisture content of the mixture and topsoil was added to introduce microorganisms. Composting was done in one batch for about three months in a shallow pit in the ground, covered with soil and grasses to mitigate evaporation.
5. CaSa-compost containing sanitized human feces (15 vol%), biochar (17 vol%; residues from microgasification of eucalyptus-sawdust with pyrolitic temperature conditions of over 500°C, residence time ≥ 120 min), kitchen waste and harvest residues (15 vol%; beans straw, banana peels), mineral material (31 vol%; ash from three stone fire with eucalyptus wood, brick particles, local soil to add minerals and soil microorganisms) and woody material (22 vol%; sawdust, grasses). In addition, 1.2 dm^3 of stored urine was added per 10 dm^3 of solid material. Urine was mixed with sawdust or charcoal two days before addition to the compost pit so that N contained in urine could be adsorbed to the charcoal. Composting was done continuously with weekly addition of one pot of about 20 dm^3 of sanitized feces and the other materials in the respective amounts. The compost pit was located in a shallow hole under the shade of a tree and covered with grasses.

Analytical assessment of the soil amendments

A series of analyses were carried out to assess the fertilizing potential of the tested amendments. Total concentrations of nutrients, P_{tot}, K_{tot}, Ca_{tot}, Mg_{tot}, Zn_{tot}, Mn_{tot}, aluminium (Al_{tot}), and iron (Fe_{tot}), were determined after nitric acid (HNO_3) digestion under pressure using inductively coupled plasma optical emission spectrometry (ICP-OES; with iCAP 6000, Thermo Scientific, Waltham, USA) and method according to König (2005). Total concentrations of C (C_{tot}) and N (N_{tot}) were analyzed after dry combustion of oven-dry material using a thermal conductivity detector (with CNS-Analyzer, Vario ELIII, Elementar, Hanau, Germany) and method according to ISO DIN 10694 (1995) for C_{tot} and ISO DIN 13878 (1998) for N_{tot}. Mineral nitrogen (N_{min}) was extracted with potassium chloride (KCl) and analyzed using test strips (AgroQuant 114602 Soil Laboratory, Merck, Darmstadt, Germany). The method involved the suspension of 50 g material of the amenders in 0.1 dm^3 of 0.1 mol KCl. Within the same solution, pH was measured by using a glass electrode (pH 330i, WTW, Weilheim, Germany). In addition, gravimetric determination of water content of the fresh matter (wc_{FM}) was made for each material by weighing the materials before and after drying in a laboratory oven, at 105°C and 24 h for compost and at 65°C and 72 h for biogas slurry. Bulk density (ρ) of the composts was determined by filling 20 dm^3 buckets with equally poured fresh matter (FM) and measuring the weight respectively. Total concentrations of nutrients and C were measured at the laboratory of TU Berlin at the department of soil science. Other analyses were done on-site in MAVUNO's laboratory.

Data analyses

We calculated mean values (x) and standard deviations (σ) using MS Excel. For the experimental measurements, the numbers of replications (n) varied and were n=1, 2 and 5 for grasses, biogas slurry and compost as well as CaSa-compost respectively. We compared the assessed data considering the interval of $x \pm \sigma$. Furthermore, we applied propagation of errors to determine the uncertainty of the calculated values.

RESULTS AND DISCUSSION

Nutrient concentrations in substrates derived from case studies

The pH of all tested substrates was similar and slightly alkaline (Table 1). According to literature, the pH of fresh urine depends on the nutrition and varies between 4.8 and 7.5. During storage the pH rises to 8.8 or 9.2 (Schönning and Stenström, 2004). The wc_{FM} ranged from 25.0 ± 13.1% to 33.6 ± 5.3 and 32.5 ± 1.9 up to 95.6 ± 0.5 % of the FM for grasses, compost, CaSa-compost and biogas slurry respectively. With 770.5 ± 8.9 g dm^{-3}, CaSa-compost had a higher bulk density of FM as compared to the local compost with 546.5 ± 1.5 g dm^{-3}. This might be related to the differences in content of C_{tot} in FM because CaSa-compost showed with 60.1 ± 6.9 g dm^3 nearly two times higher concentration than compost while concentration in biogas slurry was about half of that for CaSa-compost. With 5.3 ± 0.2 g kg^{-1} and 6.0 ± 0.5 g kg^{-1}, compost and CaSa-compost showed comparatively low N_{tot}, with a concentration of N_{tot} in DM typically around 12 g kg^{-1} for composts (Horn et al., 2010); compared to 19.9 ± 0.1 g kg^{-1} in biogas slurry. The dominant forms of available N_{min} were ammonium (NH_4^+) in biogas slurry and nitrate (NO_3^-) in compost and CaSa-compost, while the concentration was highest in biogas slurry and similar in both composts. Furthermore, CaSa-compost showed adequate fertilizing potential with concentrations of P_{tot} in DM of 3.2 ± 0.2 g kg^{-1}, compared to literature for composts made of organic residues with an average value of about 1 g kg^{-1} (Finck, 2007). With P_{tot} in FM of 1.7 ± 0.1 g dm^{-3}, the concentration was 3.6 times and 5 times higher compared to compost and biogas slurry respectively. In addition, concentrations of K_{tot}, Mg_{tot}, Ca_{tot}, Zn_{tot} were higher in CaSa-compost compared to the other amendments.

Furthermore, the ratios of C and N, P, S need to be considered to avoid immobilization of N, P or S during organic decomposition after the application of the soil amendments. Thresholds are C/N > 25, C/P > 150

Table 1. Analytical assessment of the tested soil amendments.

	pH	wc	C_{tot}	N_{tot}	N_{min}	S_{tot}	P_{tot}	K_{tot}	Mg_{tot}	Ca_{tot}	Al_{tot}	Fe_{tot}	Zn_{tot}	Mn_{tot}
	KCl	% (FM)	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	mg kg^{-1}	mg kg^{-1}
Gras		25.0 ± 13.1	426.3	1.9	ua.	1.7	1.0	13.8	2.8	8.6	4.9	4.0	24.1	172.4
Biogas slurry	7.7	95.6 ± 0.5	347.8 ± 6.4	19.9 ± 0.1	16.0 ± 0.8	3.1 ± 0.02	7.6 ± 0.2	92.9 ± 8.4	12.2 ± 0.1	17.4 ± 0.9	4.0 ± 0.7	4.3 ± 0.07	115.3 ± 1.7	282.7 ± 8.8
Compost	7.4	33.6 ± 5.3	90.6 ± 7.7	5.3 ± 0.2	0.12 ± 0.04	1.2 ± 0.05	1.2 ± 0.1	8.5 ± 1.2	3.2 ± 0.2	10.0 ± 1.2	77.5 ± 1.6	65.2 ± 10.3	59.5 ± 4.3	641.4 ± 105.6
CaSa	7.5	32.5 ± 1.9	115.6 ± 11.4	6.0 ± 0.5	0.36 ± 0.07	1.3 ± 0.1	3.2 ± 0.2	14.6 ± 1.4	5.1 ± 0.5	29.6 ± 2.8	54.5 ± 1.4	83.5 ± 17.5	67.0 ± 4.7	480.2 ± 47.7
	ρ_{FM}	ρ_{DM}	C_{tot}	N_{tot}	N_{min}	S_{tot}	P_{tot}	K_{tot}	Mg_{tot}	Ca_{tot}	Al_{tot}	Fe_{tot}	Zn_{tot}	Mn_{tot}
	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	g dm^{-3}	mg dm^{-3}	mg dm^{-3}
Gras	77.4 ± 0.7	58.0 ± 30.4	24.7 ± 13.0	0.1 ± 0.1	ua.	0.1 ± 0.1	0.1 ± 0.03	0.8 ± 0.4	0.2 ± 0.1	0.5 ± 0.3	0.3 ± 0.2	0.2 ± 0.1	1.4 ± 0.7	10.0 ± 5.2
Biogas slurry	1000 ± 50*	44.0 ± 2.2	15.3 ± 0.8	0.9 ± 0.04	0.7 ± 0.05	0.1 ± 0.01	0.3 ± 0.02	4.1 ± 0.4	0.5 ± 0.03	0.8 ± 0.1	0.2 ± 0.03	0.2 ± 0.01	5.1 ± 0.3	12.4 ± 0.7
Compost	546.5 ± 1.5	362.9 ± 57.2	32.9 ± 5.9	1.9 ± 0.3	0.04 ± 0.02	0.4 ± 0.1	0.5 ± 0.1	3.1 ± 0.7	1.1 ± 0.2	3.6 ± 0.7	28.1 ± 4.5	23.7 ± 5.3	21.6 ± 3.7	232.8 ± 53.1
CaSa	770.5 ± 8.9	520.1 ± 31.0	60.1 ± 6.9	3.1 ± 0.3	0.2 ± 0.04	0.7 ± 0.1	1.7 ± 0.1	7.6 ± 0.9	2.7 ± 0.3	15.4 ± 1.7	28.3 ± 1.8	43.4 ± 9.5	34.9 ± 3.2	249.7 ± 28.9
Urine **	1030	30	8.0	9.2	n.a.	1.5	0.5	2.2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Element concentrations in DM of the tested soil amendments [g kg^{-1} and mg kg^{-1}] and bulk density of FM (ρ_{FM}) [g dm^{-3}] were analyzed and are displayed with mean value and standard deviation with n=1, 2 and 5 for grasses, biogas slurry and compost as well as CaSa-compost respectively. Element concentrations in FM based on volume [g dm^{-3} and mg dm^{-3}] and bulk density of DM (ρ_{DM}) [g dm^{-3}] are calculated by using wc and displayed with mean values and standard error calculated applying propagation of error. *Density of slurry was unanalyzed (ua.); assumption is based on literature for liquid biogas slurry (Vögeli et al., 2014). ** Values are based on literature for stored urine (Berger, 2008; some concentrations were not available, n.a.)

and C/S > 150 (Finck, 2007). With C/N of about 18, 17 and 14for biogas slurry, compost and CaSa-compost respectively, the immobilization of N is not likely. The same was shown for the immobilization of P with C/P ratios of 46, 73 and 36 and immobilization of S with C/S ratios of 114, 74, 63 for biogas slurry, compost and CaSa-compost respectively. Compared to the assessed amendments, N_{tot}-concentration in urine is comparatively high and concentration of P_{tot} and K_{tot} are in the range of compost with 0.5 and 2.2 g dm^{-3} respectively (Berger, 2008). However, according to Finck (2007), plants will initially utilize only a certain proportion of the added nutrients of the assessed fertilizing amendments. The remaining amount will stay in the soil and be taken in the next cropping seasons, if not leached out (e.g. for S, N), volatilized (e.g. for N) or taken away through erosion (e.g. for P). Hence, the total concentrations we presented here should be considered as "apparent" utilizations (Finck, 2007) or specific nutrient recycling potential.

Assessment of the tested amendments with respect to nutrient availability in the soil

The availability of nutrients in the soil is, among other factors, a function of soil pH. The optimum range of pH for agricultural soils depends on the clay content as well as on the concentration of SOM and is, on an average, between 5.5 and 6.5 (Horn et al., 2010; Finck, 2007). An increase of soil pH in the topsoil, depending on the treatment and the respective nutrient addition, has often been considered to have an immediate impact on harvest yield (Jeffery et al., 2011; Liu et al., 2013). Falcão et al. (2009) argued that the high productivity of plants growing on Terra Preta is inter alia due to the improved pH and consequent reduction of Al-toxicity.

As mentioned earlier, in preliminary studies we found very low values of about 3.8 to 4.2 for soil pH in Karagwe. Commonly, lime ($CaCO_3$) is used to neutralize soil acidity (Horn et al., 2010). However, organic material also has the potential to buffer acids in soils (Wong et al., 1998). Furthermore, Biederman and Harpole (2013) concluded that the addition of biochar can improve the availability of nutrients in the soil through soil liming effects.

Table 2. Effects on soil acidification or alkalization of the tested soil amendments in comparison to organic (Jobe et al., 2007) and synthetic fertilizers (Sluijsmansen, 1970; KTBL, 2009; Fink, 1979) expressed in kg of CaO in 100 kg of DM and in kg of CaO in each kg of N_{tot}.

Treatment	E	
	kg_{CaO} 100 kg_{DM}^{-1}	kg_{CaO} kg_{N}^{-1}
Tested soil amendments		
Biogas slurry	+ 6.8	+ 3.4
Compost	+ 1.4	+ 2.6
CaSa-compost	+ 4.7	+ 7.8
Organic fertilizers		
Poultry manure I	+ 14	+ 10.0
Fish waste I	+ 3.5	+ 0.8
Fish waste II	+ 3.5	+ 0.8
Poultry manure II	+ 13.6	+ 9.7
Sugar molasses	+ 3.5	+ 1.4
Cattle manure	+ 2.7	+ 2.1
Synthetic fertilizers		
Ammonium sulfate	- 63	- 3
Calcium ammonium nitrate (22% N)	- 4	0
Urea	- 46	- 1
Calcium nitrate	+ 13	+ 1

Wong et al. (1998) proposed an acid titration method to quantify the acid neutralizing capacity of compost (ANC). Jobe et al. (2007) used this method and estimated ANC ranging between 95 and 500 cmol H^+ kg^{-1} for six different composts. If complete mineralization of the compost and oxidation of organic N and S are considered, which is reasonable under tropical soil conditions, the ANC may, however, simply be calculated as the difference between metal- (M+) and non-metal-equivalents (A-) in the compost. This is possible, because the mineralization of M+ is a H^+-sink and the mineralization of A- is a H^+-source (Van Breemen et al., 1983). Under these conditions the formula which was developed by Sluijsmans (1970) for the prediction of the liming effect E, expressed as kg CaO equivalent of 100 kg of DM of any fertilizer may be applied:

$$E = (1.0 \times CaO + 1.4 \times MgO + 0.6 \times K_2O) \quad (0.4 \times P_2O_5 + 0.7 \times SO_3 + 2 \times N) \qquad (1)$$

The amounts of nutrients (CaO, MgO etc.) are to be inserted into the equation in kg of nutrient per 100 kg of fertilizer. Overall, the compost application will cause acidification if E < 0 and alkalization if E > 0.

The results of our calculation using Equation 1 are presented in Table 2 and compared with literature for selected organic and synthetic fertilizers (Sluijsmansen, 1970; KTBL, 2009; Fink, 1979; Jobe et al., 2007). In addition, we calculated the liming effect related to N in the various fertilizers.

Additions of 100 kg of DM of, respectively, biogas slurry, compost or CaSa-compost are equivalent to 6.8, 1.4 and 4.7 kg of CaO. Thus, all products will cause alkalization and reduce acidity of the soil. Our results are well in line with the range of pH buffering capacity of different composts given by Jobe et al. (2007). The liming effect related to N_{tot} in the tested amendments is similar for biogas slurry and compost, with 3.4 and 2.6 kg of CaO per kg of N_{tot} respectively, while the value is more than doubled for CaSa-compost. In comparison with our results, most synthetic N-fertilizers that are commonly used would cause soil acidification. For example, if 100 kg of urea are applied as N_2-fertilizer, about 46 kg CaO are needed to buffer the acidification effect in the soil. Among the synthetic N-fertilizers only calcium nitrate ($Ca(NO_3)_2$) has a positive value for E with 100 kg of calcium nitrate being the equivalent of 13 kg of CaO and 1 kg N addition being the equivalent of 1 kg CaO.

Since Batjes and Sombroek (1997) pointed out that "stable increase in SOM in deeply weathered tropical soils occur especially with addition of phosphate and lime", we deduce that all of the assessed soil amendments can contribute to sustainable soil improvement through P-recycling and liming with this holding true especially for CaSa-compost. Increased P-levels in the soil may also contribute to mitigation measures since crops may root deeper and, thus, are less vulnerable to droughts and render P-cycling through organic residues more effective (Batjes and Sombroek,

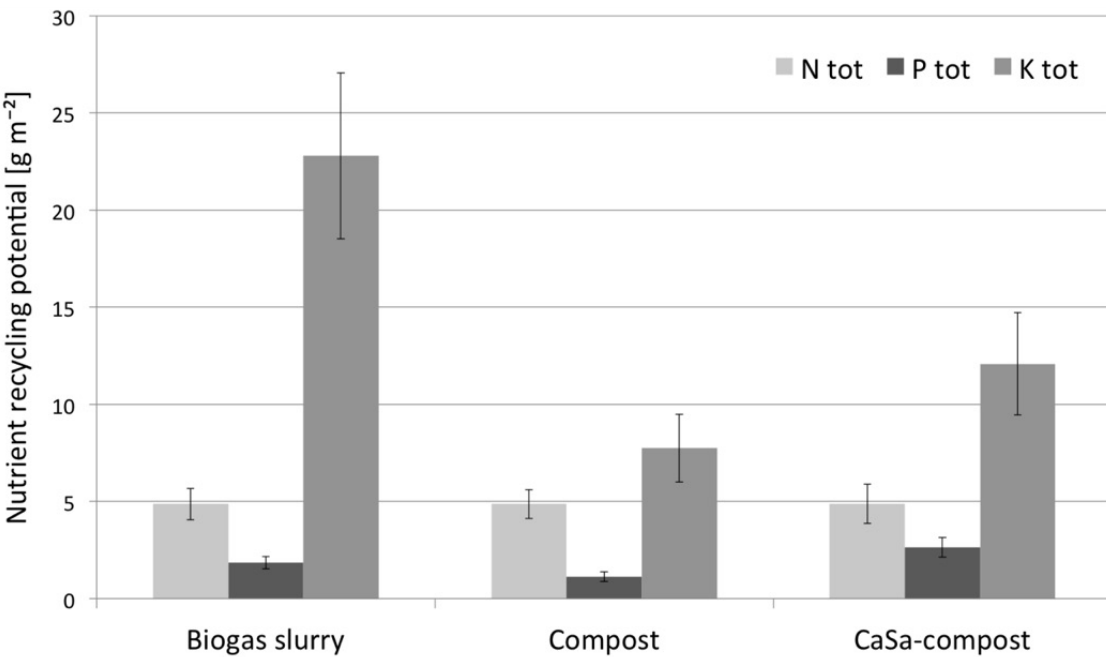

Figure 3. Total nutrient recycling potential expressed in nutrient addition [g m^{-2}] for N_{tot}, P_{tot}, and K_{tot} corresponding with application doses of 5.5, 2.5 and 1.6 dm^3 m^{-2} for biogas slurry, compost and CaSa-compost respectively.

1997).

Estimation of the total nutrient recycling potential in agricultural practice

According to Mafongoya et al. (2007), the amount of manure applied by farmers in SSA is on an average within a range of 1 to 1.5 kg m^{-2} per year which is equivalent to about 1.8 to 2.7 dm^3 m^{-2} (calculated with ρ_{FM} as presented in Table 1). Hence, we estimated the total nutrient recycling potentials for N_{tot}, P_{tot} and K_{tot} in g m^{-2} in the tested soil amendments (Figure 3).

An application of the tested local compost in FM with 2.5 dm^3 m^{-2} per year resulted in a potential nutrient addition to the soil of 4.9 ± 0.8, 1.1 ± 0.3 and 7.7 ± 1.8 g m^{-2} a^{-1} for N_{tot}, P_{tot} and K_{tot} respectively. According to the premise, that the same dose of N should be obtained with the other tested soil amendments, we subsequently calculated the necessary application of CaSa-compost and biogas slurry in FM to be 1.6 ± 0.3 and 5.5 ± 0.9 dm^3 m^{-2} a^{-1} respectively. Thus, to reach the same level of N-application, the required amount of CaSa-compost is, on average, only about 65% of the required amount of conventional compost. In other words, an available amount of 1000 dm^3 of compost material in FM would suffice for application on 400 m^2 by using compost and on about 630 m^2 by using CaSa-compost. Given these specific application doses, the resulting addition of P_{tot} by CaSa-compost would be about 1.4 and 2.3 times higher compared to biogas slurry and compost respectively. Ranging from 1.1 up to 2.6 g m^{-2} a^{-1} the estimated recycling potentials for P_{tot} are very low, especially on soils with low P-concentrations (KTBL, 2009; Finck, 2007). The calculated recycling potential for K_{tot} is about 7.7 g m^{-2} for compost and 1.6 and 2.9 times higher for CaSa-compost and biogas slurry respectively. With the estimated K-additions, the local compost as well as CaSa-compost meet the requirements for appropriate K-fertilization on soils, with an adequate K-supply of about 13 to 19 g m^{-2} on an average (KTBL, 2009; Finck, 2007). Only biogas slurry exceeds this fertilizing recommendation. According to Finck (2007), an increasing addition of K lowers the uptake of Ca and Mg during plant growth ("antagonism of nutrient uptake"). Given the K-addition with biogas slurry, it is recommendable to mix (or compost) biogas slurry prior to its application with other materials containing more N and P compared to K to reach a better balanced nutrient ratio of N:P:K. This ratio was 4:1:7, 2:1:5 and 3:1:12 for compost, CaSa-compost and biogas slurry respectively. Furthermore, the corresponding input of C_{tot} would be about the same for all tested soil amendments with 86 ± 14, 82 ± 15 and 96 ± 21 g m^{-2} for biogas slurry, compost and CaSa-compost respectively. However, the kind of C differed in the materials, as CaSa-compost contains biochar, that is, a source of stable C.

Estimation of the local potential to close the loop

Stoorvogel et al. (1993) calculated soil nutrient balances for African countries for the year 2000. They considered mineral fertilizer, animal manure, dry deposition, biological N-fixation and sedimentation as inputs to the agricultural land, while the removal of harvest products and crop residues, leaching, gaseous emissions and erosion were accounted for as losses. Their results showed an average negative balance per year and per square meter of 3.2 g N, 0.5 g P, and 2.1 g K on arable land in Tanzania. Looking at a neighboring country, bordering Kagera region, Jönsson et al. (2004) assessed that the human excreta of one Ugandan person contains in total 2.5 kg N and 0.4 kg P per year. Combining this data, we estimated the recycling potential of EcoSan for one family with 6 people to be about 15 kg N and 2.4 kg P per year, which would be sufficient to cover the negative balance of approximately 4800 m^2. Furthermore, Baijukya and de Steenhuijsen Piters (1998) calculated "Nutrient balances in the banana-based land use systems of northwest Tanzania", including Karagwe district. In addition to the balances of Stoorvogel et al. (1993), they also considered mulching and subsoil exploitation by perennial trees as input flows. Their balances were done for farms with different nutrient management levels. For farms without cattle and without brewing activities (lowest management level), they calculated an average loss per year of around 2.8 g N, 0.3 g P, and 3.0 g K on one m^2. They concluded that "substantial amounts of nutrients are lost through human feces and end up in deep pit latrines" and demanded changes in the sanitation system to "facilitate the recycling of nutrients in feces" (*ibid.*). On this basis, we assessed the potentials of the tested soil amendments to contribute to the local nutrient budget to close the loop. As P-scarcity was identified as a major problem in our pre-studies and since N-fertilization can more easily be realized with the use of urine as a fertilizer, we calculated the required amounts for compensation of the negative P-balance.

Our results show that the estimated required amount of FM is approximately 6 and 3 times higher for biogas slurry and compost respectively as compared to CaSa-compost with about 0.1 kg m^{-2} a^{-1} (Figure 4). Respective amounts based on volume are considered feasible, ranging from around 0.2 to 0.8 dm^3 m^{-2} a^{-1}. Given the fact, that one farmer household in Karagwe cultivates on average 6,225 m^2 (Tanzania, 2012), the required total amounts of FM per household to close the loop for P would be 5.0, 2.0 and 0.8 t a^{-1} for biogas slurry, local compost and CaSa-compost respectively. However, by adding the respective substrates to the soil, negative balances for N and K still remain. Considering calculated amounts and N_{tot}-concentration of the substrates, we calculated that the N-deficit would be covered by 26, 42 and 18% for biogas slurry, compost and CaSa-compost respectively. Additional nutrient requirements could be covered, for example, by applying urine as fertilizer with about 0.2 dm^3 m^{-2} a^{-1} according to own calculations. Hence, the total amount of urine required to cover the remaining N-deficit on one small-scale farm in Karagwe with 6,225 m^2 cultivated land would be about 1.7, 1.3 and 1.8 m^3 a^{-1}. According to Winblad et al. (2004) the excreta of person includes 1 dm^3 urine per day so that one family with 6 people has about 2.2 m^3 urine available per year and could finally close the local nutrient balance on their farmland.

CONCLUSION AND RECOMMENDATION

The introduced projects and case studies of this research present an integrated approach of resource management where different substrates rich in mineral nutrients, such as ash, biogas slurry, stored urine and sanitized feces are recycled in combination with C-rich materials such as biochar. The results of our first investigations support our hypothesis that new approaches that combine EcoSan, bioenergy and TPP can contribute to the recycling of nutrients and C-sequestration as well as to soil improvement. The analytical assessment of the substrates derived from these projects showed that all of the tested substrates are feasible soil amendments due to their sufficient nutrient concentrations and adequate nutrient ratios compared to literature. Based on the more practice-oriented volume [dm^3], CaSa-compost showed the highest concentration of all nutrients as well as C, followed by compost and biogas slurry. Furthermore, all tested soil amendments have good liming potential compared to other soil amendments. As $CaCO_3$ is usually quite expensive, we conclude that all tested substrates are a feasible low-cost option for liming. Especially the locally produced CaSa-compost is promising due to the comparatively high P-concentration and E-value for liming. Under the circumstances given in Karagwe, sufficient application rates of CaSa-compost can contribute to mitigating existing P-scarcity and acidification in the soil and, consequently, to increasing biomass production. Furthermore, our final evaluation revealed that amounts of FM of less than one dm^3 m^{-2} a^{-1} of the assessed materials in combination with urine are required to close existing open nutrient cycles (for P and N) in Karagwe. However, higher amounts of the soil amendments are required if they should be applied as a major source of nutrients, in order to provide a full substitution of the existing input of mineral fertilizer and animal manure. We conclude that EcoSan combined with TPP as well as the use of biogas slurry are promising practices to close the loop in the agroecosystems in SSA (as well as elsewhere). However, there is a need for practice-oriented experiments to assess short and long-term effects of these amendments on biomass production

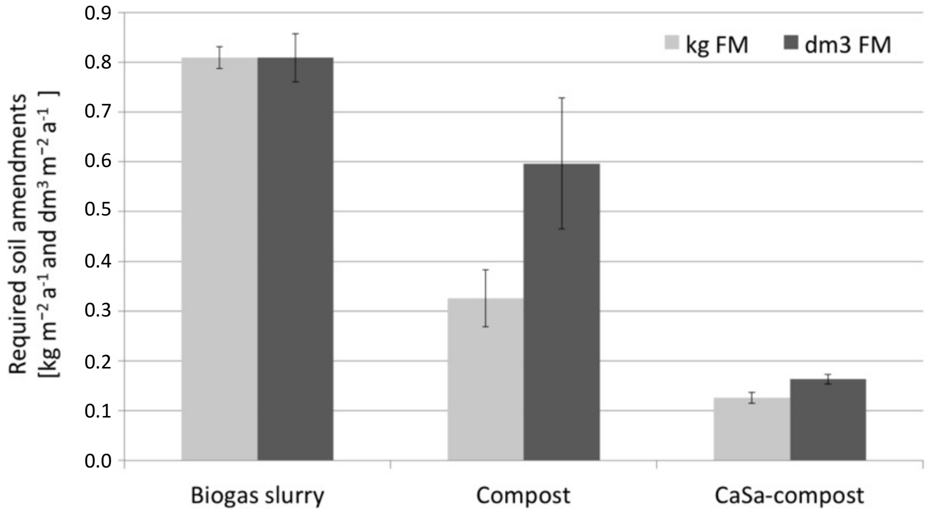

Figure 4. Calculated required amounts of FM of the tested substrates [kg ha^{-1} a^{-1} and dm^3 ha^{-1} a^{-1}] to compensate the negative P-balance of 0.3 g m^{-2} a^{-1} in banana-based land use systems of northwest Tanzania (Baijukya and de Steenhuijsen Piters, 1998).

and soil properties. Altogether, the strategies to investigate further potentials of the substrates derived from the projects include (1) practice-oriented field experiments to compare and to assess the short-term effectiveness of urine, biogas slurry, compost and CaSa-compost as a fertilizer with respect to crop productivity and crop nutrition as well as potential soil improvements. Furthermore, the applied resource management approach, as it is practiced in the introduced projects, should be (2) integrated in the local nutrient and C balance by using methods such as Material Flow Analysis and (3) should finally be evaluated including other perspectives than only the ecological one (e.g. socio-economic) by using Multi-Criteria Analysis. In addition, long-term field experiments are required to investigate the sustainable effects on SOM and other fertility-related soil parameters, such as the water holding capacity.

Conflict of Interests

The authors have not declared any conflict of interests. All partner organizations of the projects agreed to the ecological research on the projects and that the products will be assessed and that the results will be published.

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Abbreviations

Biochar, Charcoal used as soil amendment; **BiogaST,** Project “Biogas Support for Tanzania”; **CaSa,** Project “Carbonization and Sanitation”; **CaSa-compost,** Product of CaSa-project containing composted biochar and sanitized excreta; **CHEMA,** Community Habitat Environmental Management; **CREEC,** Center for Research in Energy and Energy Conservation; **EcoSan,** ecological sanitation; **EfCoiTa,** Project “Efficient Cooking in Tanzania”; **EWB,** Engineers Without Borders; **IAASTD,** International Assessment of Agricultural Knowledge, Science and Technology for Development; **ICP-OES,** Inductively coupled plasma optical emission spectrometry; **IGZ,** Leibniz Institute of Vegetable and Ornamental Crops; **MAVUNO,** MAVUNO Project Improvement for Community Relief and Services;

(“mavuno” meaning “harvest” in Swahili); **m.a.s.l.,** meter above sea level; **SOM,** soil organic matter; **SSA,** Sub-Saharan Africa; **TLUD,** top-lit up draft; **TPP,** Terra Preta practice; **TU,** Technische Universität; **UDDT,** urine diverting dry toilet; **WHO,** World Health Organization.

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Chapter 3

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Comment:
Supplements of this manuscript are presented in Supplements S1 in the General Annex.

The pH values present in Table 4 on page 154 in the publication must read as follows:

Treatment	pH in KCl	
Control Andosol	5.3	a
Biogas slurry	5.5	ab
Compost	5.6	ab
CaSa-compost	6.1	b

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Organic wastes from bioenergy and ecological sanitation as a soil fertility improver: a field experiment in a tropical Andosol

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Abstract. Andosols require the regular application of phosphorus (P) to sustain crop productivity. On an Andosol in NW Tanzania, we studied the short-term effects of amending standard compost, biogas slurry and CaSa compost (containing biochar and sanitized human excreta) on (i) the soil's physico-chemical properties, on (ii) biomass growth and crop productivity, and on (iii) the plants' nutrient status. The practice-oriented experiment design included the intercropping of seven locally grown crop species planted on 9 m^2 plots with five repetitions arranged as a Latin rectangle. Differences in plant growth (biomass production and crop yield, e.g., of *Zea mays*) and crop nutrition (total C, N, P, K, Ca, Mg, Zn, etc.) were related to pH, CEC (cation exchange capacity), total C and the availability of nutrients (N, P, K, etc.) and water (water retention characteristics, bulk density, etc.) in the soil. None of the amendments had any significant effect on soil water availability, so the observed variations in crop yield and plant nutrition are attributed to nutrient availability. Applying CaSa compost increased the soil pH from 5.3 to 5.9 and the level of available P from 0.5 to 4.4 mg per kg. Compared to the control, adding biogas slurry, standard compost and CaSa compost increased the aboveground biomass of *Zea mays* by, respectively, 140, 154 and 211 %. The grain yields of maize on soil treated with biogas slurry, standard compost and CaSa compost were, respectively, 2.63, 3.18 and 4.40 t ha^{-1}, compared to only 1.10 t ha^{-1} on unamended plots. All treatments enhanced crop productivity and increased the uptake of nutrients into the maize grains. The CaSa compost was most effective in mitigating P deficiency and soil acidification. We conclude that all treatments are viable as a substitute for synthetic fertilizers. Nevertheless, further steps are required to integrate the tested soil amendments into farm-scale nutrient management and to balance the additions and removals of nutrients, so that the cycle can be closed.

1 Introduction

1.1 Challenges cultivating Andosols

Andosols occupy just 1–2 % of the land area worldwide. They are common in high-altitude tropical environments, such as in the East African Rift Valley (Chesworth, 2008; Perret and Dorel, 1999). Their high inherent fertility makes them especially well-suited for the cultivation of high-value crops such as coffee, tobacco and banana. Andosols feature a low bulk density, variable charge characteristic (strongly dependent on the soil's pH), a low base saturation (BS), thixotropy, a strong capacity to retain phosphorus (P), a high pore volume, a high level of available water, a tendency to form microaggregates and a pronounced shrinking (Chesworth, 2008; Dörner et al., 2011; Driessen et al., 2000; Zech et al., 2014). The dominant minerals in these soils are allophanes, imogolites, ferrihydrites and halloysites, and the concentrations of aluminium (Al), iron (Fe) and silicon (Si) are all high (Chesworth, 2008). Metal–humus complexes are frequently formed when the pH exceeds 5, while under more acid conditions Al–humus complexes in combination with silica predominate (Chesworth, 2008; Driessen et al., 2000). These structures serve to protect soil organic matter from degradation, thus fostering C sequestration (Driessen et al., 2000; Chesworth, 2008; Abera and Wolde-Meskel, 2013). The total carbon concentration of these soils is often $> 6\,\%$ throughout their profile (Chesworth, 2008).

Andosols are rather sensitive to land use management (Dörner et al., 2011). For example, shifting cultivation practices tend to deplete soil fertility unless organic matter is deliberately added, while intensive mechanized cultivation risks compacting the soil, with the hydraulic properties of the soil being readily compromised (Perret and Dorel, 1999; Dorel et al., 2000).

Plants on Andosols typically suffer from P deficiency (Buresh et al., 1997), as the soils have a high P fixation potential (Batjes, 2011). Thus, crop productivity and sustainable land use require consistent P replenishment, which generates a strong demand in sub-Saharan Africa for appropriate soil amenders. Fertility amelioration measures have included both liming to increase P availability and applying either manure and/or other organic matter or synthetic P fertilizer (Driessen et al., 2000; Tonfack et al., 2009).

1.2 Organic waste materials as soil amenders on Andosols in Karagwe, Tanzania

Andosols with strong P retention potential are also present in Karagwe (Kagera region, NW Tanzania), which is located nearby volcanic areas in the East African Rift Zone (Batjes, 2011). Soil constraints for farmers in this region are the low soil pH (3.8–4.2), the low availability of nutrients (especially P) and widespread soil erosion (Krause et al., 2015). Small-scale farmers often have financially or logistically restricted access to rock phosphates or synthetic fertilizers and a lack of sufficient amounts of organic matter to replenish Andosols (Buresh et al., 1997).

However, practices like ecological sanitation (EcoSan) and bioenergy production can contribute to local matter and nutrient cycling with Andosols receiving organic waste products (Krause et al., 2015). Human excreta constitute a valuable source of plant nutrients, available in every human settlement. EcoSan technologies can be implemented for the collection and sanitization of toilet waste (Esrey et al., 2001), for example with urine-diverting dry toilets (UDDT), composting toilets, and pasteurization of faeces to ensure human health (Schönning and Stenström, 2004). The last point was recently tested in Karagwe in an EcoSan pilot project named "Carbonization and Sanitation" (CaSa) (Krause et al., 2015). In the CaSa approach, so-called microgasifier stoves (Mukunda et al., 2010) provide the heat for thermal sanitation of human faeces. In addition, further projects have been locally initiated to implement bioenergy technologies for cooking such as small-scale biogas digesters (Becker and Krause, 2011) and microgasifier stoves (Ndibalema and Berten, 2015). Hence, increasing dissemination of these technologies will supply waste matter such as biogas slurry from anaerobic digestion, powdery charcoal residues from gasification and ashes (Krause et al., 2015).

These locally available resources can be directly applied to the soil or they can be processed as compost. The benefit of charcoal as a soil amender ("biochar") has been deduced from the fertility of Terra Preta soils (Sombroek, 1966; Lehmann and Joseph, 2009). CaSa compost is a product following this ancient example of co-composting (pasteurized) human faeces, kitchen waste, harvest residues, terracotta particles, ashes and urine mixed with char residues from gasification (Krause et al., 2015).

However, there is also reasonable doubt that application of biochar is recommendable in all situations and on all soils. Mukherjee and Lal (2014) pointed out that data gaps exist, in particular, concerning field-scale information on crop response and soil quality for various soil–biochar combinations. From past experiments using biochar as a soil amendment (Herath et al., 2013; Kammann et al., 2011; Kimetu et al., 2008; Liu et al., 2012; Major et al., 2010; Nehls, 2002; Petter et al., 2012; Schulz et al., 2013) and from meta-analysis by Biederman and Harpole (2013), Jefferey et al. (2011) and Liu et al. (2013), the following lessons can be learned for future experiments: (i) pot experiments lead to overestimations of possible positive impacts on biomass growth compared to field experiments; (ii) soil chemical *and* soil hydraulic properties should be examined at the same time to be able to distinguish between the observed effects; (iii) the assessment of biomass growth should be combined with the assessment of crop yield and the evaluation of plant nutrition; (iv) locally typical and economically relevant plants should be selected and cultivated according to local practice to assess the practical relevance of biochar application in the local agroecosystem; and (v) long-term as well as short-term experiments are needed. Although the latter are often criticized for not enhancing knowledge on changes in soil hydraulic properties as well as on soil organic matter and C sequestration, they are of high practical relevance to farmers who rely on their harvests immediately.

In this study, we assessed whether and how locally available organic waste materials change the availability of nutrients and water in the soil and improve the crop productivity in a one-season, practice-oriented field experiment. In particular, our objectives were (i) to examine the effect of CaSa compost, standard compost and biogas slurry on the physico-chemical properties of the soil and (ii) to assess their impact on biomass growth, crop yield and plant nutrition.

2 Materials and methods

2.1 Field site

The experimental site (see Figs. S2–S4 in the Supplement) is located in the Ihanda ward, Karagwe district, Kagera region, NW Tanzania (1°33.987′ S, 31°07.160′ E; 1577 m a.s.l.), a hilly landscape characterized by a semi-arid, tropical climate (Blösch, 2008). The annual rainfall ranges from 1000 to 2100 mm and the mean annual potential evapotranspiration is ∼ 1200 mm (FAO Kagera, online http://www.fao.org/fileadmin/templates/nr/kagera/Documents/Suggested_readings/nr_info_kagera.pdf). The pattern of rainfall is bimodal, featuring a long rainy season from March to May and a short one from October to November (Tanzania, 2012). The predominant cropping system comprises banana, intercropped with beans and coffee. Prior to the experiment, the soil was surveyed by sampling the edges of the field (Table 1 and Fig. S1). Stone and gravel concentrations increased with soil depth. The bulk density (ρ_B) of the topsoil lay within the range expected for an Andosol. The soil's total carbon (C_{tot}) and total nitrogen (N_{tot}) concentrations were classified, respectively, as medium and adequate, and its C / N ratio is suitable for cropping (Landon, 1991). The soil pH was in the range of 3.6–3.8. The effective cation exchange capacity (CEC_{eff}) of dry matter (DM) in the soil was only 8–17 cmol kg^{-1} compared to a typical range of 10–40 cmol kg^{-1} of DM (Chesworth, 2008). The soil's BS was quite high (Ca saturation of up to 70 %). Comparable levels of CEC_{eff} and BS have been recorded in both in Kenyan Ultisols cultivated for about 35 years (Kimetu et al., 2008) and in an Ethiopian Andosol (Abera and Wolde-Meskel, 2013). The quantity of available P in the topsoil was 0.7 mg kg^{-1} (classified as "very low" according to KTBL, 2009), whereas that of potassium (K) was "very high" (244.7 mg kg^{-1}).

Table 1. The characteristics of the investigated Vitric Andosol in Karagwe, Tanzania.

	Depth	Colour	Aggregate size distribution			Structure	pH	ρ_B	FC_{field}	FC_{lab}	CEC_{eff}	BS	TOC	N_{tot}	C / N
			Clay	Silt	Sand										
	cm	Munsell	%	%	%		KCl	kg dm^{-3}	m^3 m^{-3}	m^3 m^{-3}	cmol kg^{-1}	%	%	%	
Ap	20	2.5 YR 3/2	3.2	16.1	80.7	Very crumbly	3.8	0.94	0.38	0.35	16.7	99.6	3.5	0.3	12.9
Ah	37	2.5 YR 3/2	3.6	13.0	83.4	Blocky subangular to crumbly	3.8	0.88							
B1	53	2.5 YR 2.5/3	2.2	16.3	81.5	Crumbly to blocky subangular	NA	1.08	0.36	NA	11.2	97.1	2.7	0.2	13.3
B2	74	2.5 YR 3/3	2.2	20.1	77.8	Macro: prismatic; micro: blocky subangular	NA	NA	NA	NA	8.0	94.5	2.0	0.2	12.5
C	100+	NA	NA	NA	NA	No aggregates, subangular gravel	NA	NA	NA	NA	NA	NA	NA	NA	NA

Water holding capacity (WHC) was determined in the field (FC_{field}) and in the laboratory (FC_{lab}). ρ_B: bulk density; CEC: cation exchange capacity; BS: base saturation; TOC: total organic carbon; NA: not analysed.

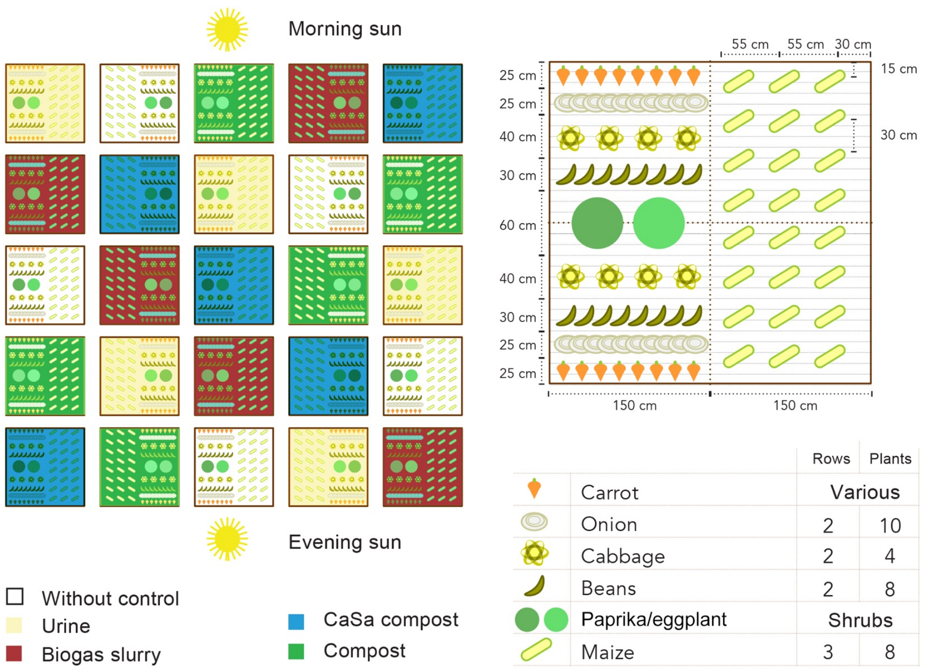

Figure 1. The experiment design: the plots were arranged as a Latin rectangle with five columns and five rows (left panel) and each plot was divided into two 4.5 m^2 sections for the cultivation of seven selected crops in an intercropping system (right panel); note that urine treatment was a posteriori excluded from the analysis due to technical problems.

2.2 Plot preparation and soil amendments

We arranged a series of 3 m × 3 m plots in the form of a Latin rectangle (Richter et al., 2009), with the five columns and five rows each separated from one another by a 0.5 m deep trench. Each of the four treatments was applied to a single row and a single column and thus studied with five replications (Fig. 1). The treatments were as follows: (1) untreated (control), (2) biogas slurry in a weekly application (from weeks 4 to 9 after sowing) of 1.7 $dm^3\,m^{-2}$ on a cover of cut grass, (3) standard compost with a pre-sowing application of 15.0 $dm^3\,m^{-2}$, and (4) CaSa compost with a pre-sowing application of 8.3 $dm^3\,m^{-2}$, passed through a 20 mm sieve. Macro- and micronutrients of the amendments were analysed according to standard methods as described in Krause et al. (2015). Values are given in dry matter ($g\,kg^{-1}$) as well as in the practice-oriented fresh matter concentrations ($g\,dm^{-3}$) in Table 2.

The biogas slurry employed derived from anaerobic digestion of banana tree stumps and cow dung (mixture 1 : 1 by volume). According to local practice, biogas-slurry-amended plots were covered with cut grasses prior to sowing. Therefore, the nutrient content of grass was analysed as well.

Standard compost was processed by local farmers during 3 months from fresh and dried grasses (0.91 $m^3\,m^{-3}$), kitchen waste (0.06 $m^3\,m^{-3}$), and ash (0.03 $m^3\,m^{-3}$). The compost heap was regularly watered and covered with soil and grasses to mitigate evaporation.

CaSa compost contained pasteurized human faeces (0.15 $m^3\,m^{-3}$), biochar from gasification (0.17 $m^3\,m^{-3}$; eucalyptus sawdust, pyrolysis at $T > 500\,°C$, residence time ≥ 120 min), kitchen waste and harvest residues (0.15 $m^3\,m^{-3}$; bean straw, banana peels), mineral material (0.31 $m^3\,m^{-3}$; ash from eucalyptus wood, brick particles, local soil to add minerals and soil microorganisms), and lignin and cellulose sources (0.22 $m^3\,m^{-3}$; sawdust, grasses). Stored urine, mixed with sawdust or biochar, was added to the compost as well (0.12 $m^3\,m^{-3}$). Every week, 60–80 dm^3 of the above-mentioned matters were added to the shaded and grass-covered compost heap.

We adjusted the amendments so that each treatment delivered a comparable quantity of mineral nitrogen (N_{min}). The N_{min} demand per cropping season ($N_{min,demand}$) was estimated as 17.5 $g\,m^{-2}$, following KTBL (2009). According to Horn et al. (2010), 33 % of organic nitrogen contained in organic fertilizers ($N_{org,fertilizer}$) is mineralized during the course of a cropping season. The amount of materials to be amended to the soil, $m_{fertilizer}$ ($kg\,m^{-2}$), was calculated based on the quantity of N_{min} present in the top 90 cm of the soil ($N_{min,soil}$ with about 7.5 $g\,m^{-2}$; see Table 3) and that provided by the amendments as follows:

$$m_{\mathrm{fertilizer}} = \frac{N_{\mathrm{min,demand}} - N_{\mathrm{min,soil}}}{N_{\mathrm{min,fertilizer}} + 0.33 \cdot N_{\mathrm{org,fertilizer}}}. \quad (1)$$

Then, the addition of the other plant nutrients (Table 3) was calculated according to Table 2.

Before planting, we hoed the soil by hand, as it is common local practice. We applied the composts by first spreading them evenly and then incorporating them with a fork hoe. Planting was carried out at the beginning of the rainy season (March 2014), and the plots were mulched in mid April (end of rainy season) to minimize evaporative loss. We harvested the crops during June and July. Precipitation was recorded on a daily basis, while the air temperature and relative humidity prevailing 2 m above ground were measured every 15 min.

We divided each plot into two 4.5 m^2 sections (Fig. 1), one used to cultivate maize cv. Stuka, and the other planted with a mixture of common bean cv. Lyamungu 90, carrot cv. Nantes, cabbage cv. Glory of Enkhuizen and local landraces of onion. In addition, African eggplant (*Solanum aethiopicum*) and sweet pepper were planted as important parts of the chosen local adjusted intercropping practice. However, as these two plant species are perennial, biomass harvest exceeded the experimental time frame, and therefore we excluded them from analysis.

The maize was sown on 4 March with two grains per dibbing hole and thinned after germination. Carrot seed was directly sown on the plot on 6 March and the beans were sown on 14 March; carrot was thinned after 40 days. The other species were transplanted as seedlings in mid March. The maize and beans were entirely rain-fed, while the other crops were irrigated as required. The plots were hand-weeded once a week, and insects were controlled by spraying with a mixture of ash and "moluku" (prepared from the leaves of the Neem tree and the Fish Poison tree suspended in soapy water).

We sampled the soil (two samples per plot) using a 1 m Pürckhauer universal gauge auger on three occasions during the experiment: the first prior to sowing (t_0, beginning of February), the second at the end of the rainy season (t_1, end of April) and the final one after harvest (t_2, beginning of July). The soil sample was divided into three subsamples: 0–30, 30–60 and 60–90 cm. The two samples from each plot were combined. For the t_0 sample, 16 sampling sites were selected, from which four mixed samples were prepared for each soil layer to represent each quarter of the field. At t_1, all 25 plots were sampled, but at t_2 the sampling involved three of the five plots for each treatment.

2.3 Soil analyses

The water retention curve (WRC) and ρ_B were determined from undisturbed soil samples taken using a 0.1 dm^3 stainless steel cylinder. In the field, we monitored the topsoils' volumetric water content (θ) ($m^3\,m^{-3}$) twice a week over the first 6 weeks after sowing at five points per plot, using

Table 2. The characteristics of the tested soil amendments according to Krause et al. (2015).

		C_{tot}	N_{tot}	N_{min}	S_{tot}	P_{tot}	K_{tot}	Mg_{tot}	Ca_{tot}	Al_{tot}	Fe_{tot}	Zn_{tot}	Mn_{tot}
		in dry matter											
		$g\,kg^{-1}$	$g\,kg^{-1}$	$g\,kg^{-1}$	$g\,kg^{-1}$	$g\,kg^{-1}$	$g\,kg^{-1}$	$g\,kg^{-1}$	$g\,kg^{-1}$	$g\,kg^{-1}$	$g\,kg^{-1}$	$mg\,kg^{-1}$	$mg\,kg^{-1}$
Gras		426	1.9	ua.	1.7	1.0	13.8	2.8	8.6	4.9	4.0	24.1	172
Biogas slurry		348 ± 6	19.9 ± 0.1	16.0 ± 0.8	3.1 ± 0.02	7.6 ± 0.2	92.9 ± 8.4	12.2 ± 0.1	17.4 ± 0.9	4.0 ± 0.7	4.3 ± 0.1	115.3 ± 1.7	283 ± 9
Compost		91 ± 8	5.3 ± 0.2	0.12 ± 0.04	1.2 ± 0.1	1.2 ± 0.1	8.5 ± 1.2	3.2 ± 0.2	10.0 ± 1.2	77.5 ± 1.6	65 ± 10	59.5 ± 4.3	641 ± 106
CaSa compost		116 ± 11	6.0 ± 0.5	0.36 ± 0.07	1.3 ± 0.1	3.2 ± 0.2	14.6 ± 1.4	5.1 ± 0.5	29.6 ± 2.8	54.5 ± 1.4	84 ± 18	67.0 ± 4.7	480 ± 48
	pH	in fresh matter											
	in KCl	$g\,dm^{-3}$	$g\,dm^{-3}$	$g\,dm^{-3}$	$g\,dm^{-3}$	$g\,dm^{-3}$	$g\,dm^{-3}$	$g\,dm^{-3}$	$g\,dm^{-3}$	$g\,dm^{-3}$	$g\,dm^{-3}$	$mg\,dm^{-3}$	$mg\,dm^{-3}$
Gras		25 ± 13	0.1 ± 0.1	ua.	0.1 ± 0.1	0.1 ± 0.03	0.8 ± 0.4	0.2 ± 0.1	0.5 ± 0.3	0.3 ± 0.2	0.2 ± 0.1	1.4 ± 0.7	10 ± 5
Biogas slurry	7.7	15 ± 1	0.9 ± 0.04	0.7 ± 0.05	0.1 ± 0.01	0.3 ± 0.02	4.1 ± 0.4	0.5 ± 0.03	0.8 ± 0.1	0.2 ± 0.03	0.2 ± 0.01	5.1 ± 0.3	12 ± 1
Compost	7.4	33 ± 6	1.9 ± 0.3	0.04 ± 0.02	0.4 ± 0.1	0.5 ± 0.1	3.1 ± 0.7	1.1 ± 0.2	3.6 ± 0.7	28.1 ± 4.5	24 ± 5	21.6 ± 3.7	233 ± 53
CaSa compost	7.5	60 ± 7	3.1 ± 0.3	0.2 ± 0.04	0.7 ± 0.1	1.7 ± 0.1	7.6 ± 0.9	2.7 ± 0.3	15.4 ± 1.7	28.3 ± 1.8	44 ± 10	34.9 ± 3.2	250 ± 29

Analyses as described in Krause et al. (2015): total concentrations of nutrients, P_{tot}, K_{tot}, Ca_{tot}, Mg_{tot}, Zn_{tot}, Mn_{tot}, Al_{tot} and Fe_{tot}, were determined using HNO_3 digestion under pressure (König, 2006) and an iCAP 6000 inductively coupled plasma optical emission spectrometry (ICP-OES) device (Thermo Scientific, Waltham, USA). Total concentrations of C, N and S were analysed according to ISO DIN 10694 (1995) for C_{tot}, ISO DIN 13878 (1998) for N_{tot} and DIN ISO15178 (HBU 3.4.1.54b) for S_{tot}, and using a Vario ELIII CNS analyser (Elementar, Hanau, Germany). Mineral nitrogen (N_{min}) was extracted with potassium chloride (KCl) and analysed using test strips (AgroQuant 114602 Soil Laboratory, Merck, Darmstadt, Germany). This method involved the suspension of 50 g material of the amenders in 100 mL 0.1 M KCl. Within the same solution, pH was measured by using a glass electrode (pH 330i, WTW, Weilheim, Germany). Values are displayed with mean value and standard deviation with $n = 1$, 2 and 5, respectively, for grasses, biogas slurry and compost as well as CaSa compost. The dominant form of available N_{min} was NH_4 for biogas slurry and NO_3 for compost as well as CaSa compost.

Table 3. Soil nutrient status before applying the amendments and the nutrient loads of the amendments.

	FM $dm^3\,m^{-2}$	FM $kg\,m^{-2}$	DM $kg\,m^{-2}$	N_{min} $g\,m^{-2}$	P $g\,m^{-2}$	K $g\,m^{-2}$	Mg $g\,m^{-2}$	Ca $g\,m^{-2}$	Al $g\,m^{-2}$	Zn $g\,m^{-2}$	Mn $g\,m^{-2}$
Soil (0–90 cm)	900	1039	869	7.5	0.4	141	1107	2761	60	n.d.	NA
Biogas slurry	10.2	10.2	0.4	4.9	3.4	41.3	5.4	7.7	1.8	0.05	0.13
Gras	15.6	1.2	0.9	5.8	0.9	12.5	2.6	7.8	4.4	0.02	0.16
$\sum$ Biogas*	25.8	11.4	1.3	10.7	4.3	53.8	8.0	15.5	6.2	0.07	0.29
Compost	15.0	8.2	5.4	10.4	6.8	46.5	17.2	54.4	421.5	0.32	3.49
CaSa compost	8.3	6.4	4.3	9.5	13.8	63.2	22.2	128.1	236.2	0.29	2.08

Concentrations in the dry soil were analysed as described in Sect. 2.3. Calculations of the content in fresh matter of the treatments derived concentrations provided by Krause et al. (2015); see Table 2 for description of methods. * For the biogas slurry treatment, the nutrient load was derived from both grasses and slurry ($\sum$ Biogas). Uncommon abbreviations: DM: dry matter; FM: fresh matter; NA: not analysed; n.d.: not detectable.

a TDR probe (Field Scout 100, 8″ rods, Spectrum Technologies, Aurora, USA). Furthermore, θ for each of the three soil layers was determined gravimetrically at t_0, t_1 and t_2. We performed double-ring infiltration experiments to determine the infiltration rate (IR) as well as the field capacity (FC) for the untreated soil at t_0 and for the treated soils at t_2 following Landon (1991). The WRC was measured using pressure plates as well as using the laboratory evaporation method (Hyprop, UMS, Munich, Germany). The latter data were used to derive the general form of the Andosol's WRC and to parameterize the Peters–Durner–Iden (PDI) model (Peters et al., 2015) (Fig. 2). The available water capacity (AWC) was calculated as $\theta_{pF\,1.8} - \theta_{pF\,4.2}$. The porosity ($e$) and pore volume (PV) were calculated from dry bulk density and particle density (ρ_p) measured using a Multipycnometer (Quantchrome, Boynton Beach, USA).

We measured N_{min} and the pH of the soil in situ at both t_0 and t_1, while at t_2 only the pH was taken; the method involved the suspension of 50 g soil in 100 mL 0.1 M KCl, which was assayed using an AgroQuant 114602 test strip (Merck, Darmstadt, Germany) and a pH 330i glass electrode (WTW, Weilheim, Germany). Further chemical analyses were carried out on air- or oven-dried t_0 and t_2 samples, which were first passed through a 2 mm sieve. The oven-dried samples were used to determine the concentration of C_{tot}, N_{tot} and total sulfur (S_{tot}), following ISO DIN 10694 (1995) and ISO DIN 13878 (1998) protocols and using an Elementar Vario ELIII CNS analyser (Elementar, Hanau, Germany). Concentrations of calcium acetate lactate (CAL) soluble P (P_{CAL}) and K (K_{CAL}) were determined with an iCAP 6000 inductively coupled plasma optical emission spectrometry (ICP-OES) device (Thermo Scientific, Waltham, USA) from air-dried soil suspended in CAL solution (0.05 M calcium acetate–calcium lactate and 0.3 M acetic acid) following the protocol given in chapter A 6.2.1.1 of VDLUFA (2012). Cations such as Al^{3+}, Ca^{2+}, Mg^{2+}, Fe^{2+}, Mn^{2+} and Zn^{2+} were exchanged with ammonium chloride (NH_4Cl) and their concentration measured using ICP-OES, following the protocol given in chapter A3.2.1.8 of König (2006). We calculated CEC_{eff} from the sum of the ion equivalents of K, Al, calcium (Ca), magnesium (Mg), manganese (Mn) and hydrogen (H). The BS represented the ratio between the sum of the ion equivalents of K, Ca and Mg and CEC_{eff}.

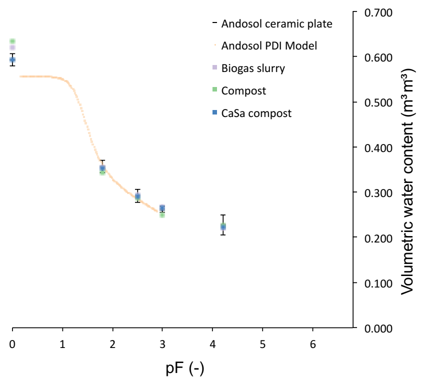

Figure 2. Water retention curve (WRC) of the untreated Andosol and of the soil treated with biogas slurry, standard compost and CaSa compost. The PDI model for the control Andosol was fitted to data measured using the simplified evaporation method. Error indicators belong to "Andosol ceramic plate". Plot data are provided in Tables S1 and S2.

2.4 Biomass production

We harvested maize plants 14 weeks after the two-leaf stage, and the other crops at maturity. For maize, bean, cabbage, carrot and onion, the above-ground biomass was considered as the "harvest product" (weight of fresh mass (FM) in $g\,plant^{-1}$), while "market product" represented the weight of maize grain, bean seed and onion bulb after a week's drying in the sun (air-dried mass in $g\,plant^{-1}$). For maize, we measured the stem diameter and plant height, and for beans, we determined the pod number per plant. In each case, a random sample of plants was used, avoiding plants at the edge of the plot. The overall numbers of samples were as follows: onion (10/20 plants), cabbage (all plants producing a head), bean (8/16 plants) and maize (5/24 plants, excluding plants without cobs). For carrots, the weight of the whole set of plants on a plot was determined. To estimate the total production per plot (Fig. 3), we multiplied means of weight per plant and the total number of harvested plants per plot. Total above-ground biomass production was estimated for 19 maize, 16 bean, 6 cabbage and 20 onion plants per plot for all the treatments (except for the control, which did not include cabbage). Values for market products were estimated for developed maize cops, onion bulbs, cabbage heads and carrots.

2.5 Plant nutritional status

Measurements of plant nutritional status were only made on maize; the plants were divided into the shoot, the corncob and the grains. Five harvested plants per treatment were bulked to give a single sample for each plant fraction per plot. The water content of the biomass was determined gravimetrically. Following oven drying, the material was ground, passed through a 0.25 mm sieve and analysed for C_{tot} and N_{tot} as above. We assessed concentration of P_{tot}, K_{tot}, Ca_{tot}, Mg_{tot}, Zn_{tot}, B_{tot}, Cu_{tot}, Fe_{tot}, Mn_{tot} and Mo_{tot} after microwave digestion with nitric acid (HNO_3) and hydrogen peroxide (H_2O_2) using an iCAP 6300 Duo MFC ICP-OES device (Thermo Scientific, Waltham, USA), following the protocol given in chapter 2.1.1. of VDLUFA (2011).

In addition, we conducted a vector nutrient analysis on harvest product, nutrient concentration and nutrient uptake following Imo (2012). Uptake and concentrations of the various nutrient elements were plotted based on the following scheme: the lower horizontal x axis represented the nutrient uptake, the vertical y axis the nutrient concentration and the z axis the biomass (Isaac and Kimaro, 2011). The control treatment's performance was normalized to 100, so that the levels of biomass production and nutrient concentration reflected the effect of the various soil treatments (Kimaro et al., 2009). Nutrient diagnosis was based on both the direction (increase, decrease or no change) and the length of the vectors (strength of response) following Isaac and Kimaro (2011).

2.6 Nutrient balance

For the section of the plots which were cultivated with maize we estimated changes in the soil nutrient status (Δ Nut) for each treatment, according to

$$\Delta Nut = Nut_{app} - Nut_{up} = \Delta Nut_{av} + \Delta Nut_{nav}, \quad (2)$$

where Nut_{app} represented nutrients supplied by the treatment (**nut**rient **app**lication), Nut_{up} nutrients taken up by the maize plants, ΔNut_{av} the changes in the soil's available nutrient stock (where "available" referred to the nutrients being extractable with CAL solution), ΔNut_{nav} the change in the soil's nutrient stock, which was "non-available" due to leaching, interflow, surface run-off, soil erosion, P fixation, not yet being mineralized, etc. The balance was calculated for P and K, firstly per plot and then per treatment as an average of three plots.

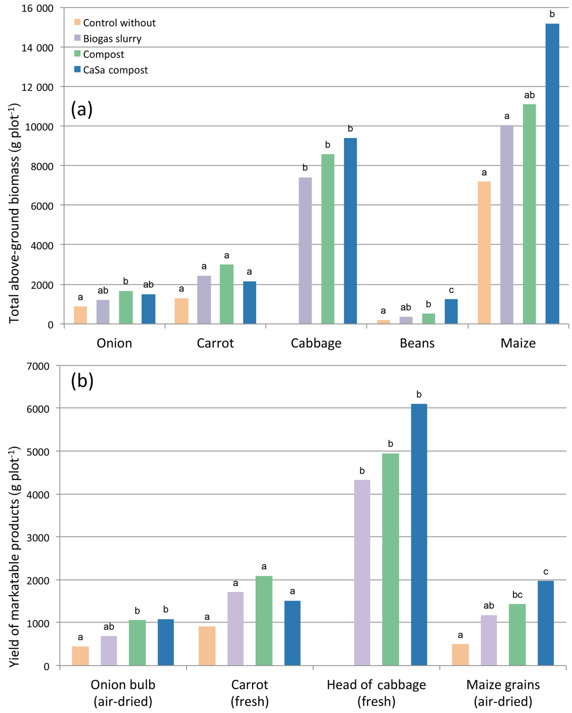

Figure 3. Total above-ground biomass production and marketable yields of food crops given as grammes per plot. Each plot comprised a 4.5 m^2 area sown with maize and a 4.5 m^2 area intercropped with onions, beans, cabbage, carrots, African eggplant and pepper. Different letters reflect means differing significantly from one another (HSD, Tukey test, $\alpha = 0.05$; $n = 4$ for the untreated control plots; $n = 5$ for the amended plots). Plot data are provided in Table S3.

2.7 Statistical analysis

Analyses of variance (ANOVA) were performed using the STATISTICA software (StatSoft Inc., Tulsa, Oklahoma, USA). The main effect was considered to be the soil treatment. Means were compared using the Tukey honest significant difference (HSD) test, with $\alpha = 0.05$.

According to the design of the experiment as a Latin rectangle, the number of replications of the four treatments did not differ and was $n = 5$ for all treatments. However, we had to eliminate one outlier in the control treatment so that for statistical analyses n was 4. Hence, $n = 5$ (for biogas slurry, compost and CaSa-compost treatment) was combined with $n = 4$ (for the control treatment) for all parameters we collected during harvesting, e.g. biomass growth and crop yields. Because of financial restrictions we had to use a block design with $n = 3$ for all soil chemical and physical parameters as well as examinations of nutrient content in the maize plants.

3 Results and discussion

Between March and May, the mean air temperature was 21.6 °C (maximum 48.9 °C, minimum 13.5 °C) (Fig. S8) and the total rainfall was ∼ 360 mm, of which 85 % fell before the end of April (Fig. S7).

3.1 The physico-chemical status of the soil

None of the amendments significantly affected the studied soil hydraulic properties IR (18–36 $cm\,h^{-1}$) and FC (0.28 and 0.20 $m^3\,m^{-3}$ in the topsoil and in the subsoil respectively) as measured with the double-ring infiltration experiments. Also, the WRCs were not significantly influenced by the amendments and still showed the typical shape of an Andosol (Fig. 2). This may be due to the low application dose of the amendments that did not influence ρ_B of the Andosol (0.99 and 1.02 $g\,cm^{-3}$). Nevertheless, we had the subjective impression during fieldwork, that CaSa compost aided the workability of the soil by making it more friable.

The topsoil's PV was estimated as being 0.59–0.63 $m^3\,m^{-2}$ and may have been homogenized throughout the treatments by tillage (i.e. with a hand hoe) and then compaction (e.g. by walking on the plots when working). The calculated FC and AWC derived from the studied WRC were, respectively, ∼ 0.35 and 0.13 $m^3\,m^{-3}$ and exhibited a low site heterogeneity with the coefficient of variance for $\theta_{pF\,1.8}$ between 1.3 % in the control and 2.8 % in plots treated with CaSa compost. The θ did not vary significantly across the three soil layers at neither t_0 nor t_1. At t_2, θ was lower in the topsoils of plots treated with the CaSa compost (0.13 $m^3\,m^{-3}$) and on biogas slurry and standard compost treated plots (0.16 $m^3\,m^{-3}$) compared to the control plots (0.17 $m^3\,m^{-3}$). These differences at the end of the growing season may be caused by higher evapotranspiration and interception losses due to higher biomass growth (see below) rather than by different soil hydraulic properties.

Similar findings are reported for the application of uncomposted biochar (10–17.3 $t\,ha^{-1}$) to a New Zealand Andosol, which failed to influence either ρ_B, PV or AWC (Herath et al., 2013). Biochar application had also little effect on AWC either in a high clay content soil (Asai et al., 2009) or in soils featuring a high carbon concentration or a low ρ_B (Abel et al., 2013). Hence, our results imply that none of the amendments altered the availability of moisture significantly, meaning that the observed treatment effects on crop yield and plant nutrition were most likely related to different nutrient availability.

The chemical status of the soil prior at t_0 is given in Tables 1 and 2. There was a significant treatment effect on P_{CAL} and pH in the topsoil (Table 4). The CaSa-compost treatment improved P_{CAL} at t_2 (4.4 vs. 0.5 $mg\,kg^{-1}$ in soil DM), but the level of P remained very low as in the remaining plots (classified based on KTBL, 2009). According to Finck (2007), a level of 10–30 $mg\,kg^{-1}$ in DM is needed to ensure an adequate supply of P, while Landon (1991) has suggested that 13–22 $mg\,kg^{-1}$ in DM should be adequate for most African soils. Possible explanations for the observation that only the CaSa-compost treatment altered P_{CAL} are (i) that the treatment provided more P (1.7 $g\,P\,dm^{-3}$ in FM) than the others did (0.3 and 0.5 $g\,P\,dm^{-3}$ in FM, respectively, in the biogas slurry and in the standard compost treatment (Table 2)); (ii) that the provision of biochar promoted nutrient capturing in the soil by the adsorption of P on the biochar particles (Gronwald et al., 2015; Kammann et al., 2015); and (iii) that the availability of the recycled P was promoted by liming (Batjes and Sombroek, 1997).

Table 4. Chemical analysis of the untreated Andosol in Karagwe, Tanzania, and the amended topsoil (0–30 cm) horizons sampled at the end of the experiment.

Treatment	pH in KCl		P_{CAL} in $mg\,kg^{-1}$	
Control Andosol	5.3	a	0.5	a
Biogas slurry	5.4	ab	0.7	a
Compost	5.5	ab	1.1	a
CaSa compost	5.9	b	4.4	b

Different letters reflect means differing significantly from one another (HSD, Tukey test, $\alpha = 0.05$; $n = 3$).

The last point can be supported by our findings, that the topsoil pH was higher at t_2 in the CaSa-compost treatment than in the control plots (5.9 vs. 5.3) (Table 4). The optimal topsoil pH range for cropping is 5.5–6.5 according to Horn et al. (2010). Glaser and Birk (2012) have shown that the highly productive Central Amazonian Terra Preta soils have a pH between 5.2 and 6.4. Through influencing soil pH, the addition of biochar is particularly effective in soils suffering from poor P availability (Biedermann and Harpole, 2013). In an earlier publication, Krause et al. (2015) derived estimates for the liming potential of the present soil amendments and found 100 kg of DM of biogas slurry, standard compost and CaSa compost to be equivalent to, respectively, 6.8, 1.4 and 4.7 kg of CaO. The applied equivalents in this study were 0.03, 0.07 and 0.2 $kg\,m^{-2}$ of CaO for biogas slurry, standard compost and CaSa compost. We found, that the application of CaSa compost had an *immediate* effect on soil pH. Finck (2007) recommended the application of lime equivalent to 0.1–0.2 $kg\,m^{-2}$ of CaO every 3 years to maintain the soil pH. Thus, amending CaSa compost at the applied rate was in the range for soil melioration if the application of the treatment is repeated every 3 years.

Neither concentration of total organic carbon (TOC) in the soil nor CEC_{eff} was altered significantly by the amendments (Table 3). Similarly, Liu et al. (2012) reported that the CEC_{eff} is hardly disturbed by a single dose of biochar. From the volume of CaSa compost applied (8.3 $dm^3\,m^{-2}$) and its composition (Sect. 2.2), we estimated the quantity of dry biochar supplied by $\sim 2.2\,\mathrm{kg\,m^{-2}}$, equivalent to a C_{tot} supplement of ~ 1.3–$1.6\,\mathrm{kg\,m^{-2}}$, a level which was modest compared to common applications of biochar ranging from 5 to $20\,\mathrm{kg\,m^{-2}}$ (Kammann et al., 2011; Herath et al., 2013). Liu et al. (2012) have suggested a rate of $5\,\mathrm{kg\,m^{-2}}$ as the minimum necessary to significantly and sustainably increase TOC in the soil. Nevertheless, Kimetu et al. (2008) were able to show that treating a highly degraded soil in the highlands of western Kenya with just $0.6\,\mathrm{kg\,C\,m^{-2}}$ for three consecutive seasons, was effective in increasing the quantity of organic matter in the soil by 45 %.

For an acid soil, the concentration of exchangeable Al was unexpectedly low. The slope of a linear regression of the concentration of exchangeable Al against the pH is two and not three (Fig. S6), as predicted if the dominant form of Al in the soil is Al_3^+ (reflecting the reaction equilibrium $Al(OH)_3 + 3H^+ = Al_3^+ + 3H_2O$). Andosols are known to accumulate organic matter through the formation of metal–humus and allophane-organo complexes. At pHs above 5, the latter structures dominate (Chesworth, 2008). Thus, most likely the observed low concentration of exchangeable Al reflected the presence of complexes involving Al and organic matter.

3.2 Biomass production

Amending compost significantly increased the harvested biomass of onion. The mass of the bulbs produced in plots provided with standard compost or CaSa compost was, respectively, 52.8 and $54.4\,\mathrm{g\,plant^{-1}}$, compared to only $22.2\,\mathrm{g\,plant^{-1}}$ for the untreated plots (Fig. 3; further see Fig. S5 for visual impressions). In contrast, the soil amendments had no effect on the yield of carrots. Cabbage plants grown on the untreated soil remained small and did not develop any heads. In contrast, amending CaSa compost, standard compost or biogas slurry delivered average yields of heads of, respectively, 1020, 825 and $720\,\mathrm{g\,plant^{-1}}$.

Significantly, the above-ground biomass of the bean plants was highest from those plots amended with CaSa compost with $78\,\mathrm{g\,plant^{-1}}$, compared to 32, 22 and $12\,\mathrm{g\,plant^{-1}}$ grown on plots containing, respectively, standard compost, biogas slurry and no amendment. There were also significant differences between the treatments with respect to the average pod number per plant, ranging from 18.8 for plants grown on CaSa compost to only 4.7 for those grown in the control soil.

The CaSa compost also promoted a greater stem diameter and height of the maize plants (respectively 22.8 and 1950 mm), compared to the 16.1 and 1423 mm achieved by the plants grown on unamended soil. The treatment with biogas slurry, standard compost and CaSa compost increased the per unit area above-ground biomass accumulated by maize to, respectively, 140, 154 and 211 % compared to plants in the control treatment (Table 5). The amendments led to grain yields of 263 (biogas slurry), 318 (standard compost) and $440\,\mathrm{g\,m^{-2}}$ (CaSa compost) compared to $110\,\mathrm{g\,m^{-2}}$ from the control plots.

Table 5. Harvest and market products of maize and in relation to the untreated control (100 %).

	Harvest product total above-ground biomass, FM			Market product maize grains, air-dry		
	$\mathrm{g\,m^{-2}}$	%		$\mathrm{g\,m^{-2}}$	%	
Control Andosol	1595	100	a	110	100	a
Biogas slurry	2229	140	a	263	238	ab
Compost	2464	154	ab	318	288	bc
CaSa compost	3372	211	b	438	397	c

Different letters reflect means differing significantly from one another (HSD, Tukey test, $\alpha = 0.05$) with $n = 4$ for control and $n = 5$ for other treatments.

The grain yield from the control plots was below both the average national Tanzanian yield (2012: $124\,\mathrm{g\,m^{-2}}$) and that for eastern Africa ($180\,\mathrm{g\,m^{-2}}$), while the yield from the CaSa-compost-treated plots matched those obtained in Croatia ($434\,\mathrm{g\,m^{-2}}$) and Cambodia ($441\,\mathrm{g\,m^{-2}}$) (FAOSTAT, 2012). A field experiment in the Dodoma region of Tanzania produced a grain yield of about $100\,\mathrm{g\,m^{-2}}$ from unfertilized plots and 380–$430\,\mathrm{g\,m^{-2}}$ from mineral-fertilized plots (Kimaro et al., 2009), while in the Morogoro region the same maize cultivar yielded 117, 257 and $445\,\mathrm{g\,m^{-2}}$ from plots supplemented with, respectively, 0, 15 and $80\,\mathrm{g\,N\,m^{-2}}$ (Mourice et al., 2014). Thus, the benefit of providing CaSa compost matched that of a higher (i.e. extremely high) input of synthetic N fertilizer, however, provided by locally available nutrients.

The observed benefits of CaSa compost were largely in line with the known effects of biochar amendments to soils. Two meta-analyses have suggested that for various crops, the addition of $2 \pm 0.5\,\mathrm{kg\,m^{-2}}$ biochar induces a -3 to $+23$ % crop yield response compared to unamended control plots (Jeffery et al., 2011; Liu et al., 2013). Maize responds to the supplement by increasing its grain yield by 16 % and its biomass by 14 %. On acidic soils (pH of < 5.0), the positive effect of biochar is between 25 and 35 %. The positive effect of the CaSa compost on the soil and on biomass growth was most probably due to its liming effect, which improved the availability of various nutrients, in particular that of P. The positive effects of applying CaSa compost may last for several cropping seasons, as shown by Major et al. (2010) in a 4-year study.

Furthermore, we experienced that biogas slurry may not be suitable as a soil amender for bean crops, since the plants did not appear to respond well compared to compost or CaSa compost. Although most recent work using biogas slurry as a soil amender observed a positive plant response in terms of productivity (Baba et al., 2013; Clements et al., 2012; Garfí et al., 2011; Komakech et al., 2015), others also revealed decreasing yields (e.g. Sieling et al., 2013). Salminen

Table 6. Nutrient concentration in dry matter of maize grains compared to levels reported in the literature. The italic writing indicates the statistical p values, which belong to the nutrient concentrations in the respective column.

	N_{tot} g kg^{-1}	P_{tot} g kg^{-1}	K_{tot} g kg^{-1}	Ca_{tot} g kg^{-1}	Mg_{tot} g kg^{-1}
Control Andosol	15.9	2.3	4.4	0.1	1.0
Biogas slurry	16.5	2.6	4.0	0.1	1.0
Compost	15.6	2.5	3.6	0.1	1.0
CaSa compost	16.8	3.0	3.9	0.1	1.1
p ($n=3$)	*0.58*	*0.08*	*0.03*	*0.71*	*0.34*
Finck (2007)	17.5	4.0	4.9	2.1	1.4
Kimetu et al. (2008) (Kenya)					
Control	11.8	2.3	2.7	0.03	0.9
Biochar	12.5	2.2	2.6	0.1	0.8

et al. (2001) attributed observed a negative plant response to organic acids and ammonia contained in biogas slurry, which can be phytotoxic for plants if not applied in moderate quantities. Nevertheless, composting could reduce the aforementioned substances as shown by Abdullahi et al. (2008). Therefore, this material should be combined with other organic matter.

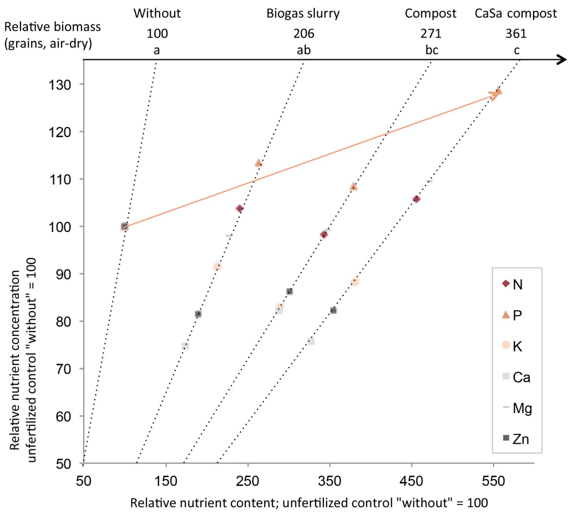

Figure 4. Vector nutrient analysis for maize, showing the responses of air-dry grain yield (g plant^{-1}), relative nutrient concentration in DM (with the untreated Andosol: 100 %) and relative nutrient uptake (with the untreated Andosol: 100 %). Different letters reflect means differing significantly from one another (HSD, Tukey test, $\alpha=0.05$; $n=3$). The arrow indicates the largest response and depicts a primary response of maize plants to mitigated P deficiency. Plot data are provided in Table S4.

3.3 Analysis of plant nutritional responses

The shoot, grain and corncob biomass produced by the maize crop was responsive to the soil amendments, whereas its water content was not significantly affected. According to Finck (2007), the concentrations of each of the nutrients were below recommended levels. However, compared to the outcomes of the experiment in Kenya reported by Kimetu et al. (2008), the grain concentrations of both N and K were slightly higher, while those of P, Ca and Mg were similar. In our experiment, the dry shoot material was deficient with respect to both P (0.7–0.9 g kg^{-1}, instead of recommended concentrations of 2.0–3.5 g kg^{-1}) and N (8–11 g kg^{-1}, compared to a recommended range of 15–32 g kg^{-1}) (Bergmann, 1999; Marschner, 2011). Only the nutrient concentrations in the maize grains responded significantly to the treatments, especially for K ($p=0.03$) and P ($p=0.08$) (Table 6). Here, we observed a dilution effect for K, while the concentration of P was slightly increased in maize grains grown on plots amended with CaSa compost. With respect to the N concentration, there was no significant treatment effect, since the N inputs had been adjusted a priori so that each treatment offered the same amount of N.

The vector nutrient analysis illustrated primarily the response of maize to mitigated P deficiency, with the longest arrow indicating the largest response (Fig. 4). Here, an increase in each of the three parameters (biomass growth, nutrient concentration, nutrient uptake) was generated by an increased supply of the limiting nutrient P. This is because (i) more P was supplied with CaSa compost (see Sect. 3.1) and (ii) its availability was increased due to the raised soil pH (Batjes, 2011). Furthermore, nutrient uptake by maize was proportional to biomass growth. Hence, plants grown on plots amended with CaSa compost were able to take up significantly greater amounts of N, P, K, Ca, Mg and Zn in their grains than those grown on the other plots (Fig. 4).

As the native soil's K_{CAL} was already very high and further K was provided by the amendments (Table 3), an antagonistic effect on nutrient uptake between K and Ca as well Mg would have been possible (Finck, 2007). However, observed changes in concentrations of Ca and Mg were not significant, but there was a significant decrease in K concentration in maize grains. However, this may possibly be due to the dilution imposed by growth stimulation.

3.4 Nutrient balancing

On the plots treated with biogas slurry, standard compost and CaSa compost, Nut_{app} of P varied with, respectively, 4.2, 6.8 and 13.8 g m^{-2}. This can be considered a low to high application compared to a recommended fertilizer rate of 7.0–8.4 g m^{-2} yr^{-1} for maize on P-deficient soils (KTBL, 2009; Finck, 2007). By contrast, Nut_{app} of K was very high with 53.8, 46.5 and 63.2 g m^{-2}, compared to a recommended dose of 9.3–12.4 g m^{-2} yr^{-1} for maize on soils with high K content (KTBL, 2009; Finck, 2007). On the plots treated with biogas slurry, plants took up ~ 19 % of the total applied P; the equivalents for the standard compost and CaSa-compost treatments were ~ 16 and ~ 12 %, respectively. These rates are consistent with the ~ 15 % reported by Finck (2007) as being available in the first year after fertilizer application. With respect to K, Nut_{up} was about ~ 10 % of Nut_{app} in the biogas slurry treatment, ~ 18 % in the standard compost treatment and ~ 17 % in the CaSa-compost treatment. These rates differ greatly from the ~ 60 % figure suggested by Finck (2007). The disparity relates most likely to the soil's high level of K_{CAL}.

We estimate that soil P_{tot} and K_{tot} were both depleted (Δ Nut < 0) on the control plots (Table 7). In the biogas slurry, standard compost and CaSa-compost-treated plots, Δ Nut was positive for both P and K. However, the only significant change to the topsoil's P_{CAL} was recorded in the CaSa-compost treatment (Sect. 3.1.). Hence, about 1.1 g P m^{-2} was assignable to $\Delta\, Nut_{av}$ in the plots supplied with CaSa compost, with the rest being "non-available". Some of the latter may include P that had not been released through mineralization of the organic matter, while some may have been immobilized in the form of metal–humus complexes, which are characteristic for Andosols (Zech et al., 2014) (i.e. assignable to $\Delta\, Nut_{nav}$ in both cases). Leaching of P is insignificant, since P gets immobilized (Finck, 2007). We assume that some of the K provided by the amendments may have been leached during the rainy season as mentioned by Finck (2007) for light soils such as the present Andosol. There were no signs of significant losses through soil erosion visible on the experimental site.

From our findings we recommend the addition of urine and sanitized faeces to the compost, since the matters provide a ready source of nutrients, accelerating, for example, compost's N_{min} and total P content (compare Table 2). Given that biochar can capture both nitrate and phosphate, as shown by Gronwald et al. (2015) and Kammann et al. (2015), we assume that combining urine and biochar as compost additives enriches compost with N and P and reduces nutrient loss during and after composting. Especially, the loss of N in the form of the greenhouse gas N_2O can be reduced, as shown by Larsen and Horneber (2015). In addition, urine can contribute to the moisture required for successful composting.

Table 7. Changes in the soil nutrient status (Δ Nut) along with nutrients applied by the treatment (Nut_{app}) and the nutrients taken up by the crop (Nut_{up}).

	Nut_{app} P $g\,m^{-2}$	Nut_{up} P $g\,m^{-2}$	Δ Nut P $g\,m^{-2}$	Nut_{app} K $g\,m^{-2}$	Nut_{up} K $g\,m^{-2}$	Δ Nut K $g\,m^{-2}$
Control Andosol	–	0.4	−0.4	–	3.3	−3.3
Biogas slurry	4.2	0.8	3.5	53.8	5.2	48.5
Compost	6.8	1.1	5.7	46.5	8.5	38.0
CaSa compost	13.8	1.7	12.3	63.5	10.7	52.5

Data based on three plots for each treatment.

4 Conclusions

To summarize: for beans and maize, crop biomass production and economic yield were significantly improved by the application of CaSa compost. For cabbage and onion, all three of the tested amendments were beneficial. The amendments, and especially CaSa compost, improved the nutrient availability, as revealed by vector nutrient analysis. This can be attributed to changes in soil pH and the addition of nutrients.

Of particular significance was the observation that the P deficiency affecting the local Andosol could be mitigated using CaSa compost. The increase in available P achieved by the CaSa-compost treatment was more than sufficient to supply the crops' requirement. Thus, we conclude that a gradual increase in soil P could be achieved by a regular application of the CaSa compost.

The chosen rates of biogas slurry and standard compost supplementation were sufficient to maintain the soil's pH, whereas the CaSa compost raised the soil pH, improving its productivity immediately. Thus, we conclude that a continuous program of composting and compost amendments over decades would probably fully ameliorate the soil.

We further conclude, that the application of local available biogas slurry needs to be tested for several crops before recommending the widespread utilization of this matter as it may contain substances which could be phytotoxic for plants if not applied in moderate quantities. In addition, composting of biogas slurry prior to soil amendment, possibly with and without biochar, is of certain practical relevance but needs preceding scientific investigation to study the specific metabolisms taking place and to identify the consequent N recovery efficiency.

Finally, we conclude that all the treatments, but especially CaSa compost, are viable as substitutes for synthetic commercial fertilizers. We further conclude that local smallholders with six people per household can produce CaSa compost at an estimated rate of ~ 5.1 $m^3\,yr^{-1}$, which would be sufficient to fertilize an area of ~ 1850 m^2 at the rate of 8.3 $dm^3\,m^{-2}$ over the course of 3 years. By this means, it would be possible to fertilize about 30 % of the average area cultivated by smallholders in Karagwe. Therefore, the CaSa approach needs to be integrated into farm-scale nutrient management by conducting a detailed analysis of nutrient flows in the farm household system and studying all potential additions and removals of nutrients to and from the planted land.

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Appendix A

Table A1. List of abbreviations.

Chemical elements	
Al	Aluminium
C	Carbon
C_{tot}	Total carbon (the same form is also used for total concentration of other elements)
Ca	Calcium
Cu	Copper
H	Hydrogen
Fe	Iron
K	Potassium
K_{CAL}	CAL-soluble K (likewise P_{CAL})
Mg	Magnesium
Mn	Manganese
N	Nitrogen
N_{min}	Mineral nitrogen
N_{org}	Organic nitrogen
P	Phosphorus
S	Sulfur
Si	Silicon
Zn	Zinc
Terms used in context of physico-chemical analyses	
ANOVA	Analyses of variance
AWC	Available water capacity
BS	Base saturation
CAL	Calcium acetate lactate
CEC_{eff}	Effective cation exchange capacity
DM	Dry matter
FC	Field capacity
FM	Fresh mass
HSD	Honest significant difference
ICP-OES	Inductively coupled plasma optical emission spectrometry
IR	Infiltration rate
PDI	Peters–Durner–Iden
pF	Decadic logarithm of the negative pressure head
PV	Pore volume
t_0	Time of sampling, beginning of February
t_1	Time of sampling, end of April
t_2	Time of sampling, beginning of July
TDR	Time domain reflectometry
TOC	Total organic carbon
WHC	water holding capacity
WRC	Water retention capacity
ρ_B	Bulk density
ρ_P	Particle density
θ	Volumetric water curve
Terms used in context of calculations in Eq. (1)	
$D_{N_{min}}$	Demand of N_{min} per cropping season
$m_{material}$	Amount of materials to be used in soil amendment
Δ Nut	Changes in the soil nutrient status
Nut_{app}	Quantity of nutrient supplied by the treatment
Nut_{up}	Quantity of nutrient taken up by the plants
Δ Nut_{av}	Changes in the soil's available nutrient stock
Δ Nut_{nav}	Change in the soil's nutrient stock which was "non-available"
Other uncommon abbreviations	
Biochar	Charcoal used as soil amendment
CaSa	Project "Carbonization and Sanitation"
CaSa compost	Product of CaSa project containing composted biochar and sanitized excreta
cv.	Cultivar
EcoSan	Ecological sanitation
m a.s.l.	Metres above sea level
NA	not analysed
NW	Northwest
TU	Technische Universität
UDDT	Urine-diverting dry toilet

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Author contributions. Ariane Krause and Martin Kaupenjohann designed the experiment and planned, discussed and evaluated soil chemical analysis. Ariane Krause carried out the experiment with the assistance of local workers. Ariane Krause and Thomas Nehls planned, discussed and evaluated the soil physical experiments that Ariane Krause conducted. Eckhard George gave valuable advice for the fertilizing strategy, analysis of plant nutritional status and data analysis in general. Ariane Krause prepared the manuscript including drafting the text and preparing figures and tables; all co-authors cooperated by correcting the text and promoting professional discussions.

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Chapter 4

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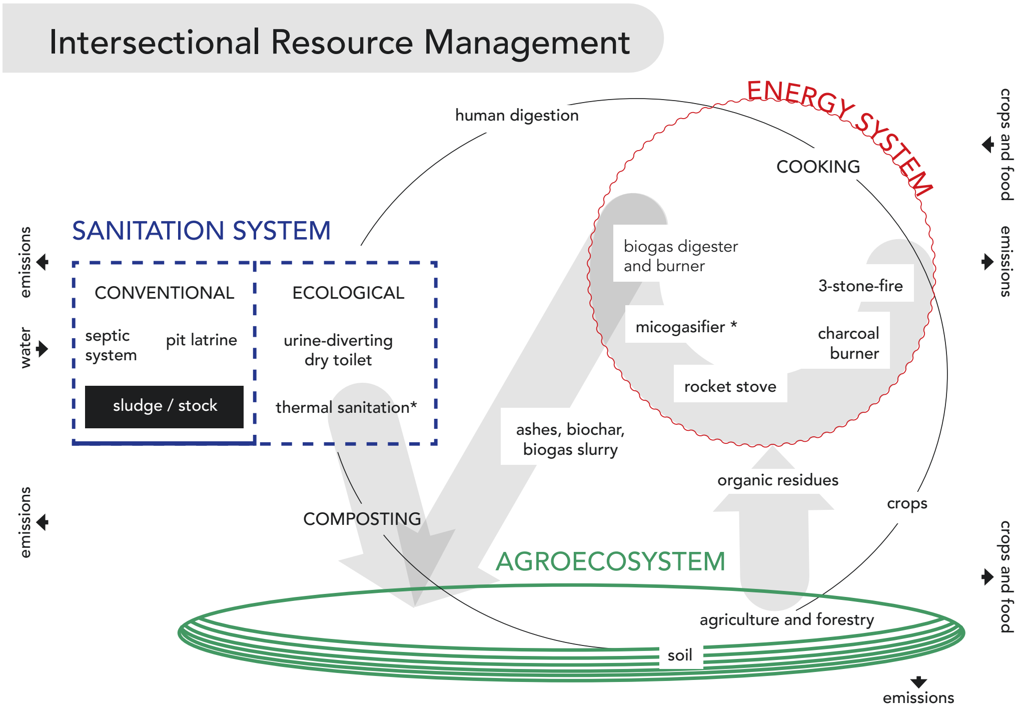

Figure 4.1: *Graphical abstract: Intersectional Resource Management.*

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Linking energy-sanitation-agriculture: Intersectional resource management in smallholder households in Tanzania

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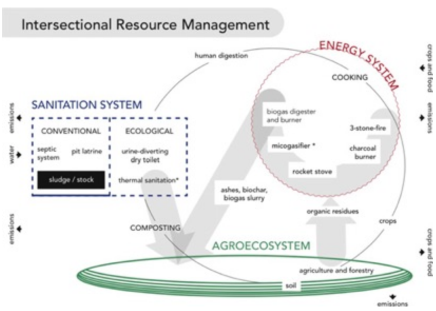
HIGHLIGHTS

- Residues from cooking and sanitation can contribute effectively to soil fertility management.
- Resource recovery can substantially promote carbon and nutrient recovery.
- Study includes an application of intersectional resource management to vulnerable smallholders in SSA.
- Study includes model-based analyses of technology specific material flows at a household level.
- Study provides aggregated data sets including empirical data from Tanzania.

GRAPHICAL ABSTRACT



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ABSTRACT

In order to create sustainable systems for resource management, residues from cooking and ecological sanitation (EcoSan) can be employed in recycling-driven soil fertility management. However, the link between energy, sanitation, and agricultural productivity is often neglected. Hence, the potential self-sufficient nature of many smallholdings in sub-Saharan Africa is underexploited.

Objective: To compare those cooking and sanitation technologies most commonly used in north-western Tanzania with locally developed alternatives, with respect to (i) resource consumption, (ii) potential to recover resources, and (iii) environmental emissions. This study examines technologies at the household level, and was carried out using material flow analysis (MFA). The specific bioenergy technologies analysed include: three-stone fires; charcoal burners; improved cooking stoves (ICS), such as rocket and microgasifier stoves; and biogas systems. The specific sanitation alternatives studied comprise: pit latrines; two approaches to EcoSan; and septic systems.

Results: The use of ICS reduces total resource consumption; using charcoal or biogas does not. The residues from microgasifiers were analysed as having a substantial recovery potential for carbon (C) and phosphorus (P). The fact that input substrates for biogas digesters are post-agricultural in nature means that biogas slurry is not considered an 'untapped resource' despite its ample nutrient content.

Exchanging pit latrines for water-based sanitation systems places heavy pressure on already scarce water resources for local smallholders. In contrast, the implementation of waterless EcoSan facilities significantly promotes nutrient recovery and reduces environmental emissions, particularly through greenhouse gas emission and nutrient leaching.

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Conclusions: Recycled outputs from the triple energy-sanitation-agriculture nexus display complementary benefits: residues from cooking can be used to restore organic matter in soils, while sanitation residues contribute to fertilisation. The combination of microgasifiers and EcoSan-facilities is the most appropriate in order to simultaneously optimise resource consumption, reduce environmental impacts, and maximise recycling-based soil management in smallholder farming systems.

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1. Introduction

1.1. The energy-sanitation-agriculture nexus

In many regions of the world, including sub-Saharan Africa (SSA), biomass is the most significant energy carrier for domestic cooking (Parikka, 2004). In this context, "bioenergy" refers to the technical recovery of energy from biomass resources, such as firewood, organic waste, energy plants, etc. (Kaltschmitt et al., 2009). To avoid exhausting natural resources, it is necessary to manage biomass resources effectively, both in its collection, and its efficient use. The former is realised through sustainable resource management techniques, such as forestry management. The latter is achieved largely through employing well-designed technology, such as those for cooking. The simplest and most prominent application of bioenergy is likely to be the three-stone fire. There are, however, more environmentally friendly, technologically sophisticated bioenergy alternatives available that have been designed with the aim of reducing, or substituting, the use of firewood. These include improved cooking stoves (ICS), which use firewood or organic waste materials with a low moisture content, such as sawdust, maize cobs, rice husks, coffee husks, etc. ICSs are employed to provide heat for cooking in both households and institutions (Jetter and Kariher, 2009; Mukunda et al., 2010). So-called microgasifier stoves are a particularly technologically advanced example of ICS (Roth, 2011). After cooking with a microgasifier stove, a mix of ash and char particles with a significant carbon (C) content is produced as a by-product (McLaughlin et al., 2009). Referred to as 'biochar,' it can be used as an additive for compost (Kammann et al., 2015) and thus as a soil amendment (Lehmann and Joseph, 2015), after the principles of the genesis of Terra Preta soils (Glaser and Birk, 2012). Organic matter with comparatively higher moisture content, meanwhile, such as cow dung, kitchen waste, harvest residues, etc., can be anaerobically fermented in small-scale biogas digesters (Tumwesige et al., 2011; Vögeli et al., 2014). The residue of biogas production, biogas slurry (also called bio-slurry or digestate), is particularly rich in nutrients and is a suitable fertilizer in organic farming (Möller and Müller, 2012). To sum up, depending on the availability of the respective fuel resources, bioenergy technologies can (i) substitute firewood as the main energy carrier, which reduces pressure on forest resources, and (ii) provide residues, which can in turn be used to recover nutrients and C for agriculture.

Bioenergy can also be applied to sanitation processes in order to destroy or deactivate pathogens from human excreta (Krause et al., 2015). Preventing the transmission of disease when managing human excreta (i.e. urine and faeces) is an essential element of ecological sanitation (EcoSan) and needs to take place at as early a stage as possible during the process (WHO, 2006). For this reason, thermal sanitation must take place *directly* after the faeces, which have the highest pathogen content, have been collected in a urine-diverting dry toilet (UDDT) or composting toilet, and *before* the matter is composted. Thermal sanitation follows the time-temperature relationship to deactivate pathogens as described by Feachem et al. (1983), and is realised in practice via pasteurisation (Krause et al., 2015), co-pelletising with subsequent gasification (Englund et al., 2016), or direct incineration (Niwagaba et al., 2009). Further approaches for sanitation include drying (Richert et al., 2010), composting (Ogwang et al., 2012), or lacto-acid fermentation (Factura et al., 2010). Sanitising urine, in contrast, is relatively easy and safe. The World Health Organisation recommends simply storing it, which leads to a rise in pH that inactivates pathogens (WHO, 2006). Once sanitation has been completed, human excreta constitutes a valuable resource of nitrogen (N), phosphorus (P), potassium, and micronutrients. Against this background, within the framework of EcoSan, human excreta is no longer regarded as 'waste' but rather as a resource. To sum up, EcoSan is an alternative to conventional 'one-way' or 'end-of-pipe' sanitation systems which aims to (i) prevent environmental pollution, especially that of aquatic ecosystems, and (ii) recycle resources, including the nutrients in human excreta and wastewater (Esrey et al., 2001; Winblad et al., 2004).

1.2. Research objectives & questions

The prime source of energy in Tanzania (TZ) is wood, either utilised directly as firewood, or in the form of processed charcoal (Msuya et al., 2011). When looking at farming households in rural TZ, meanwhile, we find a variety of different biomasses used as cooking fuels, though firewood still clearly dominates (Grimsby et al., 2016). Furthermore, while septic systems are most common in peri-urban and urban areas, pit latrines are the most common sanitation system in rural areas (Chaggu, 2004; Cheruiyot and Muhandiki, 2014). The widespread installation of pit latrines from the 1940s, largely through 'development cooperation', has led to the abandonment of locally adapted recycling practices (Rugalema et al., 1994). This means that those nutrients removed from the soil by crops are no longer fully recycled back into the agricultural soils. The result of this is that depletion of nutrients and soil organic matter (SOM) is, alongside erosion, a major threat to smallholder farming in SSA (Markwei et al., 2008; Montanarella et al., 2016). As mentioned above, residues from bioenergy and EcoSan are a potential resources to recover C for restoring SOM and nutrients, thereby filling the fertiliser gap.

To the best of knowledge, there have been as yet no *integrated* resource studies carried out that combine an analysis of both applied cooking and sanitation technologies in relation to smallholder households in SSA. It is the aim of the present work to develop a model that enables an assessment of the added benefits intersectional resource management could bring to a model region in north-western TZ. The study was conducted on a micro-level, i.e. on a household level, and is presented with three specific projects as case studies. The objective was to compare *locally available* cooking and sanitation technologies in regards to (i) resource consumption, (ii) potential for resource recovery for use in agriculture (i.e. ash, biochar, biogas, slurry, and human excreta, as well as the nutrients and C contained therein), and (iii) environmental emissions. In order to meet this objective, we identified, quantified, visualised, and evaluated technology-specific material flows within the anthroposphere of a smallholder farming system in TZ. Negative effects on the ecosystem were assessed using global warming potential (GWP) and eutrophication potential (EP). It is our aim through this study to (i) advance the practical application of bioenergy and EcoSan technologies in SSA, and (ii) promote the recycling of resources through established methods, including agroecology, composting, integrated plant nutrient management, and Terra-Preta practices.

We identified our underlying research questions as follows: (Q1) How do locally available bioenergy alternative, such as rocket stoves, microgasifiers, and biogas systems, compare to more widespread technologies, such as three-stone fires and charcoal burners, in terms of input, output, and potential recycling flows? (Q2) How does a locally available EcoSan facility, namely a UDDT with or without additional thermal treatment of faeces, compare to both septic tank systems with flush toilets, and the current practice of favouring pit latrines in terms of input, output, and potential recycling flows?

2. Material and methods

2.1. Study area & case studies

This study was carried out in Karagwe, one of eight districts in Kagera region, north-west TZ (lat. 01°33′ S; long. 31°07′ E; alt. 1500–1600 m.a.s.l.). Kagera forms part of the Lake Victoria basin, close the East African Rift Zone. Local soil is *vitric* Andosol (Krause et al., 2016), and there are two rainy seasons, from March to May and October to November. Precipitation varies between 500 and 2000 mm $year^{-1}$, and mean temperatures range from 20 to 28 °C (Tanzania, 2012). The regional economy is dominated by smallholder agriculture (Tanzania, 2012). Farming households in Karagwe consist of, on average, six people including adults and children (*ibid.*). Around 96% of households use firewood, while just 3% use charcoal, with the remaining 1% classified as using 'other sources' (*ibid.*). Approximately 88% use simple pit latrines, complemented by ventilated improved pit latrines in 4% of households (*ibid.*). Just 1% of households have flush or pour water toilets in combination with septic tanks, whereas 6% have no toilets at all. The sanitation facilities of the remaining 1% of households were not specified (*ibid.*).

Two Karagwe farmer's initiatives have recently initiated a set of project with the aim of providing clean cooking energy and safe sanitation to the local community (Krause et al., 2015). These are (i) *Biogas Support for Tanzania* (BiogaST), which focuses on small-scale biogas digesters, and (ii) *Efficient Cooking in Tanzania* (EfCoiTa), which disseminates ICSs, including the rocket stove, an advanced sawdust gasifier, and the Top-Lit UpDraft (TLUD) microgasifier. In addition, (iii) *Carbonization and Sanitation* (CaSa) works with an EcoSan-approach based on the principles of Terra Preta. Applied sanitation technologies include the UDDT and thermal sanitation of faeces via pasteurization in a clay oven fired by a microgasifier. The resulting sanitized matter is co-composted with other organic residues, including biochar, which has been collected either after cooking with microgasifiers, or after the prior thermal sanitation, or a combination of both.

The joint objective of these initiatives is to develop countermeasures to local environmental threats including soil depletion and deforestation, which has led to appropriate technologies being developed or adopted for implementation in local households. Increased adoption of such technologies will inevitably lead to a greater availability of residues such as biochar, biogas slurry, and sanitized human excreta. This means, local farmers can use these *locally available* resources for soil fertility management through nutrient recycling and SOM restoration, and thus will contribute towards sustaining local agricultural productivity. The three initiatives act as case study projects, whilst the present study in its entirety constitutes an *ex-ante* assessment of the potential for locally adopted, intersectional resource management.

2.2. Material flow analysis (MFA)

This section first introduces the concept of Material flow analysis (MFA), with fundamental terms given in *italics*, and then follows with an explanation of the specific modelling approach of the present study.

According to Baccini and Brunner (2012), MFA is an analytical approach to understanding complex systems, and is thereby an appropriate method for (natural) resource management. The method supports the early identification of environmental problems, and the design of strategies for protecting natural resources (*ibid*). MFA aims at generating a basis for making profound and rational decisions, regarding, for example, regional development (*ibid.*). Baccini and Bader (1996), Baccini and Brunner (2012), and Brunner and Rechberger (2004) conceptualized the systematic framework of MFA. According to their description, a *system* describes a group of interacting *processes*, defined in time and space. The main components of this system are (i) the *anthroposphere* (e.g. private households, agriculture, and waste management), that interacts with (ii) the *ecosystem* (i.e. atmosphere, hydrosphere, and lithosphere/pedosphere). The umbrella term *material* refers to (i) *goods*, which are economic entities (e.g. wood, charcoal, etc.), and (ii) the *substances* of these goods, which might be chemical elements (e.g. C, P, N, etc.), or compounds (e.g. NH_4, P_2O_5, etc.). A *material flow* ($\dot{m}$) is a mass flow of *goods* or *substances* per unit of time, for example, in kilograms per year. To define *substances* of interest, so-called *indicator elements* are chosen. A *process* describes any activity within the system and comprises either (i) the chemical or physical transformation, (ii) the transportation, or (iii) the storage of materials. *Input flows* ($\dot{m}_{input}$) and *output flows* ($\dot{m}_{output}$) describe materials entering and leaving a process. *Import flows* ($\dot{m}_{import}$) and *export flows* ($\dot{m}_{export}$) describe an exchange of *materials* between the *anthroposphere* (i.e. within the *system boundaries*) and the *ecosystem* (i.e. outside the *system boundaries*) including, for example, emissions. It follows, therefore, that the *system* in question is generally an *open system*. Material *stocks* are located within a certain process, and describe the accumulation, storage, or depletion of *materials*, including processes such as landfill, mining, nutrient depletion on agricultural land, etc. The basic mathematical law applied is the so-called 'principle of mass conservation' (Eq. 1), which can be applied either to a single *process* or to the *system* as a whole. In order to simplify calculations, the function between $\dot{m}_{input}$ and $\dot{m}_{output}$ is commonly assumed to be linear.

$$\sum_{i=1}^{k} \dot{m}_{input,i} = \sum_{j=1}^{l} \dot{m}_{output,j} \pm \dot{m}_{storage} \quad (1)$$

where $\sum_{i=1}^{k} \dot{m}_{input,i}$ and $\sum_{j=1}^{l} \dot{m}_{output,j}$ are the total mass of k input and j output material flows, respectively, and $\dot{m}_{storage}$ causes $\pm \Delta$ stock. For the whole system, $\dot{m}_{import,i}$ $\dot{m}_{import,i}$ and $\dot{m}_{export,j}$ are used instead of $\dot{m}_{input,i}$ and $\dot{m}_{output,j}$, respectively.

Applications of MFA in SSA have often been related to topics around solid waste management, sanitation, and strategic planning, in a mostly urban, rather than rural, setting (cf. Forster et al., 2003; Gumbo, 1999; Lederer et al., 2015; Meinzinger, 2010; Montangero, 2006; Yiougo et al., 2011). The following paragraph describes the manner in which MFA was applied in the present study (Fig. 1): Before starting our system analysis, we found it necessary to understand and define relevant local challenges in relation to the subject matter of our study, and to describe those technologies developed as appropriate countermeasures by the case study projects. This initial step was facilitated through pre-studies in Karagwe, conducted in 2010 and 2012, an excessive literature review, practical experience from project participation, and, perhaps most significantly, through working with local professionals, including agricultural technicians, stove technicians, farmers, etc. We then defined the *system*, including system boundaries (Table 1). Our aim was to describe the real situation as simply as possible, but at the same time, in as complex a manner as necessary for our research to be meaningful. Therefore, only those goods and processes were selected (Fig. 2) which are relevant regarding the research objectives. In order to determine flows and stocks, and pursuant to Brunner and Rechberger (2004), data was collected from various sources: (i) primary data from case study projects and our own experiments, including household surveys, field tests, laboratory analysis, etc., (ii) secondary data, e.g. literature review, statistics from private and public organizations, etc., and (iii) estimations/judgements of experts. The latter was specifically used if no sufficient data was available or, not available for the specific context. When aggregating data, all parameters were assumed to be normally distributed, and independent variables (Laner et al., 2014) and *Gauss's law of error propagation* (FAU physics, n.d.) were applied. The resulting

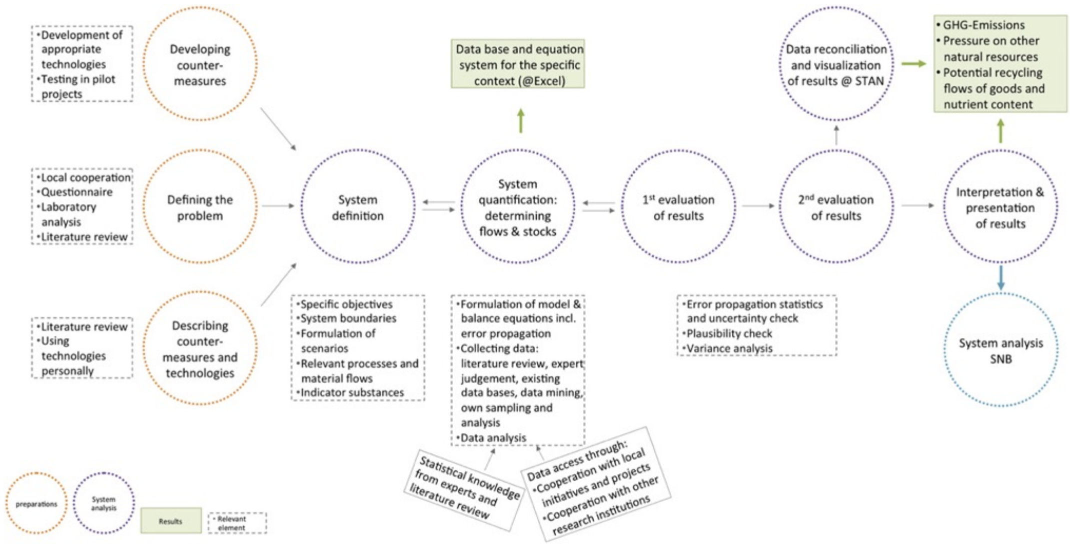

Fig. 1. Proceeding of the material flow analysis (MFA) in the present system analysis of micro energy and sanitation systems in smallholder households in Karagwe according to Baccini and Bader (1996), Baccini and Brunner (2012) and Brunner and Rechberger (2004).

data uncertainty is expressed by presenting the statistical variance of the collected data set with its arithmetic mean value ($\bar{x}$), the standard error (Δx), and the relative uncertainty (RU) defined as Δx in % of $\bar{x}$ (Brunner and Rechberger, 2004). Data collection, the equation-based model, and all auxiliary calculations were combined in an Excel spread sheet (one sheet for each system; see appendices). MFA, as is usual, was conducted in an iterative process. After evaluating the results, some improvements were necessary, such as including new flows and processes if the system description was not detailed enough, or excluding them when it was too complicated. When facing data gaps or unsatisfying data quality (e.g. extremely high RU), the database was expanded through an extended literature review as well as the results of our own experiments. After a second evaluation, the intermediate results were transferred from Excel to the MFA-software, in this case, the freeware application *subSTance flow ANalysis* (STAN) of Cencic et al. (2012) and Cencic and Rechberger (2008). STAN supported our work by (i) recalculating inserted figures through *data reconciliation* (cf. Cencic and Rechberger, 2008; Narasimhan and Jordache, 1999) and (ii) displaying results in *flow diagrams*. Finally, previously defined plausibility criteria were used for cross-checking our estimated results with literature sources (Tables A.10 and B.7). For checking uncertainties, data was classified with low, average, or high uncertainty, with an RU of, respectively, ±25%, ±50% and ±90%, following Laner et al. (2013) (Tables A.11 and B.8). Further information on the quality of data (e.g. origin, sample size, etc.) was also summarized (Tables A.12 and B.9). In addition, we manually compared planned and deviating values for selected variables that are particularly vulnerable to changes in human behaviour in a *variance analyses*.

Table 1
Definition of the system for the material flow analysis.

Defining element	Description of the "farming system"
Problem description	(i) Dependency on firewood as main energy carrier causes high pressure on natural forest resources, (ii) unsatisfactory sanitation service causes net losses of nutrients in the local agroecosystem, and (iii) the organic matter available for sustainable soil management is insufficient.
Developed countermeasures	Appropriate technologies were recently introduced by local initiatives, such as ICSs (including rocket stove, advanced sawdust microgasifier, TLUD microgasifier), biogas digester, and EcoSan (including UDDT, pasteurization of faeces, composting of excreta mixed with biochar according to the principles of Terra Preta).
Specific objective	Comparison of existing and widespread technologies (e.g. three-stone fire, pit latrine), which reflect the "current state" in Karagwe, and locally developed and adopted alternatives concerning the (i) resource consumption, (ii) the potential to recover resources for agriculture, and (iii) environmental emissions.
Spatial system boundary	One farming household with 6 people living in Karagwe.
Temporal boundary	One year.
Activities	To subsist (for the farming system) which includes (i) to cook and to eat (for the micro* energy system) and (ii) to go to toilet and to sanitize (for the micro sanitation system).
Indicator elements	C as carrier of chemical energy; N and P as essential plant nutrients in farming.

* 'micro' refers to the micro (economic) perspective of our work, meaning 'on the household level'.
Non-common abbreviations: C: carbon; EcoSan: ecological sanitation; ICS: improved cooking stove; N: nitrogen; P: phosphorus; UDDT: urine-diverting dry toilet; TLUD: Top-Lit UpDraft.

2.3. Systems defined & technologies studied

In the case of Karagwe, the *anthroposphere* of its integrated farming system could be divided into three parts: (i) the micro[1] energy system (MES), and (ii) the micro sanitation system (MSS), both of which belong to the farming household; and (iii) the agroecosystem (AES), which represents the farmland (Fig. 2). The atmosphere, the pedosphere, and the hydrosphere are all located outside the system boundaries. In the farming household, (i) resources are required to meet the daily needs of the people (i.e. $\dot{m}_{input}$; e.g. food, water, fuel, etc.) and (ii) residues are produced (i.e. $\dot{m}_{output}$; e.g. kitchen waste, excreta, ash, etc.). The MFAs of the MES and MSS constitute the content of his study. Relevant processes and material flows are defined from a technological perspective and are based on the analysed technologies (Tables 2 and 3). Integrating the identified recovery potential of residues from MES and

[1] The present MFA focussed on smallholder households and thus took a *micro*-perspective.

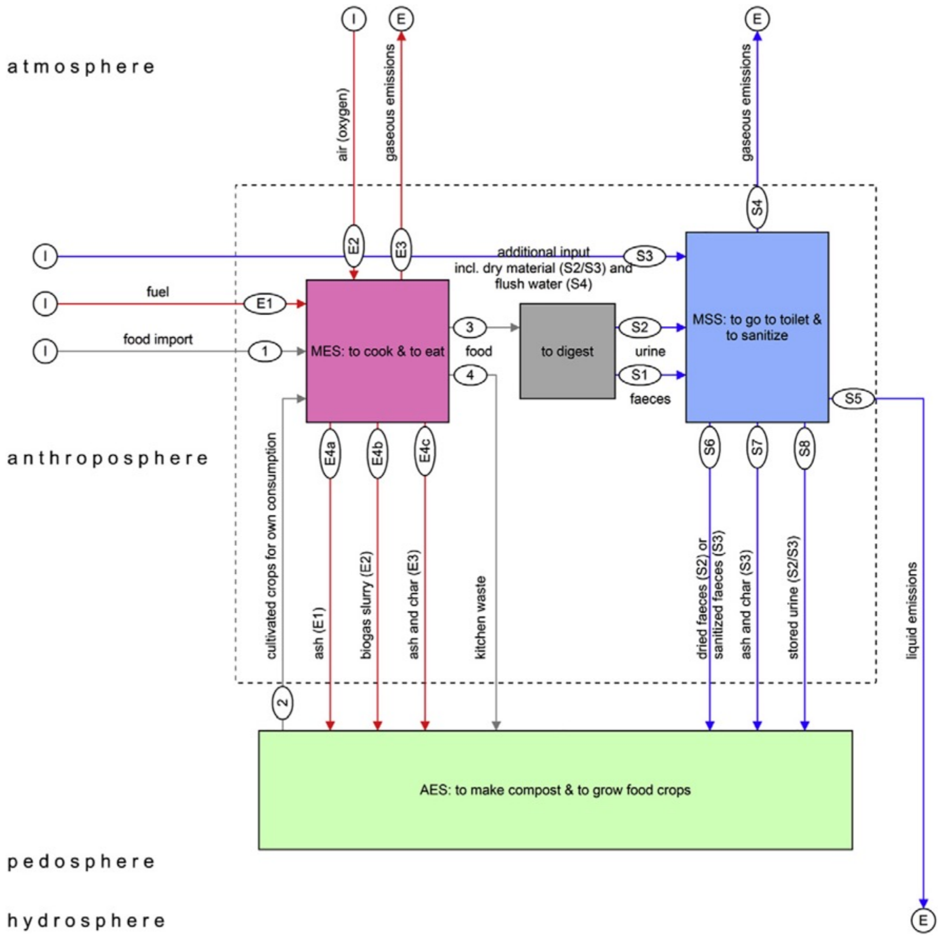

Fig. 2. The farming system of smallholders in Karagwe including the household, with the micro energy system (red) and the micro sanitation system (blue), and the agroecosystem (green). The three systems are connected through the use crops as food in the household and the use of resources recovered from the household for soil management (simplified model with most relevant material flows). The MES and MSS are content of the present MFA-study; the AES has been analysed in a subsequent study employing MFA in combination with soil nutrient balancing (SNB). Processes are indicated with boxes, material flows with arrows including import flows (I) and export flows (E); the dotted lines represent the system boundaries of the present analysis. Material flows in red and blue were estimated with the MFA of this work; those in grey were not part of the present system analysis.

MSS as resources to support the AES has already been the subject of a research series. In the follow-up study, residues from cooking and sanitation are composted in the AES alongside other organic wastes. Composting is the central process linking smallholder households to farmland assigned to the AES. In the AES, compost serves as fertilizer and contributes to soil management for growing food crops.

Two scenarios for locally available cooking and sanitation technologies were compared in the study: (i) three-stone fire and pit latrine (cf. Section 2.1), which is the most common current technology combination found in Karagwe smallholder households, (ii) 'alternative' technologies, including those represented in our case study projects (biogas system, three types of ICSs, two approaches to EcoSan), and (iii) other widespread alternatives (charcoal burner, septic system). Technology-specific material input and output flows were analysed separately for each alternative in the household energy (E) and sanitation (S) systems. In the discussion of this article, further scenarios were established enabling a comparison of selected E and S combinations.

Modelling of MES and MSS is briefly described in the following section. Note that in the case of resource consumption and recovery potential, results are presented in terms of fresh matter (FM). Our reasons for this are discussed at the end of Section 3.1.2. Further details of (i) those alternatives analysed, including descriptions and pictures of the technologies in question, and an introduction to the case study projects, (ii) modelling, including assumptions made regarding to specific metabolisms and processes, flow diagrams, and equations, and (iii) a summary of all collected data in tabular form are presented in Appendices A and B.

2.3.1. Modelling micro energy systems (MES)

The *functional unit* of the MES model was calculated on the thermal energy required to prepare two meals per day for six people over the course of one year. This definition was based on the fact that around 75% of the farming households in Karagwe eat two meals per day (Tanzania, 2012). We focused exclusively on using biomass resources and bioenergy technologies for cooking. Our analysis comprised six alternatives (E1–E6) including eight technologies (Tables 2 and A.2). The cooking process was defined and quantified using scientific and practitioner data from Water Boiling Tests (WBTs), a standardized procedure, which is internationally recognised and well established in the

Table 2
Bioenergy alternatives analysed, with applied technologies, defined in- and output flows, and the assumed energy conversion processes.

Nr.	Technology	Abb.	Input flow: Resources	Output flow: Residues	Output flow: Environmental emissions	Energy conversion processes assumed
E1	Three-stone fire	3SF	Firewood	Ash	CO, CO_2, H_2O, N_2, NO, SO_2	Combustion: complete oxidation of wood
E2.1.	Charcoal production	CP	Firewood	Ash and brands	CO, CO_2, CH_4, TNMHC, H_2, N_2, NO, PM; water and non-water liquids	Thermo-chemical conversion of firewood to charcoal via pyrolysis
E2.2.	Charcoal burner	CB	Charcoal	Ash	CO, CO_2, H_2O, N_2, NO, SO_2	Combustion: complete oxidation of charcoal
E3	CHEMA rocket stove	RS	Firewood	Ash	CO, CO_2, H_2O, N_2, NO, SO_2	Combustion: complete oxidation of wood
E4	CHEMA sawdust microgasifier	SG	Sawdust	Biochar	CO, CO_2, H_2O, N_2, NO, SO_2	Stove-internal gasification of sawdust and subsequent complete oxidation of wood gas
E4*	CHEMA SG* next morning	SG*	Sawdust	Biochar	Like E4 plus: CO_2, H_2O, N_2, NO, SO_2	Like E4, plus: continues oxidation of char residues to ash (if not extinguished)
E5	TLUD microgasifier	TLUD	Firewood	Biochar	CO, CO_2, H_2O, N_2, NO, SO_2	Stove-internal gasification of firewood and subsequent complete oxidation of wood gas
E5*	TLUD* next morning	TLUD*	Firewood	Biochar	like E5 plus: CO_2, H_2O, N_2, NO, SO_2	Like E5, plus: continues oxidation of char residues to ash (if not extinguished)
E6.1.	MAVUNO biogas digester	BGD	Mix of cow dung and banana stem	Biogas slurry	slurry storage: CO_2, CH_4, N_2O, NH_3; biogas leakages: CO_2, CH_4, H_2O, H_2S, O_2,	Bio-chemical conversion of organic wastes to biogas via anaerobic fermentation and digester-internal biogas storage
E6.2.	Biogas burner	BGB	Biogas	*None*	CO_2, H_2O, SO_2	Combustion: complete oxidation of biogas

Non-common abbreviations: Abb: abbreviation; TLUD: Top-Lit UpDraft; TNMHC: total non-methane hydrocarbons//CHEMA and MAVUNO are non-governmental organisation based in Karagwe, facilitating the case studies of this work. Note: Only those materials are listed as residues and emissions that were considered in our study and quantified in the MFA; others were not considered due to simplification of the system or lack of available data. Residues can potentially be recycled to the agroecosystem; emissions are "losses" to the environment. Also see Table A.2 for pictures, description of local production, and local prices of the technologies analysed in the MES-model.

scientific community. WBTs are a simplified simulation of the cooking process that can determine various parameters, such as cooking power, total energy use, efficiency, emissions, and so on, in order to describe a stove's performance (WBT, 2014). The 'daily cooking task' was defined as a series of cooking phases (Table A.1) and thus quantified at a duration of approximately 3.2 h per day per household. This duration corresponds to local routines (EfCoiTa, 2013) and literature (Vögeli et al., 2014). In addition to 'cooking on the stove,' analysis for the charcoal burner (E2.2) and biogas digester (E6.2) included the preparation phases of charcoal production (E2.1) and use of biogas digester (E6.1) respectively. In contrast, resources for three-stone fires and ICSs are typically gathered from remote fields and woodlands in the case of firewood, or from carpentries as a locally available waste resource in the case of sawdust. Material flows related to the provision of these

Table 3
Sanitation alternatives analysed, with the applied technologies, defined in- and output flows, and the assumed bio-chemical processes.

Nr.	Technology	Abb.	Input flows	Output flows: Residues	Output flows: Emissions	Storage flows: Stocks	Assumed processes
S1	Pit latrine	PL	Faeces, urine, cleansing water, disposed grey water	None	EmV: CO_2, CH_4 EmL: NH_4^+ ($\rightarrow NO_3^-$), H_2O, PO_4^{3-}	Sludge stored in pit	Anaerobic processes are dominant in bio-chemical degradation. Storage and decomposition of sludge in the pit. Neither gas nor sludge is used.
S2	UDDT	EcoSan	Faeces, urine, dry material, cleansing water	Stored urine, stored solids, waste water from anal cleansing	EmV: CO_2, CH_4, H_2O, NH_3 EmL: none	Precipitation in urine storage	Ammonia volatilisation during collection and storage of urine. Drying and aerobic bio-chemical degradation of faeces during storage in toilet; the latter was assumed to be similar to open defecation (simplification, due to lack of more precise and specific data).
S3.1	UDDT	CaSa	According to S2.	According to S2.	According to S2.	According to S2.	According to S2.
S3.2	Sanitation oven	CaSa	Sawdust, firewood, air, stored Solids	sanitized solids, biochar	EmV: CO_2, H_2O, N_2, NO, SO_2 EmL: none	none	Sanitation of solids is realized via pasteurization at Approx. 65 °C for min. 30 min in a loam oven: only evaporation of moisture from faeces, no thermo-chemical degradation of organic matter or N-volatilization because of moderate process temperature. Sanitation oven is heated with microgasifier: stove-internal gasification of sawdust and subsequent complete oxidation of wood gas.
S4.1	Water toilet	WC	Faeces, urine, cleansing water, disposed grey water, flush water	Sludge to store	None	None	Only transport; no metabolism.
S4.2	Septic tank	ST	Sludge to store	None	EmV: CO_2, CH_4 EmL: NH_4^+, H_2O, PO_4^{3-}	Sludge stored in pit	Anaerobic processes are dominant at bio-chemical degradation. Storage and decomposition of sludge in the pit. Neither gas nor sludge is used

Non-common abbreviations: Abb: abbreviation; EmL: liquid emissions through leaching; EmV: gaseous emissions through volatilisation; UDDT: urine-diverting dry toilet.
Note: Only those materials are listed as residues and emissions that were part of our study and quantified in MFA; others were not considered due to simplification of the system or lack of available data.
Residues from S2 and S3 can potentially be recycled to the agroecosystem whilst residues from S1 and S4 remain deposited in the pit; emissions are "losses" to the environment.
Also see Table B.2 for pictures, description of construction and operation, and local prices of technologies analysed in the MSS-model.

materials were not included within the scope of this study. Charcoal production, however, has been considered in the analysis as charcoal is commonly produced by rural smallholders (Ellegård et al., 2003). The biogas alternative (E6) refers specifically to *small-scale* biogas digesters which are directly to homestead kitchens. Here, we considered two scenarios taking into account different levels of technological maturity, as the local digester type is still under development. In the 'real world' scenario (E6.1r), calculations were based on the performance of the BiogaST pilot digester, whereas in the 'ideal world' scenario (E6.1i), calculations were based on biogas production from feeding substrates, such as cow dung and banana stems, as recorded in laboratory testing (Table A.12). The results presented in E6 are means for these two scenarios.

The main process considered in our MES-analysis was the combustion of fuel. Therefore, fuel (containing C as energy carrier) and air (providing the stoichiometric amount of oxygen) was required as $\dot{m}_{input}$. The $\dot{m}_{output}$ included residues and exhaust gases (Table 2). Biomass conversion was assumed as complete oxidation, but with modifications in order to depict the reality more precisely (Section A.2.3). First, specific emissions in the exhaust gases (i.e. CO_2 N_2, NO, SO_2, and H_2O) were quantified according to reaction equilibriums for completely oxidisation of the biomass (Joos, 2006; Kaltschmitt et al., 2009). In practice, not only CO_2 is emitted, but also CO (*ibid.*). Based on experimental emission data from the WBT, we defined the 'CO-factor' to quantify the percentage of C that is converted to CO instead of CO_2 (Eq. A.36). Additional emissions were also considered for biogas alternatives such as (i) leaching of biogas from the digester, and (ii) emissions from the digester-internal slurry storage (Figs. A.6–A.7). Residues from biogas digesters comprise three streams of biogas slurry: (i) slurry which is *removed* from the outlet basin of the digester to be directly used as fertilizer (biogas slurry, rem); (ii) slurry which pours out of the digester via an *overflow* to balance the filling level of the digester (biogas slurry, over); and (iii) slurry which is *recycled*, i.e. taken from the outlet in buckets, and re-filled into the digester through the inlet (biogas slurry, rec). Slurry recycling allows the circulation of microbes and the dilution of fresh input material. We considered gaseous and liquid emissions as well as solid residues from charcoal production; the latter, however, were not accounted for as potential recovery flows (Fig. A.2). Climate relevant emissions were assessed by using GWP-factors provided by Myhre et al. (2013) (Table A.6). Emissions with eutrophying effects were assessed with the EP-equivalence factors recommended by Heijungs et al. (1992) and Guinée (2002) (Table A.7).

In order to reflect user behaviour when cooking with a microgasifier stove, we analysed variables for alternatives E4 and E5, which are noted as, respectively, E4* and E5*. In practice, we observed that after someone had cooked with a microgasifier, the available quantity of biochar differed depending on whether the matter was removed from the stove and extinguished immediately after cooking (E4, E5), or was left inside the stove until the next morning (E4*, E5*). In the latter scenario, the matter diminishes due to continued oxidation (Fig. A.8 and A.9).

Data on material characteristics (e.g. elemental composition of fuels and residues) and process parameters (e.g. distribution of pyrolysis products) was collected through an extensive literature review (Table A.12). For the WB data, we consulted a variety of sources, including the case studies (Table A.8). Evaluated WBT data (cf. Section A.4.1) was used to characterize specific technologies, and to quantify the required $\dot{m}_{input}$ of fuel for the defined cooking task. Data from the pilot study of the BiogaST-project was evaluated and utilized for describing the performance of biogas alternatives (cf. Section A.4.2).

2.3.2. Modelling the micro sanitation system (MSS)

The *functional unit* of the model was 'to manage the amount of excreta produced by six people during one year.' The model contained four alternatives (S1–S4) and included six technologies (Tables 3 and B.3). Excreta management is realized either through storage (conventional sanitation systems) or treatment (EcoSan-systems). In S1 and S4, human excreta is collected in the toilet alongside wastewater (Fig. B.1 and B.4). The matter is then transferred to an earth pit (S1) or septic tank (S4) as sludge-to-store. In S2 and S3, urine and faeces are collected separately in the waterless UDDT, where dry material is added to the faeces for accelerating drying. The main processes inside the UDDT are (i) the drying of solid matter (i.e. faeces and dry material), and (ii) the storage of urine (Fig. B.7–B.9). Water used for anal cleaning is also managed in the UDDT. Wastewater is directly processed through a soil filter at the back of the UDDT, which takes the form of a flower-bed, enabling plant roots to easily access the water in the gravel-soil mix. In S3, additional thermal treatment of stored solids is realized via pasteurization with a microgasifier stove (equivalent to that analysed in E4) used as a heat source, in combination with a loam oven for heat storage (Fig. B.10 and B.11). This sanitizing process is modelled as pasteurization with the assumption that only water is evaporated, and there is no volatilisation of C or N. In all four systems, biological degradation of the matter collected inside the toilet or pit also occurs, leading to gaseous emissions from volatilisation (EmV), and liquid emissions through leaching (EmL) (Table 3). Greenhouse gas (GHG) emissions were assessed using GWP factors after Myhre et al. (2013) (Table B.5). EP was assessed with equivalence factors provided by Heijungs et al. (1992) (Table B.6). Finally, we quantified (i) *stocks* of sludge deposited in the pits in S1 and S4, and (ii) the recovery potential of residues in S2 and S3.

In practice, it is often not possible to collect 100% of human excreta at home. For example, children may use school toilets, and parents may work off-farm or urinate outdoors during agricultural activities. We therefore considered home toilet use for either urination or defecation as a variable. The basic assumption was that toilets in smallholder households are used, on average, for 65% to 70% of the total daily need for urination and defecation, respectively. In comparison, varying scenarios with utilisation-values for urination and defecation of 50% and 100% were also studied.

Data on material characteristics (e.g. nutrient composition in excreta) and on process parameters (e.g. emission factors) (Table A.3) was collected through an extensive literature review and from case study documents (Table B.9). In addition, we performed our own experiments if data was not sufficiently available (Section B.2).

3. Results and discussion

The following chapter contains (i) a presentation of selected results from the MFA, checked for plausibility and briefly discussed in relation to relevant factors, (ii) a synthesis of results from MES and MSS from an integrated perspective, and (iii) a brief discussion of the applied methodology.

3.1. Material flows in the household energy system

Figs. 3 and 4 show example results of MFA modelling for alternatives E4 and E6.1 (the 'ideal world' model). Additional flow diagrams of other alternatives, and including sub-processes, are presented in the Supplements.

3.1.1. Resource consumption

When compared to the current state of affairs in Karagwe, replacing applied bioenergy technologies with ICSs reduces resource consumption (Table 4; Fig. S.1). This is not the case, however, if charcoal stoves or biogas digesters plus biogas burners are used for cooking. When using a charcoal burner (E2.2), calculated fuel consumption is only 23 ± 1% as compared to E1. To produce this amount of charcoal, however, 117 ± 16% of the firewood used in E1 would be needed for carbonization in pyrolysis kilns (E2.1). Furthermore, biogas production (E6.1) requires agricultural residues on a different scale to those actually available.

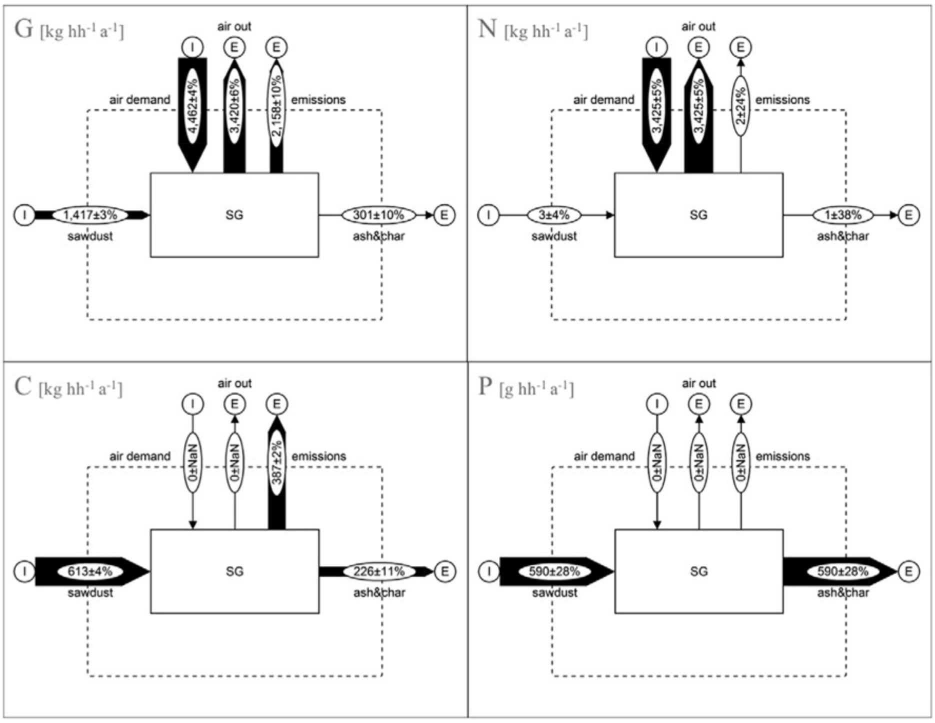

Fig. 3. Flow diagrams of the analysed bioenergy alternatives E4, the sawdust gasifier (SG), for the layer of goods (G) and indicator elements C, N, P in kg per household per year. Material flows are indicated with arrows including import flows (I) and export flows (E). Processes are indicated with boxes.

In general, estimated resource consumption is at a similar scale to, for example, that found by Akbar et al. (2011) and O'Sullivan and Barnes (2007). In particular, $\dot{m}_{input}$ of fuel in E1, E4, and E5 is very close to that reported in the literature (approximately 100% of average fuel consumption in the reference studies), but is lower in E2 and E3 with 55–75% (*ibid.*). Estimated fuel consumption of the ICSs analysed in E3 to E5 is also confirmed in field studies carried out by EfCoiTa, through their 'kitchen performance test' (Ndibalema and Schmid, 2015). For this experiment, stoves were delivered to households and tested in home kitchens by cooking typical local meals in order to measure fuel consumption and thereby extrapolate annual fuel demands. Annual biogas consumption as estimated through our model, is approx.

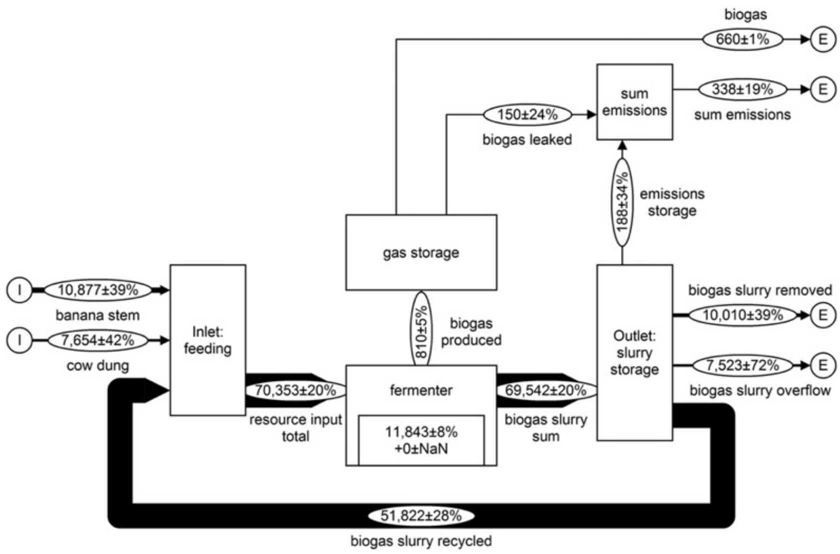

Fig. 4. Flow diagram of the analysed bioenergy alternative E6.2, the biogas digester, for the layer of goods in kg per household per year. Material flows are indicated with arrows including import flows (I) and export flows (E). Processes are indicated with boxes.

Table 4
Results MES-modelling: material input flows of *resources* (i.e. fuel required to fulfil the cooking task) and output flows of *residues* (i.e. resources recovered for nutrient recycling and C recovery).

Alternative	kg hh^{-1} yr^{-1}		kg C hh^{-1} yr^{-1}		kg N hh^{-1} yr^{-1}		kg P hh^{-1} yr^{-1}	
	$\dot{m}_{input}$: Resource consumption (i.e. fuel use)							
E1 (firewood)	1775	±128	763	±51	5.1	±0.9	1.0	±0.2
E2.1. (firewood)	2072	±282	780	±64	5.9	±1.3	1.2	±0.3
E2.2. (charcoal)	408	±19	287	±15	1.5	±0.2	0.3	±0.1
E3 (firewood)	970	±43	417	±19	2.8	±0.5	0.6	±0.1
E4 (sawdust)	1417	±39	613	±24	3.2	±0.1	0.6	±0.2
E5 (firewood)	1340	±35	576	±22	3.8	±0.1	0.8	±0.2
E6.2. (biogas)	660	±4	291	±3	0.0	±0.0	0.0	±0.0
E6.1. (cow dung)	11,465	±3372	578	±196	34	±10	8.6	±2.1
E6.1. (banana)	16,298	±4514	476	±173	14	±4	0.9	±0.3
	$\dot{m}_{output}$: Resource recovery/recycling potential							
E1 (ash)	23	±4	0	±0	0	±0	1.0	±0.2
E2.1. (ash & brands)	88	±41	28	±13	0.2	±0.1	0.9	±0.3
E2.2. (ash)	13	±2	0	±0	0	±0	0.3	±0.1
E3 (ash)	12	±2	0	±0	0	±0	0.6	±0.1
E4 (biochar)	301	±29	226	±25	0.9	±0.4	0.6	±0.2
E4* (biochar)	181	±57	91	±29	0.0	±0.0	0.6	±0.1
E5 (biochar)	267	±55	201	±23	0.8	±0.4	0.8	±0.2
E5* (biochar)	72	±15	20	±4	0.0	±0.0	0.8	±0.1
E6.1. (biogas slurry, rem)	14,975	±4079	273	±73	20	±6	5.0	±1.3
E6.1. (biogas slurry, over)	11,696	±5723	293	±133	20	±9	4.5	±2.1
E6.1. (biogas slurry, sum)	26,671	±7027	566	±152	41	±11	9.5	±2.5

Results are displayed for the four analysed layers: goods in FM and substances of C, N, P contained in goods in kg per household and year; figures after data reconciliation in STAN- software; plot data for Fig. S.1 (resources consumed) and for Fig. S.2 (resources recovered). Non-common abbreviations: hh: household; C: carbon; FM: fresh matter; MES: micro energy system; N: nitrogen; P: phosphorus; yr: year

140% higher than values provided by Rajendran et al. (2012) or Vögeli et al. (2014).

Providing sufficient $\dot{m}_{input}$ of banana stem requires approximately 0.13 ha of *shamba* (Swahili term for the locally typical banana-based homegardens). This area is equivalent to around 30% of the total land that farmers in Karagwe commonly cultivate as *shamba* (Tanzania, 2012). With biogas production, we estimated that it is therefore only generally possible to provide sufficient resources for a biogas digester *if* the household possesses cattle (cf. Section A.4.2). The household should possess a minimum three cows, which is the case for <20% of households in Karagwe (*ibid.*). Cow dung may, however, be substituted by dung from other livestock (e.g. pigs or chicken), as the specific gas production of pig manure and chicken manure is largely comparable to that of cattle manure (KTBL, 2009).

3.1.2. Potential for the recovery of resources

Corresponding to reduced fuel consumption, estimated $\dot{m}_{output}$ of ash available after cooking for charcoal or rocket stoves are less than available with a typical three-stone fire (Table 4; Figs. S.2–S.4). A notably greater $\dot{m}_{output}$ of residues is potentially available, however, when using a microgasifier or operating a biogas digester. In particular, the total $\dot{m}_{output}$ of biogas slurry (i.e. removed and overflow) is on a completely different scale in terms of FM. Consequently, the ultimate recovery potential of C, N and P was also highest in E6. It must be noted that recovery potential depends on the utilization of slurry from the overflow outlet. According to the case study, approximately 55% of total biogas slurry is removed with buckets for agricultural use, whilst just 45% of slurry exits the digester through the overflow. In addition, 77,600 ± 15,400 kg hh^{-1} $year^{-1}$ [hh = household] of FM of biogas slurry must be recycled within the digester. Slurry is most commonly removed from the digester's outlet basin with buckets, and refilled into the inlet basin; thus, it has to be handled manually (see Discussion below). In contrast, no C or N is recoverable from any of the alternatives E1, E2.2 or E3, due to the assumed combustion of the biomass in these kinds of stoves. The recovery rate for P however was 100% in E1–E5. Under the given thermal conditions (<700–800 °C), P remains stable as a mineral in ashes and biochar particles (Knicker, 2007).

The estimated recovery potentials from the microgasifiers for biochar as regards C content differ depending on how the stove is used, and how residues are treated. Leaving the hot char inside the stove overnight has a marked effect on total quantity, and on the recovery of C. Recovery potential in E4* and E5* diminishes to approx. 60% and 30% of total FM of residues that are recoverable directly after cooking with a microgasifier in E4 or E5, respectively. Likewise, the C recovery rates in E4* and E5* decrease to approximately 40% and 10% of the C recovery rates in E4 and E5, respectively (i.e. reductions ranging from approximately 35% to 4–15% (Table S.5)). Accordingly, the recovery of N is inhibited whilst the P recovery rate remains stable at 100%.

Estimated nutrient concentrations in biogas slurry (i.e. 2.9 ± 0.7 and 0.76 ± 0.02% of total N and total P in dry matter (DM), respectively) are generally comparable with average ranges summarized by Möller and Müller (2012) (i.e. 8.5 ± 0.7 and 0.55 ± 0.15% of total N and total P in DM, respectively) and Zirkler et al. (2014) (i.e. 7.6 ± 6.0 and 1.1 ± 0.6% of total N and total P in DM, respectively). The concentrations observed in Karagwe, however, are lower when compared to those found in digesters elsewhere in TZ (Gyalpo, 2010; Vögeli et al., 2014); N and P concentrations in Karagwe slurry were approx. 30% and 55% of the concentrations measured in the reference material, respectively. One explanation for this difference is the use of different kinds of input materials (i.e. canteen wastes and human excreta) in the reference studies. Estimated transfer of C in resources (banana stem and cow dung) to biogas slurry is 52 ± 19% of the total C input. Estimated C recovery rate is thus equivalent to Gyalpo (2010) and Wendland (2009), who showed that approximately 43% of total C input is recoverable. Estimated N recycling rate of both material flows of biogas slurry was 85 ± 28% of the total N input.

Despite the ample nutrient recovery potential in biogas slurry, it must be considered whether fermentation substrates had already been used as organic input matter for banana-based homegardens, as shown by Baijukya and de Steenhuijsen Piters (1998). It is vital that biogas slurry is recycled into the *shamba* in order to replace prior inputs of banana stem and cow dung, thus avoiding an exacerbation of nutrient depletion (Baijukya and de Steenhuijsen Piters, 1998).

Overall, estimations of $\dot{m}_{input}$ and $\dot{m}_{output}$ demonstrate that using charcoal stoves or ICSs reduces the total weight of FM that household members need to transport in day-to-day life (Table 5). The effort expended in carrying material during fuel collection, and for recycling

Table 5
Transportation effort required for carrying materials in the MES on a daily basis: sum of weights of *resources* and *residues*.

Alternative	Resource	kg hh^{-1} d^{-1}		Residues	kg hh^{-1} d^{-1}		Sum of matter	kg hh^{-1} d^{-1}	
E1	Firewood	4.9	±0.3	Ash	0.06	±0.01	firewood & ash	4.9	±0.3
E2.2	Charcoal	1.1	±0.1	Ash	0.04	±0.01	charcoal & ash	1.2	±0.1
E3	Firewood	2.7	±0.1	Ash	0.03	±0.005	firewood & ash	2.7	±0.1
E4	Sawdust	3.9	±0.1	Biochar	0.8	± 0.1	sawdust & biochar	4.7	±0.1
E4*	Sawdust	3.9	±0.1	Biochar*	0.5	±0.2	sawdust & biochar*	4.4	±0.2
E5	Firewood	3.7	±0.1	Biochar	0.7	±0.2	firewood & biochar	4.4	±0.2
E5*	Firewood	3.7	±0.1	Biochar*	0.2	±0.04	firewood & biochar*	3.9	±0.1
E6.1.	Cow dung	31	±9	Biogas slurry, rem	41	±11	cow dung, banana, sum of biogas slurry	330	±46
E6.1.	Banana	45	±12	Biogas slurry, rec	213	±42			
E6.1.	Sum	76	±15	Biogas slurry, sum	254	±42			

Results are displayed in goods in kg of FM per household and day; figures after data reconciliation in STAN- software.
The *-sign refers to the scenario "next morning" as described in Section 2.3.1.
Non-common abbreviations: d: day; hh: household; FM: fresh matter; MES: micro energy system.

residues to agriculture, is reduced by approximately 77% and 45% when cooking with a charcoal burner or rocket stove, respectively. Using microgasifiers reduces transportation efforts in the range of approximately 5 to 20%, depending on the kind of gasifier and the particular way in which the stove is used. In contrast, operating a biogas digester demands a markedly higher effort every day for carrying resources and residues - approximately 70 times higher than the currently.

3.1.3. Environmental emissions

According to the results for resource consumption, replacing three-stone fires with locally available ICSs reduces total GHG-emissions, and therefore, GWP associated with cooking; this is not the case when changing to either a charcoal stove or a biogas system (Figs. 6a and S.5; Table S.7). Using a rocket stove (E3) decreases GHG-emissions to 55 ± 8% of climate relevant emissions in E1. For microgasifier stoves, GHG-emissions were reduced irrespective of whether residues were immediately removed from the stoves in E4 and E5 (approx. 40–60% of GWP in E1), or left inside until the next morning in E4* and E5* (approx. 55–85% of GWP in E1). In contrast, GWP of E2 is comparable to that of the current state (93 ± 10% of GWP in E1). Total GHG emissions in E2 are distributed by approximately 60% and 40% to charcoal production (E2.1) and the charcoal burner (E2.2), respectively. Finally, GHG emissions from biogas systems significantly exceed those from other cooking alternatives, despite the fact that biogas burners themselves are environmental friendly technologies, which showed the lowest GWP in the analysis. Hence, the exceptionally high environmental emissions in E6 (250 ± 50% of GWP in E1) can mainly be ascribed to emissions from the digester. The GWP of E6.1 is made up of approximately 40% from biogas leakages from digester-internal gas storage, in addition to 60% from intermediate slurry storage in the outlet basin of the digester. Biogas leaching can be reduced through appropriate construction and maintenance work. For example, '7-layer plastering' can improve gas-tightness of the digester significantly, when carried out effectively (Ullrich, 2008). In order to reduce emissions of GHG from slurry storage, it is important (i) to cover the outlet where the slurry is stored, and (ii) to monitor pH of matter left in the basin, which can alkalinise and thereby promote volatilization of ammonia (NH_3) (Möller et al., 2008). Further attention is required when applying the biogas slurry to the soil, but a discussion of these processes is considered to be outside the scope of this article.

Overall, estimated GHG emissions for MES alternatives are generally of a similar magnitude to those calculated with ultimate emission factors provided by Smith et al. (2000) (Table S.9; Fig. S.6). The estimated results of the present MFA are on average 20 to 40% lower than the plausibility values. A possible reason for this is our omission of CH_4, N_2O, and total non-methane hydrocarbons (TNMHC) emitted from fuel combustion in our calculations. In the calculations of Smith et al., meanwhile, these emissions contribute up to 15% to total GHG. This is corroborated by the fact that, in our study, CO_2 emissions considered in isolation are highly consistent with the reference literature (≈100%) whilst the $\dot{m}_{export}$ of CO was lower in our model. Since the GWP of CO is twice as high as CO_2 (Myhre et al., 2013), underestimating CO emissions could easily have lowered total GHG emissions in our model. (Interestingly, cooking with an ICS in Karagwe produces lower GHG emissions than cooking with an electric stove in Germany or the rest of Europe (Atlantic consulting, 2009), although the total energy consumption was assumed as equal. It is likely that the use of lignite coal in the electricity mix in Europe contributes significantly to a high GWP when cooking with electricity.) Total GHG emissions recorded for biogas systems (approximately 65 kg CO_2e for each ton of $\dot{m}_{output}$ in FM) were also comparable to literature. For example, Nzila et al. (2012) estimated approximately 74 kg CO_2e t^{-1} for the best performing biogas systems in Kenya. Komakech et al. (2015), meanwhile, assessed GHG emissions from anaerobic digestion of solid waste in Kampala at approximately 60 kg CO_2e t^{-1} including net soil emissions from applying biogas slurry. We acknowledge that we did not consider particulate matter (PM) in assessing the GWP of energy alternatives, largely due to the fact that appropriate and reliable data were missing in both the case studies and literature. PM is, however, assigned to 'black carbon' and assessed with a GWP of 100–1700 (Myhre et al., 2013; for comparison, the GWP of CH_4 is 28 and that of N_2O gas 265). Thus, overall GWPs of the analysed energy alternatives could see a significant increase if PM was included in the assessment. This would be especially relevant for alternatives except biogas systems, as biogas burners are known to demonstrate outstanding performance with respect to PM-emissions (e.g. Khandelwal and Gupta, 2009).

Results also show that environmental emissions with a eutrophying effect are reduced in all alternatives, except the biogas system, when compared to the three-stone fire (Fig. 6b; Table S.8). When using a charcoal burner (E2) or ICSs (E3–E5), EP accounts for approximately 30%, or 45–60% of the EP in E1, respectively. Liquid emissions from kiln pyrolysis in E2.1 (i.e. water and non-water emissions) are presumably in total 690 ± 50 kg hh^{-1} $year^{-1}$, which enter the ecosystem as untreated, and cause local environmental damage. However, respective emissions were not further assessed, as their final fate is not clear. Finally, the EP of the biogas alternative E6 is 310 ± 130% of the EP in E1, mostly due to NH_3-emissions from the digester-internal slurry storage.

3.2. Material flows in the household sanitation system

Fig. 5 shows example results of MFA modelling for alternative S3. Additional flow diagrams of other alternatives, and including sub-processes, are presented in the Supplements.

3.2.1. Resource consumption

The $\dot{m}_{input}$ of faeces, urine, and cleansing water in household toilets is approximately 383, 1605, and 383 kg hh^{-1} $year^{-1}$, respectively (Table S.10; Fig. S.7). The $\dot{m}_{input}$ of N and P contained in excreta can be

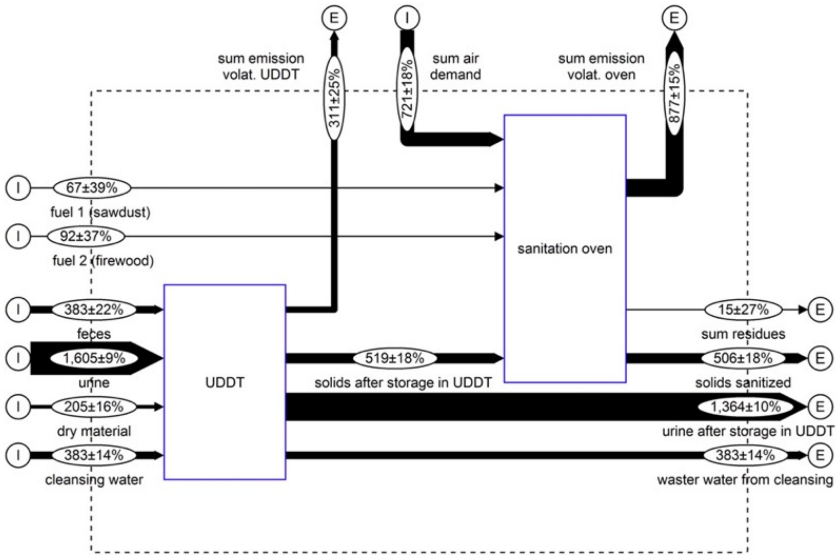

Fig. 5. Flow diagram of the analysed sanitation alternative S3, the urine-diverting dry toilet (UDDT) in combination with a sanitation oven (i.e. the 'CaSa' concept), for the layer of goods in kg per household per year. Material flows are indicated with arrows including import flows (I) and export flows (E). Processes are indicated with boxes; the blue box represents a process that was modelled with further sub-processes.

considered as plausible, since the estimated values are approximately 65–80% of the values provided by Richert et al. (2010) and 130–150% of the values provided by Jönsson and Vinnerås (2004). In EcoSan-alternatives S2 and S3, an additional 205 ± 33 kg hh^{-1} $year^{-1}$ of dry material is collected in the UDDT together with the faeces. Pursuant to the CaSa pilot project, the operation of a sanitation oven (analysed in alternative S3) requires sawdust and firewood as fuel, with 67 ± 26 and 92 ± 34 kg hh^{-1} $year^{-1}$, respectively. Resource consumption for thermal sanitation is, therefore, about 10% of the fuel required annually for cooking with the MES alternatives E1 or E4. Moreover, when using the same facilities as in the CaSa pilot project, thermal sanitation is presumably performed 34 times per year, or approximately every 10 days. Implementing a storage facility could reduce this workload, so that, for example, three to five pots might be treated in one batch. Further development of the CaSa sanitation technology is evidently required. As a result, the 'Kon-Tiki' cone kiln (Schmidt and Taylor, 2014) extended with a swivel grate is currently being tested for use in Karagwe. The objective is to follow up on the combination of biochar production with thermal sanitation of human excreta, but at a larger scale (i.e. a larger mass throughput per batch), and, potentially, with greater efficiency (i.e. less fuel consumption in mass per mass unit of treated excreta). Furthermore, co-firing of firewood with dried faeces for operating the Kon-Tiki will be part of future experiments.

During our literature review, we found that toilet usage patterns are mostly neglected in studies assessing the nutrient recovery potential from human excreta, even though this parameter clearly influences the results. Therefore, we adjusted our assumptions regarding toilet usage, and interpolated the calculated results to outline the linearity of $\dot{m}_{input}$ (Fig. S.14) and $\dot{m}_{ouput}$ (Fig. S.15) of a household UDDT to that adapted toilet usage. In comparison to our standard assumption (cf. Section 2.3.2), the total $\dot{m}_{input}$ in S2 and S3 is approximately 150% or 80% when assuming a maximal 100%, or a mere 50% usage of the UDDT, respectively (Table S.10). In addition, we find it likely that the estimated recovery potentials of N and P from S2 and S3 might still be slightly underestimated for two reasons: Firstly, we did not consider the $\dot{m}_{input}$ of urine and faeces that were not disposed directly into the toilet, despite the fact that the contained nutrients are recycled into agricultural soils, for example, in the case of urination during fieldwork. Secondly, visitors were not considered in the analysis.

Finally, the $\dot{m}_{input}$ of flush water in S4 accounted to 15,330 ± 3330 kg hh^{-1} $year^{-1}$. However, the estimated flush water use is lower than that found in, for example, Winblad et al. (2004), who figures the same volume as annual black water stream *per person*. We argue, that although rather conservative, our assumption of 10 dm^3 flush water use per person per day is generally consistent with other calculations of 6 (Meinzinger, 2010), 10 (Tumwine et al., 2002) or 21 dm^3 p^{-1} d^{-1} (Londong, 2015). However, it should be noted that excessive water toilet operation consumes a large proportion of available water resources. In Karagwe, water supply is decentralised, meaning that there is no central, pipeline-based supply of tap water. Instead, members of a household either have to fetch water from wells or other sources, or possess a storage facility for rainwater harvesting. Most water tanks in the area have a capacity of 5000 to 20,000 dm^3 (Mavuno, 2015). Although the tank could theoretically be refilled twice a year under local climate conditions, operating a flush toilet with septic tank would highly pressure scarcely available water resources in the households.

3.2.2. Potential for the recovery of resources

The recovery of residues, including nutrients and C, from the MSS is basically only possible through EcoSan alternatives S2 and S3 (Table 6; Fig. S.8). Moreover, approximately 60% of the total recovery potential in terms of weight is accounted for by stored urine. Another approximately 23% of the material flow is so-called solid matter (i.e. faeces and dry material), which is either stored and dried (S2), or dried and sanitized (S3). Biochar residues from the sanitation oven add < 1% to the total $\dot{m}_{output}$ in S3.

The absolute potential for recovery of C is higher in S3 than S2 (Table 6; Figs. S.9–S.11). However, the actual C recovery rate is higher in S2 than S3, with 95 ± 22% and 55 ± 10% of the total C-input, respectively (Table S.14). We reason that in S3, approximately 50% of the C input is contained in fuels for heating the sanitation oven, which are largely oxidized during gasification. The recovery rates for N and P are comparable in S2 and S3 with, respectively, 97 ± 11% versus 93 ± 9% for N, and 91 ± 19% versus 92 ± 17% for P. Overall, solid matter contributes the most to the recovery of C, with approximately 83% and 72% of the total C input in S2 and S3, respectively. Urine makes a significant

Table 6
Results MSS-modelling: material output flows of *residues* that are potentially available from the sanitation facilities for recovering nutrients and C.

Alternative	kg hh^{-1} yr^{-1}		kg C hh^{-1} yr^{-1}		kg N hh^{-1} yr^{-1}		kg P hh^{-1} yr^{-1}	
	$\dot{m}_{output}$: Residues and stocks							
S1 (sludge)	816	±615	39	±6	1.9	±0.9	0.5	±0.2
S2 (stored urine)	1364	±134	11	±2	6.6	±0.5	0.6	±0.1
S2 (dried solids)	519	±107	54	±10	3.8	±0.6	1.1	±0.2
S2 (cleansing water)	383	±54	0	±0	0	±0	0	±0
S3 (stored urine)	1364	±134	11	±2	6.6	±0.5	0.6	±0.1
S3 (sanitized solids)	506	±93	54	±8	3.8	±0.6	1.1	±0.2
S3 (biochar from sanitation)	15	±4	11	±4	0.04	±0.02	0.08	±0.02
S3 (cleansing water)	383	±54	0	±0	0	±0	0	±0
S4 (sludge)	716	±1862	32	±4	1.0	±0.5	0.5	±0.1

Results are displayed for the four analysed layers: goods in FM and substances of C, N, P contained in goods in kg per household and year; figures after data reconciliation in STAN- software; plot data for Fig. S.8 (residues) and Figs. S.9–S.11 (recycling potential for C, N, and P)
Non-common abbreviations: hh: household; MES: micro energy system.

contribution to nutrient recycling with approximately 60% and 40% of the total recoverable N and P, respectively. As a plausibility check, Chaggu (2004) assumed a C recovery rate of 100% for EcoSan, and justified this by the alkaline conditions in the UDDT, after adding ashes, which hinders biological degradation of faeces. Hotta and Funamizu (2006) determined that approximately 90% of total N contained in human excreta could be recovered by using an UDDT, which supports our estimations of a recovery rate of approximately 80% of total N only from urine. Nevertheless, during our literature review we recognised that empirical scientific evidence quantifying emissions from UDDTs are, in general, either scarce or absent.

Residues from sanitation ovens add approximately 14%, 0.4%, and 4% of total C, total N, and total P contained in all recycling flows in S3, respectively. In addition, 0.2 ± 0.1 kg P hh^{-1} $year^{-1}$ remains in the urine storage container in the UDDT in S2 and S3 (i.e. as *stock*). The latter resource is most likely not recovered as this would require a thorough cleaning of the urine storage containers from the inside, which might be difficult to realise with standard jerry cans. Finally, approximately 17% of recoverable $\dot{m}_{output}$ in S2 and S3 is cleansing water. This water is used as a resource for irrigating flowers, bushes, and other horticultural plants in the direct vicinity of the toilet.

In principle, potential C and nutrient recovery from toilet sludge is higher for a pit latrine (S1) than a septic system (S4), because the emissions from the septic tank are higher. However, according to local practices, the recovery potential is utilized in neither S1 or in S4. Instead, the sludge remains in the pit or tank, from where proportion of it infiltrates the surrounding soil. When the pit becomes full, a new one is dug and a new toilet is constructed. Consequently, estimated recovery rates of S1 and S4 are not utilized, and there are no recycling flows but only sludge as $\dot{m}_{storage}$ to the pit. Hence, the results presented should be interpreted as transfer rates of the total input of an indicator element to the sludge. The C transfer to the sludge stored (after C losses to the atmosphere via CH_4 and CO_2 emissions) is 79 ± 21% and 61 ± 14% of the total C input in S1 and S4, respectively. In comparison, Meinzinger (2010) accounted for approximately 43% of total C being transferred into latrine sludge. This indicates that the estimated C emissions into the environment might be underestimated in S1 and S4.

3.2.3. Environmental emissions

Implementation of EcoSan significantly reduces $\dot{m}_{export}$ from household sanitation systems into the environment. GHG emissions decrease when using a UDDT, compared to a pit latrine or water-based septic alternatives, due to the fact that less CH_4 is emitted from the toilet. In comparison to a pit latrine (S1 = 100%), the estimated emissions with GWP are significantly lower in S2, with 35 ± 10%, similar in S3, with 129 ± 35%, and significantly higher in S4, with 153 ± 26% (Figs. 7a and S.12–S.13; Table S.17). Additional GHG emissions in S3 originate from operating a microgasifier stove, and the subsequent use of biogenic and renewable material. Nutrient leaching into aquifers is also significant in conventional systems S1 and S4, whilst effluents to the pedo- and hydrosphere are of a different scale than gaseous emissions to the atmosphere. EcoSan alternatives, meanwhile, avoid leaching of N and

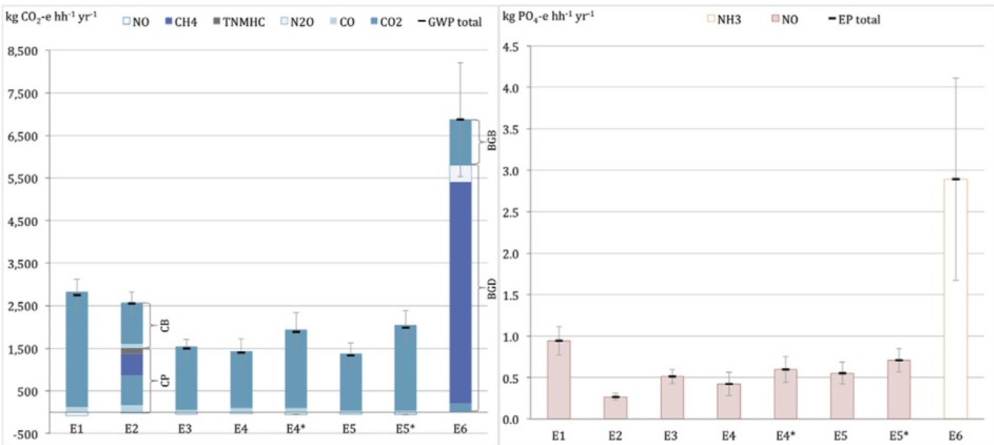

Fig. 6. Environmental impacts of the bioenergy provision assessed with the global warming potential (a; left) and the eutrophication potential (b; right) for the MES alternatives E1-E6. Plot data provided in Tables S.7 and S.8; alternatives are defined in Table 2.

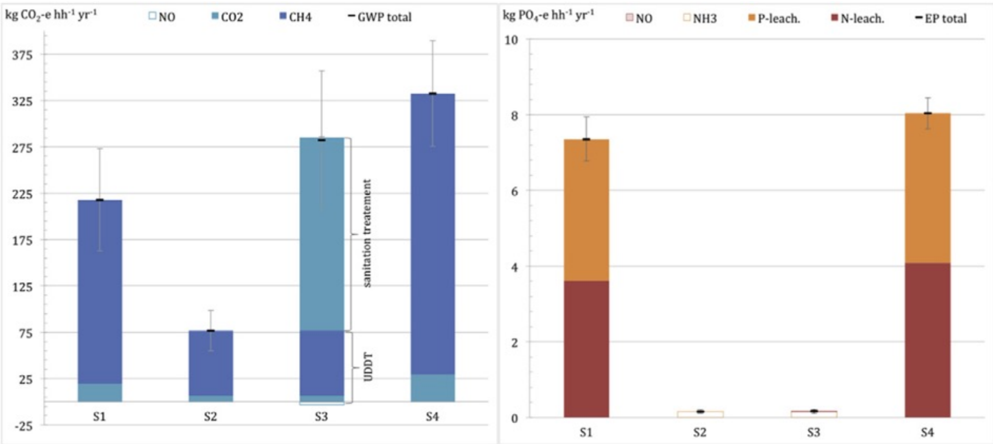

Fig. 7. Environmental impacts of the sanitation service assessed with the global warming potential (a; left) and the eutrophication potential (b; right) for the MSS alternatives S1–S4. Plot data provided in Tables S.17 (GWP) and S.18 (EP); alternatives are defined in Table 3.

P, and thus significantly reduce emissions with eutrophying effects (Figs. 7b and S.12; Table S.18). When switching from pit latrine (S1 = 100%) to UDDT in an EcoSan-approach (S2/S3) or to using a septic system with a flush toilet (S4), emissions with EP are 2 ± 1% and 109 ± 6%, respectively. Overall, conventional alternatives emit approximately 80 to 90% of total N and 70 to 75% of total P contained in the sum of $\dot{m}_{export}$ into the ecosystem.

Despite these results, we judge that analysed eutrophying emissions are likely over-estimated. We assessed EP according to Heijungs et al. (1992) and consequently included total N and total P contained in liquid emissions. Given that a high P-fixation can be expected for local soils (Chesworth, 2008), and given that P is rather immobile in the soil (Van der Eijk et al., 2006), we presume that phosphate (PO_4^{3-}) would probably remain in the soil surrounding the pit. Nonetheless, pollution of underground water resources is more likely from ammonium (NH_4^+) emissions (Jacks et al., 1999). If we exclude P-leaching from our assessment, the estimated EP of S1 and S4 could possibly be reduced to half the results presented in Fig. 6b.

3.3. Integrating household energy and sanitation systems into smallholder farming

Synthesizing the results, it appears that GHG emissions from the MSS total only around 8% of those from the MES, when referring to current state alternatives (i.e. a comparison of S1 versus E1). Otherwise, the EP of the MSS is approximately eight times higher than that of the MES. The potential to recover biochar from cooking with a microgasifier and the potential to recover sanitized solids from EcoSan result in comparable annual material flows in terms of volume (i.e. approximately 1.0 and 1.2 m^3 hh^{-1} $year^{-1}$ of FM of sanitized solids and biochar, respectively). This in turn fits very well into the applied practices of the CaSa pilot project to produce so-called CaSa-compost as fertilizer (Krause et al., 2015). For this purpose, Kammann et al. (2015) demonstrated that using biochar as a compost additive is the most promising approach in terms of biochar applications. Kammann et al. assumed that during composting, biochar is 'loaded' with nutrients by capturing N and P. The co-composting of C rich biochar and nutrient rich human excreta can therefore positively affect the turnover of N and P through the reduced leaching of nutrients. As interesting as these ideas are, we considered processes involved in composting itself outside the scope of this current study.

Opportunities (in terms of 'added values') of analysed energy or sanitation alternatives become more tangible when examining the integrated potential for utilising residues in agriculture. To this end, we defined three scenarios: (A1) describes the current state of using a three-stone fire for cooking, and a pit latrine for sanitation (i.e. the combination of E1 and S1); (A2) represents a technology change towards using a biogas system for energy provision, and a UDDT for sanitation

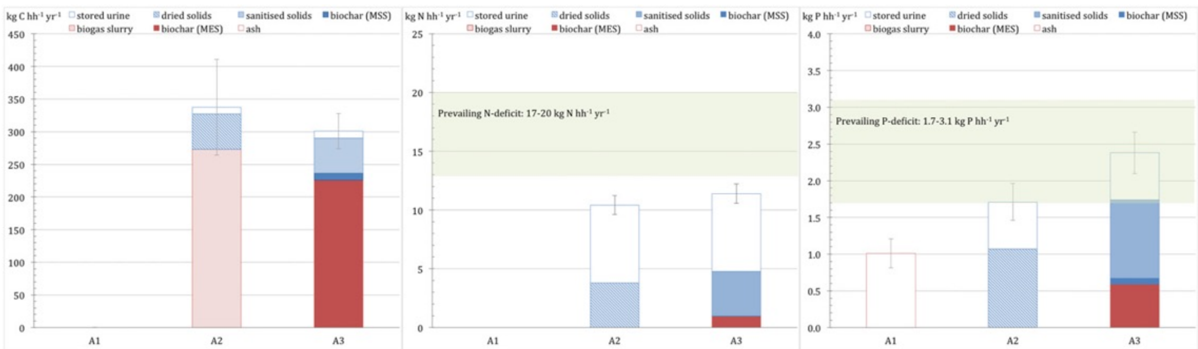

Fig. 8. Integrated recycling potential of C (Fig. 8a; left), N (Fig. 8b; centre), and P (Fig. 8c; right) in kg of the respective element per household and year. The green boxes in b and c indicate the average nutrient deficit on the farm land calculated from the estimated per hectare deficits in SSA and TZ provided by Stoorvogel et al. (1993) and Baijukya and de Steenhuijsen Piters (1998) and for 0.6 ha arable land per household (Tanzania, 2012).

(i.e. E6 and S2); and (A3) represents a technology change towards using a sawdust gasifier for cooking, and a UDDT with subsequent thermal sanitation of faeces (i.e. E4 and S3). The integrated recovery potential is then compared to soil nutrient deficits that generally exist in TZ, as shown by Baijukya and de Steenhuijsen Piters (1998) and Stoorvogel et al. (1993). Soil nutrient balancing (SNB) in Baijukya et al. refers specifically to banana-based *shamba* homegardens in Karagwe. Biogas slurry cannot contribute to the net recycling of nutrients in this scenario, because (as already discussed in 3.1.2), the fermentation substrates have formerly been used in the *shamba*, and are thus already included in the SNB of Baijukya et al. Scenario A2 was, therefore, affected in that potential for recovery of N and P from biogas slurry was *ex*cluded from the integrated recycling potential. However, we included the recovery of C because previous studies (*ibid.*) did not yet discuss the potential for reproducing SOM for Karagwe.

To sum up, utilizing residues from the MES and MSS can contribute considerably to offset soil nutrient deficits of N (Fig. 8b) and P (Fig. 8c) in Karagwe. Whilst no N can be recycled from either the MES or the MSS with current technologies, in scenarios A2 and A3, recycled N meets the medially required quantities of this macronutrient by approximately 60%. Local P demand is covered by around 40% with current technologies and practices, which can be significantly improved to nearly 100% and around 70% in scenarios A3 and A2, respectively. Overall, the contribution of residues from the MES is marginal; only biochar from microgasifiers add to the total recycling of P. The MSS contributes 100% and approximately 75% of recovered P in scenarios A2 and A3, respectively. Households potentially recover comparable quantities of C per year in both scenarios A2 and A3, whilst no C is captured in scenario A1 (Fig. 8a). The MES thereby contributes 75 to 80% of total C recovery from the household in scenarios A2/A3. Capacity to restore SOM also depends on the form in which C is recovered. Compost and biogas slurry typically provide about 50% and 25% respectively of total organic C content for reproducing SOM (KTBL, 2009). The net recovery of C in A2 or A3 corresponds, therefore, to a SOM reproduction potential of approximately 100 or 150 kg SOM-C hh^{-1} $year^{-1}$, respectively. In practice, this means that the estimated potentials in A2 and A3 are theoretically sufficient for cultivating maize on 0.1–0.15 and 0.15–0.2 ha hh^{-1} $year^{-1}$, respectively (with maize consuming 700–1000 kg SOM-C ha^{-1} (KTBL, 2009)). In addition, the C input in scenario A3, in which biochar accounts for around 80% of recovered C, is probably adequate for sequestering C (i.e. long-term storage of CO_2 in the form of SOM in order to mitigate global warming (Demessie et al., 2016)). Biochar has been propagated due to its relatively recalcitrant organic compounds (cf. Lehmann and Joseph, 2015). Under the present circumstances in Karagwe, local soils further promote C sequestration. Soils of volcanic origin, such as the Andosol found in Karagwe, have excellent abilities to accumulate organic carbon (Chesworth, 2008). During this process, soil protects organic matter from degradation by forming either metal-humus (i.e. often Al-Fe) or allophane-organo complexes (Abera and Wolde-Meskel, 2013; Zakharova et al., 2015).

3.4. Discussion of the methodology

Applying MFA in the given context and with our defined research interests was logical and reasonable because MFA aims at producing a structured analysis of certain substances flowing in an arbitrary complex system. Overall, the MFA-framework supported our work (i) to incorporate private households and waste management in the system analysis, and (ii) to compute an analysis that incorporated uncertainties. However, initially, we were faced with the limited availability of data to study *locally available* technologies, and thereby assess their application to smallholder farming systems in rural TZ. We aggregated data from various sources to determine flows and stocks, including interdisciplinary data from both the scientific and practitioner's sphere. We integrated approaches such as: (i) measuring, which was time and cost intensive, but provided specific data for Karagwe; (ii) using existing data and information, which provided sound estimations of real life; and (iii) calculating flows. Hence, as already emphasized by Brunner and Rechberger (2004), MFA is an appropriate method in the context of data uncertainty, and thus also in the context of resource-oriented technology assessment in rural areas of SSA. Finally, our study has a strong interdisciplinary character, which we consider valuable.

Despite these obvious strengths, during the course of our research, we identified certain limitations in the applied methodology as outlined above: With respect to the design of MES-analysis, we acknowledge that by assuming that households would use exclusively either one or the other option for cooking, we simplified real-life cooking behaviour for the purposes of our model. Field investigations by Grimsby et al. (2016) have shown that farming households in rural TZ tend to use a variety of different fuel sources, as well as different stoves. The versatile three-stone fire is also usually included in all domestic energy mixes (*ibid.*). To describe this cooking pattern, Masera et al. (2000) introduced the 'multiple fuel' model. It would, however, have been too complex to model the variety of different fuel-stove combinations that are actually found in farming households. We argue, despite this simplification, that our work still delivers appropriate estimations of resource consumption and sheds light on the practical potentials of different stove types for resource recovery and environmental protection. The results of the present study can also, of course, be transferred into a multiple fuel model in future research. Illustrating the results in a flow diagram was an expected benefit of STAN, which, however, did not come to pass, as the MFA we conducted resulted in too many different flow diagrams to display.

We included the CO_2 emissions in the GWP of MES alternatives, even though emissions of this GHG originate in renewable biomasses. In accordance with Gómez et al. (2006), we included GHG emissions from bioenergy in order to compare various technologies in terms of possible reductions or increases in GHG emissions. Christensen et al. (2009) also found it feasible to assess CO_2 emissions from biomasses into the atmosphere. In addition, sequestered C could have been subtracted from total GWP according to the Kyoto Protocol. However, C sequestration rates of local soils are, to the best of our knowledge, largely unknown. For this reason, it would have entered the realms of speculation to go beyond our current discussion around the potential to restore SOM (Section 3.3). According to Christensen et al. it is valid to exclude C-sequestration in GWP accounting *if* biogenic CO_2 emissions are included in the assessment, as they were in our model.

Finally, an integrated assessment allowed us to show how certain analysed technologies fit together in terms of providing resources for their subsequent use in agriculture, which constitutes an important added value (or potential productive use) for smallholders. However, we recognize that, apart from certain practices targeted in the present study (e.g. potentially reducing the use of firewood, avoiding emissions to the ecosystem, etc.), all these technologies come with an associated price tag. The inclusion of a socio-economic assessment into the impact of these costs would have gone beyond the scope of this paper. The results of this study, which focus on the household level, may therefore serve as a starting point for further studies, such as a multi-criteria analysis ('sustainability assessment') or an up-scaling of the analysis from the micro- to the meso-perspective (i.e. community or district level).

4. Conclusions

By adopting an integrated perspective on cooking and sanitation in smallholder households in TZ, the following conclusions with respect to the research objectives can be drawn:

- ICSs and the biogas system reduce the demand of firewood in smallholder households. The resulting reduced resource consumption can consequently ease pressure on local forest resources.
- Capturing residues from sanitation systems contributes to the recycling of nutrients, whilst recycling of residues from energy systems facilitate the recovery of C.

- Environmental emissions greatly increase when households switch from using three-stone fires and pit latrines, to using a biogas digester and a septic system.
- Overall, bioenergy technologies contribute to the total GWP from households, whilst sanitation systems entail the risk for eutrophication of aquifers.

When considering the analysed technologies from an agro-ecological point of view, we emphasise that:

- Despite ample content of nutrients in biogas slurry, these material flows should not be considered as an 'untapped resource' for the agroecosystem in all cases. In our case study, both input materials for the biogas fermentation had previously been used as fertilizer input in the banana-based homegardens.
- Irrespective of the above, an important precondition for using biogas slurry efficiently (i.e. with an adequate N recovery rate) and in an environmentally friendly way (i.e. with as low a GWP as possible) is to reduce N emissions during slurry storage and possible subsequent treatments.
- Adopting EcoSan increases the recovery of P, which is particularly useful in the case of Karagwe. Through utilizing human excreta in agriculture, which had hitherto been an 'untapped resource,' prevailing P deficits can be mitigated. Moreover, specific challenges of the region are addressed, such as the strong P absorption characteristics of the local Andosol, and the scarcity of plant-available soil P.
- Implementing the use of ICSs provides significant quantities of biochar, and, therefore, introduces a substantial potential to recover C. Used as a compost additive, biochar contributes to C-sequestration.

Overall, our findings clearly show that using a microgasifier for cooking and EcoSan-facilities for sanitation is the most appropriate option to simultaneously optimise resource consumption, reduce environmental impacts, and maximise recycling-based soil management in smallholder farming systems in Karagwe. We conclude that examining the triple nexus of Energy-Sanitation-Agriculture as an approach to a sustainable community development is superior to either of the double nexuses of energy-agriculture or sanitation-agriculture.

Finally, human beings, their attitudes, behaviour, daily routines, and willingness to contribute to, and to be engaged in, these processes often set the agenda for steering and directing material flows. In the present study, we demonstrated that certain material flows are affected by human behaviour. For example, the potential to recover biochar from microgasifiers depends on usage patterns of the stove; nutrient recovery potential from EcoSan hinges on the extent to which the UDDT toilet is actually used. In the case of the former scenario, we recommend removing biochar directly after cooking, and extinguishing hot residues with sand, water, or some other means of depriving it of oxygen. These measures stop further thermo-chemical reactions, emissions, and the loss of mass. Methodologically, taking the diverse behaviours of human subjects and their preferences into consideration is often limited in studies analysing biomass potentials. Hence, we conclude that the 'human factor' needs to be integrated into studies on biomass dynamics. Stochastic methods and statistical models could be applied to reproduce this distinctive 'human fuzziness.'

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Abbreviations

A	Abbreviation part of the analysed scenarios indicating the integrated use in agriculture
AES	Agroecosystem
BiogaST	Project "Biogas Support for Tanzania"
C	Carbon
CAMARTEC	Centre for Agricultural Mechanisation and Rural Technology
CaSa	Project "Carbonization and Sanitation"
CHEMA	Programme for Community Habitat Environmental Management (project partner)
DM	Dry matter
E	Abbreviation part of the analysed technologies indicating the energy alternatives
EcoSan	Ecological sanitation
EfCoiTa	Project "Efficient Cooking in Tanzania"
EP	Eutrophication potential
FM	Fresh matter
GHG	Greenhouse gas
GWP	Global warming potential
hh	Household
ICS	Improved cooking stoves
$\dot{m}$	Material flow
MAVUNO	Swahili for "harvest", name of a farmers' organization (project partner)
MES	Micro energy system
MFA	Material flow analysis
MSS	Micro sanitation system
N	Nitrogen
P	Phosphorus
PM	Particulate matter
RU	Relative uncertainty
S	Abbreviation part of the analysed technologies indicating the sanitation alternatives
SOM	Soil organic matter
SNB	Soil nutrient balancing
SSA	Sub-Saharan Africa
STAN	subSTance flow Analysis
TNMHC	Total non-methane hydrocarbons
TU	Technische Universität
TZ	Tanzania
UDDT	Urine-diverting dry toilets
WBT	Water boiling test

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.cbpc.2016.10.005. These data include the Google map of the important areas described in this article.

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Chapter 5

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Article

Recycling Improves Soil Fertility Management in Smallholdings in Tanzania

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Abstract: Residues from bioenergy and ecological sanitation (EcoSan) can be utilized to sustain soil fertility and productivity. With regard to certain cooking and sanitation technologies used in smallholder households (hh), we systematically analyzed how utilization of the respective potentials to recover residues for farming affects (i) soil nutrient balances, (ii) the potential for subsistence production of composts, and (iii) environmental emissions. On the example of an intercropping farming system in Karagwe, Tanzania, we studied specific farming practices including (1) current practices of using standard compost only; (2) a combination of using biogas slurry, urine, and standard compost; (3) a combination of using so-called "CaSa-compost" (containing biochar and sanitized human excreta, Project "Carbonization and Sanitation"), urine, and standard compost. The system analysis combines a soil nutrient balance (SNB) with material flow analysis (MFA). Currently, nitrogen (N) and phosphorus (P) are depleted by -54 ± 3 and -8 ± 1 kg·ha^{-1}·year^{-1}, respectively. Our analysis shows, however, a clear potential to reduce depletion rates of N, and to reverse the SNB of P, to bring about a positive outcome. Composts and biogas slurry supply sufficient P to crops, while urine effectively supplements N. By using resources recovered from cooking and sanitation, sufficient compost for subsistence farming may be produced. Human excreta contribute especially to total N and total P in CaSa-compost, whilst biochar recovered from cooking with microgasifier stoves adds to total carbon (C) and total P. We conclude that the combined recycling of household residues from cooking and from sanitation, and CaSa-compost in particular, is especially suitable for sustainable soil management, as it mitigates existing P-deficiency and soil acidity, and also restores soil organic matter.

Keywords: integrated plant nutrient management; counteracting soil nutrient depletion; biochar; biogas slurry; carbon recovery; ecological sanitation; vegan organic farming

1. Introduction

1.1. The Challenge of Closing the Loop

Managing soil appropriately requires replacing those nutrients which have been taken from the soil during cultivation [1]. The International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) sees "Agriculture at a crossroads", and calls for focusing on efficient, small-scale agroecosystems with material cycles that are as closed as practicably possible [2]. Agroecology, nutrient recycling within the agroecosystem, and the use of locally available resources represent, therefore, agreed prerequisites for soil conservation and amelioration, and also, as a consequence, for long-term food production [3–9]. As a holistic farming approach to jointly manage soil, nutrients, water, crops, and vegetation in the context of sub-Saharan Africa (SSA), the IAASTD and the Food and Agricultural Organisation of the United Nations (FAO) further promote *integrated plant nutrient management* (IPNM) [10,11]. When tailored to a particular cropping system, IPNM aims to provide a solution to the triple challenge of (i) sustaining soil fertility, (ii) improving land productivity, and (iii) reducing environmental degradation [11].

Applied IPNM combines the use of organic inputs, such compost, farmyard manure, mulch, etc., with mineral inputs, such as synthetic fertilizers, alongside practices including intercropping, agroforestry, liming, low-tillage, crop rotation, etc. [12]. Composting is a widespread and common method, whereby various organic residues, mixed with mineral components, are aerobically and biochemically decomposed by macro- and microorganisms. The composting process, e.g., [13–15], as well as the combined use of compost with inorganic nutrient sources, cf. [16], has been well studied in the context of SSA. Regular input of organic matter to agricultural soils is needed to restore soil organic matter (SOM) and maintain soil humus. Pursuant to [17], however, *on-farm* availability of organic matter is often restricted in the case of many farmers in SSA, due to poor land productivity. As a consequence, SSA has been identified as a hotspot for the depletion of SOM [18]. Moreover, existing organic materials tend to be characterized by comparatively low contents of phosphorus (P) [19]. Pig and poultry manure, which constitute a possible P-rich resource, however, are not sufficiently available, especially to structurally poor farming households [20]. For these reasons, a lack of P is a very common factor in limiting plant growth in SSA [17]. Consequently, many smallholders face being locked into a vicious circle of low soil P, resulting in low production of food crops, and then a limited supply of organic material for soil fertility management [17].

1.2. Monitoring and Assessing Soil Fertility Management Practices

To effectively enhance soil fertility, the FAO recommends the development of IPNM approaches alongside the identification of existing soil nutrient balances [21,22]. The concept of *soil nutrient balance* (SNB) was introduced by [23], in order to analyze and monitor changes in soil fertility, particularly in SSA. The methodology aims at measuring, calculating, and balancing various input and output flows of nutrients to and from agricultural land.

For the wider Lake Victoria region (East Africa), however, existing annual rates of soil nutrient mining and replenishing remain mostly unknown [24]. As an exception, [25] identified existing annual nutrient depletion rates on arable land in Eastern Uganda with 33 $kg \cdot ha^{-1} \cdot year^{-1}$ and 6 $kg \cdot ha^{-1} \cdot year^{-1}$ for nitrogen (N) and P, respectively. For Tanzania (TZ), estimated average annual losses of N and P range from 20 to 40 $kg \cdot ha^{-1} \cdot year^{-1}$, and 3.5 to 6.6 $kg \cdot ha^{-1} \cdot year^{-1}$, respectively [26]. Furthermore, [27] estimated SNBs for N and P of banana-based farming in Northwest TZ as ranging from −30 to +11 $kg \cdot ha^{-1} \cdot year^{-1}$, and −3 to +9 $kg \cdot ha^{-1} \cdot year^{-1}$, respectively. According to [27], nutrients are increasingly exported out of farmland in the region, since the market economy has intensified sales and trading of food products, and since the use of pit latrines has increased, which act as sinks for nutrients. The most significant nutrient inputs to home gardens derive from imports of fodder grasses from off-farm grassland, or bought bananas and brewing grasses, respectively [17]. The worst depletion rates were, therefore, identified for structurally poor households without livestock. As a countermeasure, [27] recommend the rigorous recycling of all household refuse, including human excreta, alongside an increased application of composting.

1.3. Intersectional Resource Management for Subsistence Fertilizer Production

Hence, the recovery of resources from the farming household could effectively promote *on-farm* nutrient cycling. Especially the use of residues from cooking with bioenergy and from ecological sanitation (EcoSan) provides a viable option to increase subsistence production of soil amenders for IPNM. Residues available after cooking depend on the technology applied, and include (i) ash from three-stone fires, charcoal stoves, or rocket stoves; (ii) biochar from microgasifier stoves; or (iii) biogas slurry from anaerobic fermentation of organic wastes to produce biogas. The latter is particularly rich in nutrients, and is well known for its suitability as a fertilizer for organic farming [28]. The term "biochar" refers specifically to carbonised organic matter—i.e., (powdery) charcoal with significant carbon (C) content—that is used for soil amelioration [29,30]. Biochar has attracted significant interest from scientists and practitioners within the last decade, largely due to the findings of Terra Preta, an Anthrosol in the Amazon basin with exceptional soil fertility [31,32]. Using biochar as a compost additive is the most promising approach for maximising the positive effects of biochar applications, as demonstrated by [33].

Residues available from EcoSan facilities include urine and faeces that can be collected separately in a *urine-diverting dry toilet* (UDDT). In order to prevent the transmission of disease, additional treatment of human excreta is vital in order to inactivate pathogens [34,35]. Treatment should be carried out at as early a stage as possible during the process [36]. Urine must simply be stored for a period of at least two months after collection in the UDDT [36,37]. After this period, stored urine is a fast-acting and rapidly available N-fertilizer [38]. Urine is often diluted with water in a ratio of from 1:3, to up to 1:5 parts urine to water, in order to avoid over-application and to reduce odour [38]. For balancing nutrient doses, urine should be complemented with either mineral P and potassium (K) additives, or an organic amendment, such as compost. Sanitation of human faeces is possible by different means [36,39]. In this study, we focus on *thermal sanitation* of faeces, which is based on an appropriate combination of time and temperature [40]. As an example, *pasteurization* can take place at temperatures between 65 to 75 °C, over periods ranging from 30 to 120 min. Here, pasteurization is realized *before* composting and takes place in a loam oven, whereby a microgasifier stove provides the heat required [39]. The use of a microgasifier means that additional biochar is potentially available as an output of this sanitation process [41]. For the subsequent composting, it is recommended to mix human faces with other organic residues, such as kitchen wastes, harvest residues, ashes, or biochar [42]. This mixing of various types of waste aims to create a well-balanced content of C and other nutrients, as well as of dry and wet matter, which in turn sustains a well-functioning composting process [43].

Studies observing plant response to biogas slurry, e.g., [28,44–47] or (composted) biochar e.g., [33,48–55], have often revealed positive results in terms of stimulated crop productivity. Furthermore, co-composting of source-separated human faeces has also been empirically studied, cf. [34,35,38,56]. In the SSA context, however, plant responses to applications of biogas slurry, e.g., [57], biochar, e.g., [58], human urine e.g., [59] *or* faeces e.g., [37,60] have, to date, only rarely been studied. Nevertheless, existing scientific studies can be used to extrapolate overall improved soil properties and stimulated biomass growth with, for example, increasing maize grains yields to 200–400%, compared to plants grown on unamended soil. This given, we reason that studies observing *the combined use* of household residues, such as biogas slurry, urine, and co-composted biochar and human faeces, are of a strong interest for contemporary scientific studies.

1.4. Research Objectives and Questions

To the best of our knowledge, analytical studies focusing on IPNM potentials around the *nexus energy–sanitation–agriculture*, and based on SNB, have not yet been scientifically targeted for smallholder systems in SSA in general, or in East Africa in particular. Moreover, the SNB has, to date, in the vast majority of studies, been applied for *ex-post* analyses of *existing* depletion or replenishment of soil nutrients. Nonetheless, SNB could also be used as analytical *ex-ante* evaluation or assessment method, considering potential effects of technology-related changes in farming systems on soil fertility.

Against this background, it is the objective of the present work to develop a model that enables an *ex-ante* assessment of integrating residues from cooking and EcoSan into soil fertility management in the context of smallholder farming in SSA. In prior studies focusing on a household level, we already introduced [39], demonstrated [61], and analyzed, in detail, the recycling potentials of an *intersectional resource management* for the example of smallholdings in Karagwe, TZ [41]. In the present work focusing on a farm level, we systematically compare specific approaches to recover residues as resources for IPNM, such as biogas slurry, urine, or co-composted human faeces, and biochar. Therefore, the following research question has been formulated: How do identified modifications in the farming system (i.e., technology use and residue recovery) affect (i) soil nutrient balances; (ii) availability of resources for subsistence production of compost; and (iii) environmental emissions assessed with global warming potential (GWP) and eutrophication potential (EP)? In addition, we estimate the potential for counteracting existing soil degradation, and sustain soil fertility and food production through recycling of nutrient and restoration of SOM.

2. Materials and Methods

In this section, we firstly introduce the study area (Section 2.1) and the research methodologies (Section 2.2). Then, we describe how we define the system analyzed (Section 2.3), and the tailored modelling approach (Section 2.4). The appendix of the present article presents further details of (i) those IPNM alternatives analyzed, including descriptions and pictures of the substrates in question (Supplementary 1); (ii) the modelling, including equations and assumptions made regarding to specific metabolisms and processes; and (iii) a summary of all data collected (Supplementary 5). Further information on the study area, the case study projects, and the technologies studied is presented in [39,41], and in the supplements to this article.

2.1. Study Area & Case Studies

The study area of this work is Karagwe, one of eight districts in Kagera region, Northwest TZ, part of the Lake Victoria basin, and located near to the volcanic areas of the East African Rift zone (lat 01°33′ S; long. 31°07′ E; alt. 1500–1600 m.a.s.l.). Rainfall is bi-modal (March to May and October to November), and varies between 500 and 2000 mm year^{-1}; the mean temperature ranges from 20 to 28 °C [50]. Hence, local climate conditions allow harvesting twice a year for most annual crops. Households in Karagwe consist, on average, of six people, including adults and children [62].

The regional economy is dominated by smallholder agriculture, and about 90% of households sell agricultural products grown on their farms [17]. Banana is the most prominent perennial crop and staple food in Kagera, while beans and maize dominate annual cropping; Karagwe is also an important producer of onions and cabbage within Kagera (cf. Supplementary Table S1). Approximately 40% of agricultural land in Karagwe is occupied by banana-based home gardens surrounding farmers' houses [17], named *shamba* in Swahili (Supplementary Figure S1). The *shamba* (Supplementary 6) is a mixed cultivation system of perennial crops such as bananas, coffee, etc., annual crops such as beans, cassava, etc., and fruit trees including mango, orange, etc. [27]. Fields used for intercropping of annual crops are called *msiri* in Swahili [27] (Supplementary Figure S2) and cover approximately 20% of the planted land in Karagwe [62]. Other types of land use comprise mono-cropping of annual crops, tree planting, fallow land, and animal husbandry. Cattle are kept by one sixth of the households, mostly in herds of less than five animals [17].

As for many smallholders in SSA, farmers in Karagwe are challenged by soil constraints including nutrient deficiencies and soil acidity with pH < 4.0 [39]. (In addition, unusual rainfall patterns indicate the approaching effects of climate change, and increasingly threaten the predominantly rain-fed agriculture in Karagwe). Andosols, the predominant soil type in Karagwe [61], typically suffer from P deficiency [17], as P retention potential is relatively high [63]. Crop productivity and sustainable land use therefore requires constant replenishment of P. Unbalanced inputs of N with organic and/or mineral fertilizers and uptake of N by crops often contribute to the problem [64,65]. As an initiative towards soil improvement, and as a countermeasure against deforestation, two Karagwe farmer's organisations recently initiated a set of projects that deal with the development of "sustainable" cooking (cf. Supplementary Table S2) and sanitation technologies (cf. Supplementary Table S3), as well as with the promotion of the use of residues in agriculture [39]. The three projects and respective technologies act as case studies for our work. Assessing the use of residues for IPNM and potential effects on local SNBs are subjects of the present system analysis.

2.2. Research Methods: MFA & SNB

In order to answer our research questions, we applied SNB methodology in combination with *material flow analysis* (MFA). This paragraph introduces the conceptual background of these two methods, with fundamental terms given in *italics*.

According to the definition of the MFA [66,67], a *system* is a group of interacting *processes* that cause either a chemical or a physical transformation, transportation, or storage of materials. A *material flow* ($\dot{m}$) is a mass flow of a good (economic entity) or substance (chemical element or compound) per unit of time (e.g., kg·year^{-1}). The systems in question are generally *open systems*, as $\dot{m}$ are exchanged between the *anthroposphere* and the *ecosystem*. Material *stocks* describe the accumulation, storage, or depletion of materials within the *anthroposphere*. Likewise, following the SNB, one calculates and then balances five *input flows* (IN) and five *output flows* (OUT) to and from agricultural land [23]. Both methods follow the same mathematical law, known as "the principle of mass conservation" (Equation (1)), and assume a linear function between $\dot{m}_{IN}$ and $\dot{m}_{OUT}$, to simplify calculations.

$$\sum_{i=1}^{k} \dot{m}_{IN,\,i} = \sum_{j=1}^{l} \dot{m}_{OUT,\,j} \pm \dot{m}_{stock} \qquad (1)$$

where $\sum_{i=1}^{k} \dot{m}_{IN,\,i}$ and $\sum_{j=1}^{l} \dot{m}_{OUT,\,j}$ are the total mass of k input and j output material flows and $\dot{m}_{stock}$ causes $\pm\Delta$ stock.

To effectively support local soil fertility interventions, [68] emphasize downscaling SNB to site-specific balances, and recommend focusing on a specific cropping system. When applying SNB to the farm level, [69] further suggest splitting the analysis into a *natural balance* (NB) and a *partial balance* (PB). The NB comprises all inputs and emissions from and to the environment. The PB reflects the "way of farming", and solely consists of organic and mineral fertilizer inputs and nutrient removals through food products and crop residues. The combination of the NB and the PB results in the *full SNB*.

A negative result of the SNB indicates nutrient depletion and declining soil fertility. A positive net balance can be interpreted positively, for example, when P in surplus replenishes P-stocks in P-deficient soils, or negatively, when, for example, heavy metals accumulate in the soil. Apart from specific cases in which soils are deficient in certain essential nutrients, it is most preferable that IN and OUT are balanced.

2.3. Systems Defined & Scenarios Studied

For our analyses, we divided the *anthroposphere* of an integrated farming system into (i) the farming household, and (ii) the agro-ecosystem (AES) (Figure 1). The former consists of the micro energy system for cooking (MES) and the micro sanitation system (MSS) (referring to a *micro*-perspective, respectively a focus on smallholder *households*). Both are systematically studied in [41] by comparing selected technologies, that are available to smallholders in Karagwe (cf. Supplementary Tables S2 and S3), with respect to relevant material flows. The latter represents the farmland, composting, and the disposal of residues through burning. Composting constitutes the central process linking smallholder households to farmland. In our model, we consider two ways of composting: (i) Karagwe-standard composting (Figure 2a), and (ii) CaSa-composting (Figure 2b) (cf. Supplementary 2.6). The composition of Karagwe-standard compost follows local practices [39]. The so-called "CaSa-compost" is based on the approach of the local project "*Carbonization and Sanitation*" (CaSa) to jointly exploit biochar, stored urine, sanitized faeces, and harvest and kitchen residues.

The *functional unit* of the system analysis is "to cultivate nutritious and market relevant annual food crops for subsistence farming on a total of 0.125 ha of *msiri*-land (*spatial system boundary*), over one year with two cropping seasons (*temporal system boundary*)". The crops chosen include maize as a staple food, beans as a source of protein, and onion and cabbage as vegetables. These crops are inter-cropped following local practices. *Indicator elements* of the analysis are C, and the macronutrients

N and P. The atmosphere, the pedosphere, and the hydrosphere are all located outside the spatial system boundaries.

To identify the contribution of residues from cooking and sanitation to managing soil fertility on the farmland, two scenarios are compared: (i) the most common current practices for smallholder farming in Karagwe, and (ii) alternative farming practices based on IPNM, utilizing resources captured from different technologies that are potentially used for cooking and sanitation (Table 1). In total, the analysis comprises five alternatives for *msiri* cultivation (AM) that mainly differ from one another in respect to their organic and mineral IN to maize and beans: when compared to the current state of affairs (AM1), the further scenarios represent a shift of technologies used in the household towards either using a biogas system for cooking and a UDDT for sanitation (AM2), or using a microgasifier for cooking and as sanitation system a combination of the UDDT with thermal treatment of faeces on a loam oven, following the approach of the CaSa-project (AM3–5). In AM2, we only considered the use of urine as mineral IN; not the use of faeces. We reason that in the case of simply using a UDDT, faeces are not thermally sanitized and thus not "safe" to be used in crop production. In accordance with *omushote* practice, faeces could rather be used in the *shamba*, which is, however, out of the scope of the present model. (Omushote was a common practice in Karagwe before pit latrines were implemented, and entails adding faecal matter on a rotation basis into the planting holes for trees or cuttings of banana plants [70].) Cabbage and onion receive nutrient inputs through application of standard compost in all scenarios. This is also because application of composts that contain human faeces, such as the CaSa-compost, should, in general, not be used for crops growing *underground* [38]. We further followed [17], who recommended that, in order to restore soil P stocks efficiently, there are two principal types of organic fertilizer application: either (i) seasonal moderate applications (AM1–4), or (ii) a one-off large application that is repeated every three years (AM5). In all alternatives studied, biogas slurry (AM2) and urine (AM2–5) are used with seasonal applications. The annual recovery potentials of biogas slurry, biochar, urine, and sanitized faeces derive from an earlier MFA presented in [41]. Table 2 summarizes the quantities identified to be available annually, as well as the respective C and nutrient contents estimated.

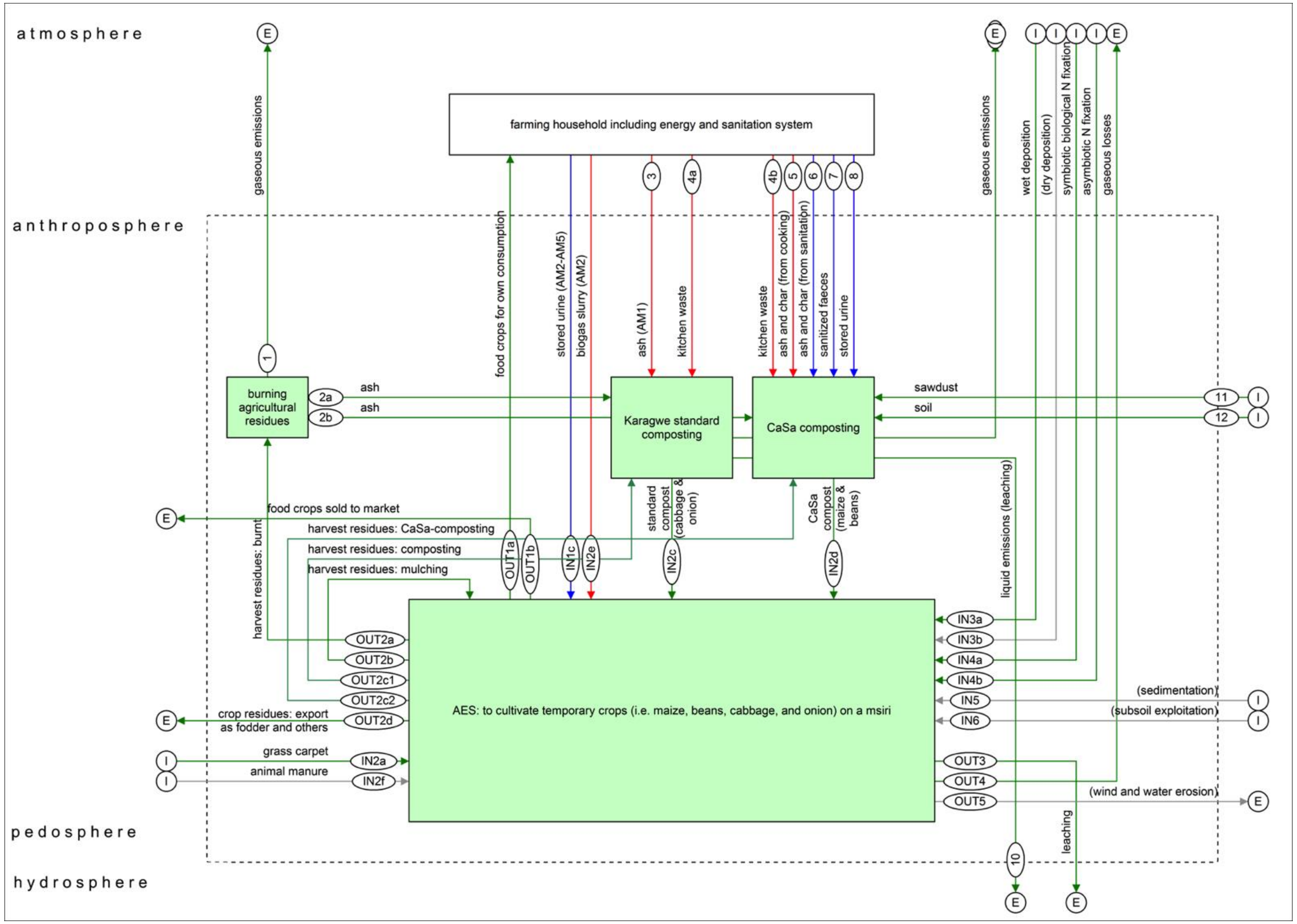
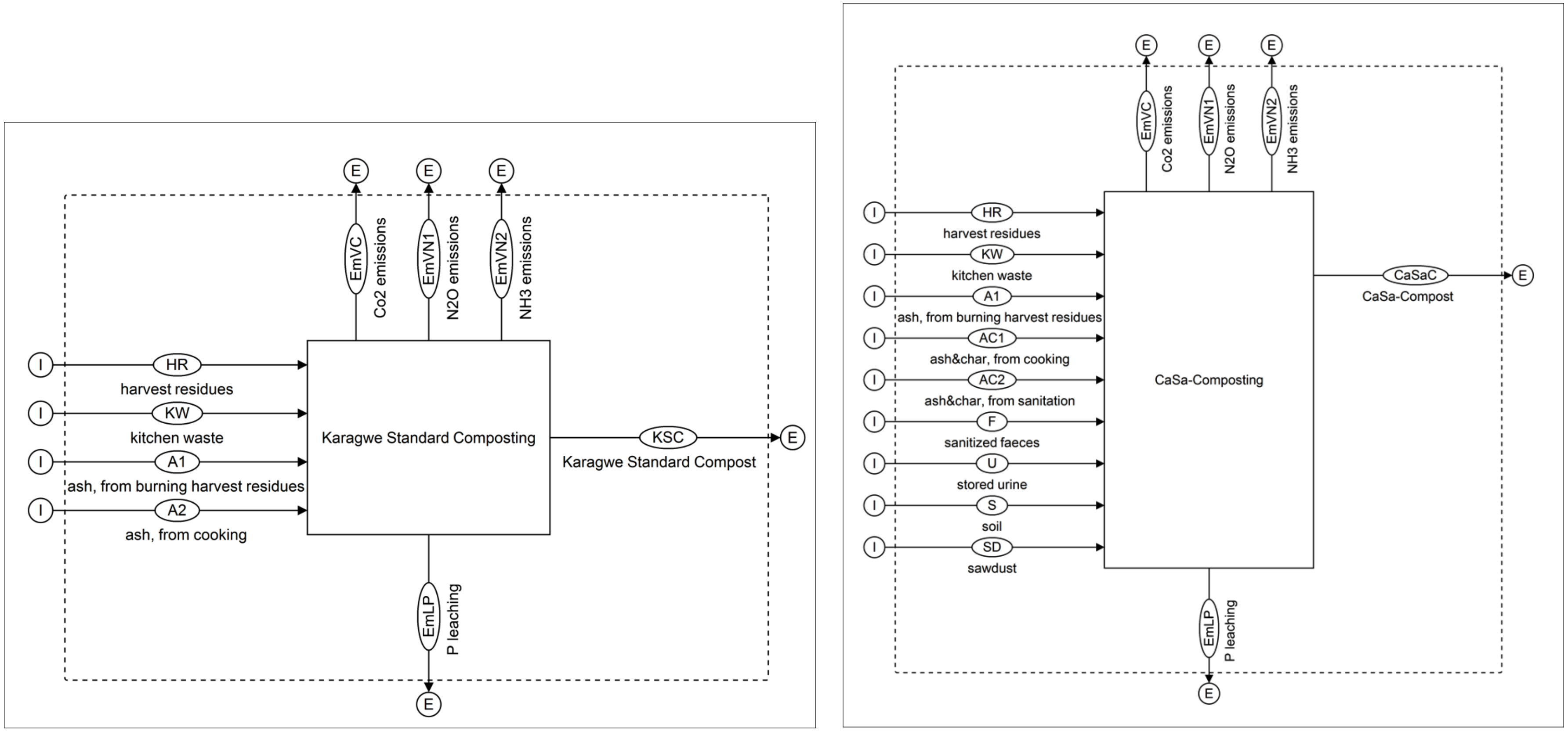


Figure 1. The integrated farming system analyzed comprises the farming household (white) and the agro-ecosystem (AES; green). Processes are indicated with boxes, material flows with arrows; the dotted line represents the system boundaries. Material flows in green were part of the present work; red and blue flows/arrows were part of [41]; grey flows/arrows were not considered in the system analysis. AM: Abbreviation part of the scenarios indicating the agroecosystem of a *msiri*.



(**a**) (**b**)

Figure 2. Flow charts showing in- and output flows of materials considered in modelling Karagwe standard composting (**a**) and CaSa-composting (**b**). Processes are indicated with boxes, material flows with arrows. A: ash; AC: ash and char; CaSaC: CaSa-compost; EmVC: emissions of carbon through volatilization; EmVN: emissions of nitrogen through volatilization; EmLP: emissions of phosphorus through leaching; F: faeces; HR: harvest residues; KSC: Karagwe standard compost; KW: kitchen waste; S: soil; SD: sawdust; U: urine.

Table 1. Alternatives defined to compare different integrated plant nutrient management (IPNM) strategies (AM2–5) to the current practice (AM1) in an intercropping system in Karagwe, TZ.

No.	Organic Input to Maize & Beans	Organic Input to Onion & Cabbage	Mineral Input to all Crops	Cooking Alternative	Sanitation Alternative	Comment
AM1	None	Standard compost (cabbage only)	None	Three-stone fire	Pit latrine	
AM2	Biogas slurry	Standard compost	Urine	Biogas digester & burner	UDDT	
AM3	CaSa-compost	Standard compost	Urine	Microgasifier	UDDT & thermal sanitation	
AM4	CaSa-compost	Standard compost	Urine	Microgasifier	UDDT & thermal sanitation	like AM3, but with lower yield prognosis
AM5	CaSa-compost	Standard compost	Urine	Microgasifier	UDDT & thermal sanitation	like AM3, but with larger application of composts every 3 years

AM: agroecosystem *msiri* (abbreviation used to name the alternatives studied); CaSa-compost: compost prepared according to practices of the project "Carbonization and Sanitation" (CaSa); EcoSan: ecological sanitation; IPNM: integrated plant nutrient management; TZ: Tanzania.

Table 2. Quantities and qualities of the organic, organo-mineral, and mineral inputs used in the IPNM strategies analyzed.

Substrates	Recovery Potential	Subsistence Production	Total C	Total N	Total P
	kg·year^{-1}	kg·year^{-1}	g·kg^{-1} (in FM)	g·kg^{-1} (in FM)	g·kg^{-1} (in FM)
Biogas slurry	14955 ± 4409		15.3 ± 0.3	0.9 ± 0.0	0.3 ± 0.0
Biochar & ash (from cooking)	301 ± 29		751 ± 296	2.9 ± 2.2	1.9 ± 0.8
Biochar & ash (from sanitation)	15 ± 6		694 ± 461	3.1 ± 1.2	5.2 ± 2.7
Stored urine	780 ± 80		7.9 ± 3.2	5.0 ± 1.2	0.5 ± 0.2
Sanitized solids	506 ± 186		106 ± 51	7.5 ± 3.5	2.1 ± 1.0
Standard compost		292 ± 20	60 ± 11	3.5 ± 0.6	0.8 ± 0.1
CaSa-compost		2350 ± 132	78 ± 9	4.0 ± 0.4	2.1 ± 0.2

Note: Data for the recovery potentials of biogas slurry, biochar, stored urine, and sanitized faeces stem from [41]. The potential for subsistence production of Karagwe standard compost and CaSa-compost are estimated in the present study. Values represent the mean percentage calculated for all scenarios. Water contents are 95.6 ± 0.5, 33.6 ± 5.3, and 32.5 ± 1.9 g·kg^{-1} in FM (Fresh matter) of biogas slurry, standard compost, and CaSa-compost, respectively.

2.4. Specific Modelling Approach & Equations Applied

In the present study, we combined SNB with MFA in order to (i) estimate the potential for C recovery available for restoration of SOM; (ii) model the potentials for subsistence production of composts by using household and farming residues; and (iii) assess environmental emissions. The following paragraph describes the manner in which we applied the two methods (cf. Supplementary Figure S3 with plot data in Table S17). The SNB largely follows the basic concepts laid down by [23], with modifications pursuant to [26,68,69,71]. At the outset of this study, we carried out an intensive literature review in order to collect data (cf. Supplementary 5), and to plan and design the system to be analyzed (cf. Supplementary Table S4). In reference to [67], we collected data for determining flows and stocks from various sources, including (i) primary data from case study projects, our own experiments, and previous studies, including household surveys, field tests, laboratory analysis, material flow modelling, etc.; (ii) secondary data, including literature review, statistics from private and public organizations, etc.; and (iii) estimations/judgements of experts. The latter was specifically used if no sufficient data was available or, not available for the specific context. Finally, those IN and OUT that are most relevant and quantifiable to the specific context were selected (Table 3).

Table 3. Selected flows considered in soil nutrient balance.

Input flows of partial balance	
IN1c	Urine
IN2a	Grass carpet
IN2b	Mulching with crop residues
IN2c	Standard compost
IN2d	CaSa-compost
IN2e	Biogas slurry
Input flows of natural balance	
IN3a	Atmospheric deposition
IN4a	Symbiotic BNF
IN4b	Non-symbiotic BNF
Output flows of partial balance	
OUT1a	Food products for self-consumption
OUT1b	Food products sold to market
OUT2	Crop residues
Output flows of natural balance	
OUT3	Leaching
OUT4a	Gaseous losses (from denitrification)

Abbreviations: BNF: biological nitrogen fixation.

Calculations were made through a series of steps (cf. Supplementary 2). The first step was to calculate total biomass production, including crop yields and plant residues, and the respective total nutrient uptake by plants (OUT_{crops}). Grass carpeting and mulching with residues are considered local standard practices, and are therefore included as organic IN into "*PB I without fertilization*" (Equation (2)). It follows, therefore, that PB I reflects the "*net nutrient requirements*" of crops. Application of organic (i.e., Karagwe standard compost and CaSa-compost), organo-mineral (i.e., biogas slurry), and mineral (i.e., urine) fertilizers are considered in "*PB II with organic fertilization*" (Equation (3)), and "*PB III with organic and mineral fertilization*" (Equation (4)), respectively. Organic and mineral INs are quantified based on PB I. As suggested by [17,72], if the ratio of N/P of the crops' nutrient requirement is higher than the N/P ratio found in organic amendments—which is the case in our model (Supplementary Table S26)—then organic matter should be used first to balance the P uptake of crops. In this way, the underlying fertilization approach aims to avoid over-fertilization with P and under-fertilization with N, whilst optimizing P-use efficiency. Mineral fertilizer can also be used to meet crops' N requirements. As part of the NB, *biological nitrogen fixation* (BNF) is estimated from the N uptake determined for beans. Values of other IN and OUT for the NB derive from literature (Supplementary Table S27). Finally, the "*full SNB I with organic fertilization*" (Equation (5)) and "*full SNB II with organic and mineral fertilization*" (Equation (6)) are calculated.

$$\begin{aligned}\mathrm{PBI} &\stackrel{\mathrm{def}}{=} \mathrm{IN}_{carpeting} + \mathrm{IN}_{mulching} - \mathrm{OUT}_{\mathrm{crops}} = \mathrm{IN}_{2a} + \mathrm{IN}_{2b} - \sum(OUT_{1a} + OUT_{1b} + OUT_{2}) \\ &\stackrel{\mathrm{def}}{=} \left|\text{nutrient requirement}_{crops}\right|\end{aligned} \tag{2}$$

$$\mathrm{PB\ II} \stackrel{\mathrm{def}}{=} \mathrm{PB\ I} + \mathrm{IN}_{compost} + \mathrm{IN}_{CaSa\ -compost} + \mathrm{IN}_{biogas\ slurry} = \mathrm{PB\ I} + \mathrm{IN}_{2c} + \mathrm{IN}_{2d} + \mathrm{IN}_{2e} \tag{3}$$

$$\mathrm{PB\ III} \stackrel{\mathrm{def}}{=} \mathrm{PB\ II} + \mathrm{IN}_{urine} = \mathrm{PB\ II} + \mathrm{IN}_{1c} \tag{4}$$

$$\mathrm{SNB\ I} \stackrel{\mathrm{def}}{=} \mathrm{NB} + \mathrm{PB\ II} \tag{5}$$

$$\mathrm{SNB\ II} \stackrel{\mathrm{def}}{=} \mathrm{NB} + \mathrm{PB\ III} \tag{6}$$

where IN is the nutrient input flows, OUT is the nutrient output flows, PB is the partial balance, NB is the natural balance, and SNB is the full soil nutrient balance.

Furthermore, several gaseous and liquid emissions are considered in the analysis (Figure 1), which originate from covering soil with carpeting grasses and mulching material, from applying urine or biogas slurry, from burning agricultural residues, and from composting processes. We assessed the climate-relevant gas emissions with those GWP-factors provided by [73] (Supplementary Table S30). Emissions with eutrophying effects were assessed with EP-equivalence factors suggested by [74,75] (Supplementary 3, Supplementary Table S31).

In aggregating the data, we assumed that all parameters were normally distributed and independent of variables [76]. We also applied *Gauss's law of error propagation* (FAU physics, n.d.) [77]. The resulting *uncertainty of data* is expressed by presenting the statistical variance of the collected data set with its arithmetic mean value ($\overline{x}$), the standard error (Δx), and the relative uncertainty (RU), defined as Δx in % of $\overline{x}$ [67]. Further information on data collected is summarized in Supplementary 4. Data collection, the equation-based model, and all auxiliary calculations were combined in one Excel spreadsheet.

3. Results and Discussion

The following chapter contains (i) a presentation of selected results, checked for plausibility and briefly discussed in relation to relevant factors; (ii) a synthesis of results from a sustainability perspective; and (iii) a brief discussion of the applied methodology.

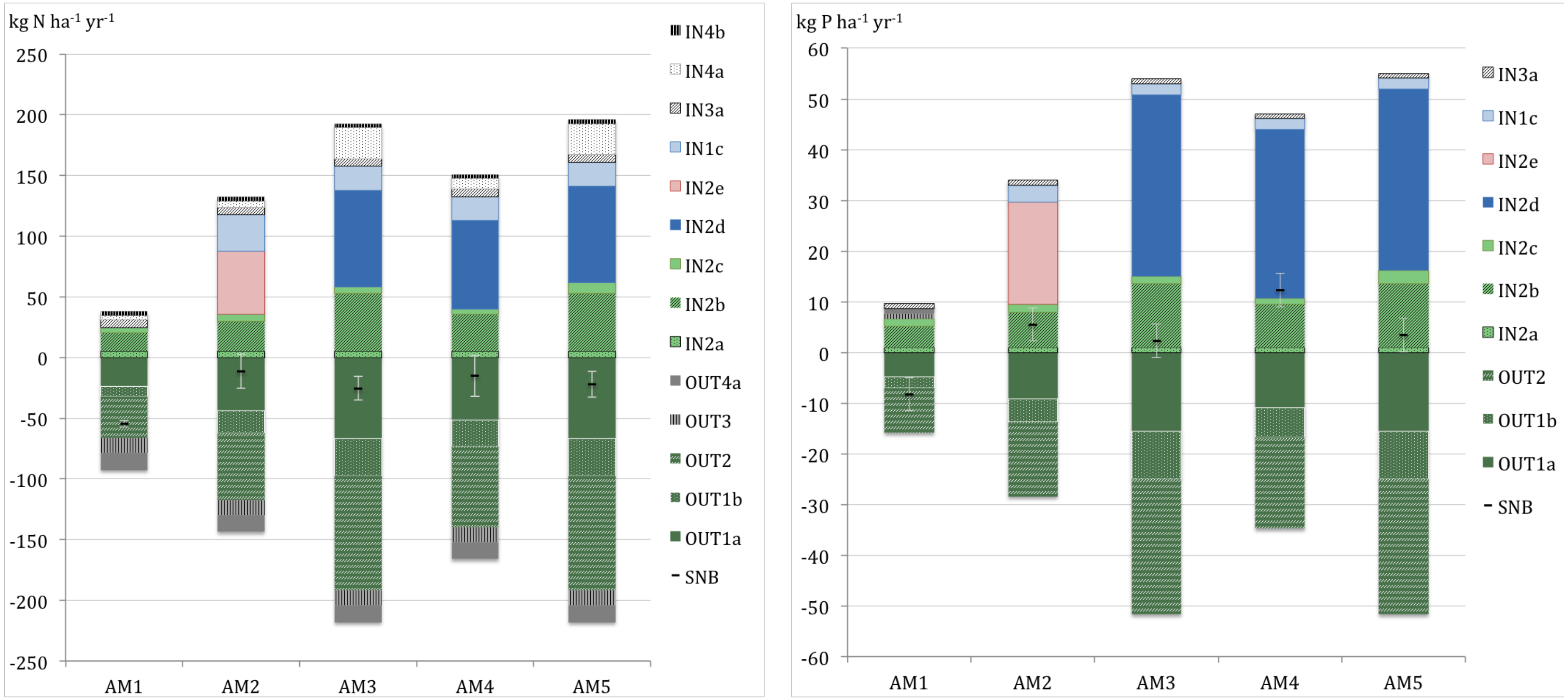
3.1. Soil Nutrient Balances

Currently, the intercropping system analyzed for Karagwe results in nutrient depletion of the soil (Figure 3). This Table 4 refers to the full SNB with organic input and not including (SNB I), but with (SNB II) additional mineral fertilization. The results identified for the SNB II in the current situation reflect the state-of-knowledge on SNBs in the region very well [25–27]. Means of AM1, however, significantly differ from means of AM2–5 for both N and P, as overlapping error bars for the SNB II in Figure 3a,b indicate, respectively [78]. Hence, integrating resources recovered from cooking and sanitation into agriculture has the potential to clearly improve the net SNBs.

Table 4. Results of the SNB for intercropping of annual crops (maize, beans, cabbage and onion), on *msiri* land sized 0.125 ha located in Karagwe, TZ.

	Nutrient Requirement of Crops		**Nutrient Supply with Organic Fertilization**		**Nutrient Supply with Organic and Mineral Fertilization**		**Natural Balance**		**Full SNB with Organic Fertilization**		**Full SNB with Organic and Mineral Fertilization**	
	PB I		**PB II–PB I**		**PB III–PB I**		**NB**		**SNB I**		**SNB II**	
	$Kg{\cdot}ha^{-1}$ $year^{-1}$											
Alternatives	N	P	N	P	N	P	N	P	N	P	N	P
AM1	−46 ± 2	−11 ± 1	4.1 ± 0.1	1.5 ± 0.0	4.1 ± 0.1	1.5 ± 0.0	−13 ± 2	0.9 ± 0.3	−54 ± 3	−8 ± 1	−54 ± 3	−8 ± 1
AM2	−87 ± 3	−20 ± 2	57 ± 7	22 ± 2	88 ± 14	25 ± 4	−11 ± 2	0.9 ± 0.3	−41 ± 10	2 ± 3	−11 ± 14	6 ± 3
AM3	−139 ± 5	−38 ± 3	87 ± 5	38 ± 2	105 ± 9	39 ± 5	9 ± 2	0.9 ± 0.3	−43 ± 10	1 ± 5	−25 ± 10	2 ± 4
AM4	−104 ± 8	−25 ± 4	58 ± 4	25 ± 2	97 ± 18	37 ± 7	−8 ± 5	0.9 ± 0.3	−54 ± 13	1 ± 6	−15 ± 17	12 ± 5
AM5	−139 ± 5	−38 ± 3	88 ± 9	38 ± 5	108 ± 12	41 ± 6	9 ± 2	0.9 ± 0.3	−41 ± 7	1 ± 4	−22 ± 11	3 ± 6

PB: partial balance; NB: natural balance; SNB: soil nutrient balance; TZ: Tanzania. Alternatives AM1–AM5 are defined in Table 1.



(**a**) (**b**)

Figure 3. The estimated SNB II for N (**a**); left) and P (**b**); right) comprises natural input (IN3a, 4a, 4b) and natural output (OUT3, 4a) flows; organic (IN2a-2e) and mineral (IN1c) input flows; and output flows (Out1a, 1b, 2) with agricultural products. Mean values for the estimated SNB II are indicated with black dashes; standard errors of the means with grey error bars. Scenarios are defined in Table 1; the IN and OUT flows are in Table 3. Plot data is provided in Supplementary Table S12.

As shown for the example of Karagwe, IPNM strategies that utilize residues from the farming household can reverse results of net P balance to positive figures, and mitigate, but not completely avoid, depletion rates of N. When compared to the current state (AM1 = 100%), the total N deficit (i.e., referring to SNB II) is only one fifth that of the biogas-scenario (AM2 ≈ 20%), and less than half that of the CaSa-scenarios (AM3–5 ≈ 30–45%). Differences identified between analyzed IPNM alternatives (AM2–5) are, however, not significant, because error bars (Figure 3) do not overlap [78].

Nutrient requirements of crops (PB I) vary according to the yield assumptions for each alternative. They are lowest for the scenario, reflecting the current state of affairs (AM1) and highest for AM3 and AM5. Note that, as yield assumptions are equivalent in AM3 and AM5, we further refer to these alternatives jointly as AM3/5 for results depending on this shared equal parameter.

The balances of organic and mineral INs and OUTs relevant for the PB vary across IPNM alternatives for both N and P (Figure 3). For example, nutrient inputs with mulching (In2b) correspond to the availability of harvest residues (Supplementary Tables S10 and S23), and thus, also to underlying yield assumptions. After carpeting and mulching, the limited use of organic IN (because compost is used only for cabbage) and the exclusion of mineral IN results in a deficient supply of nutrients in the current state. Specifically in AM1, N and P requirements are, in total, compensated by only 10% and 15% of their demand, respectively.

Organic soil amendments, such as biogas slurry, standard compost, and CaSa-compost, completely meet the P demand of crops (i.e., PB II of AM2–5), while N demand of crops is met by 55–65% of requirements. After organic *and* mineral fertilization, the total compensation of P in PB III of AM2–5 is approximately 105% to 145% of requirements. The use of urine ultimately satisfies crop N demand in PB III of AM2 by approximately 100%, while N requirements are only partially compensated in PB III of AM3–5 by 75–95% of requirements. Despite biogas slurry and urine fully balancing N demand of crops in AM2, SNB II for N is negative, due to additional N losses through natural flows. Finally, we emphasize the need to consider the fact that nutrients contained in biogas slurry were previously recycled to banana-based homegardens, together with the feeding material of the biogas digester itself [41]. Thus, when switching to a biogas system and using the slurry for fertilizing crops cultivated on *msiri* fields, compensation or replacement of nutrients in the *shamba* is required to avoid amplifying existing nutrient deficits there [27].

The balance of natural IN and OUT, relevant for the NB for N, differs between the alternatives analyzed, due to varying BNF. In our model, BNF is 12 ± 3 kg·N·ha^{-1}·year^{-1} in AM1, compared to 17 ± 4, 29 ± 7, and 85 ± 17 kg·N·ha^{-1}·year^{-1} in AM2, AM4, and AM3/5, respectively. The BNF estimated for the current state is therefore appropriate, compared to a typical value of approximately 12–16 kg·N·ha^{-1}·year^{-1} for East African farming systems [25–27,68,79,80]. The amount of N fixed by leguminous beans, meanwhile, depends on assumed crop yields. Only in AM3/5, where we assume the highest level of bean productivity, does the NB estimated for N reveal a positive result. A regression analysis comparing results of NB and the BNF of AM1–5 shows that at least 55 kg·N·ha^{-1}·year^{-1} are required in order to reverse the net balance of all natural N flows from a negative to a positive result (Supplementary Figure S5). Given that this BNF value falls between the estimated BNF for scenarios AM4 and AM3/5, we deduce that a seasonal biomass growth of beans of at least 30 ton·ha^{-1} in FM is needed to reach the break-even threshold, where the NB turns from a net negative to a net positive result. This corresponds to a crop yield of about 3.8 ton·ha^{-1} air-dry beans. The NB for P is positive in all scenarios, as its quantification was based on data collected from literature only. This data was equivalent for all alternatives.

3.2. Potential for Subsistence Production of Compost

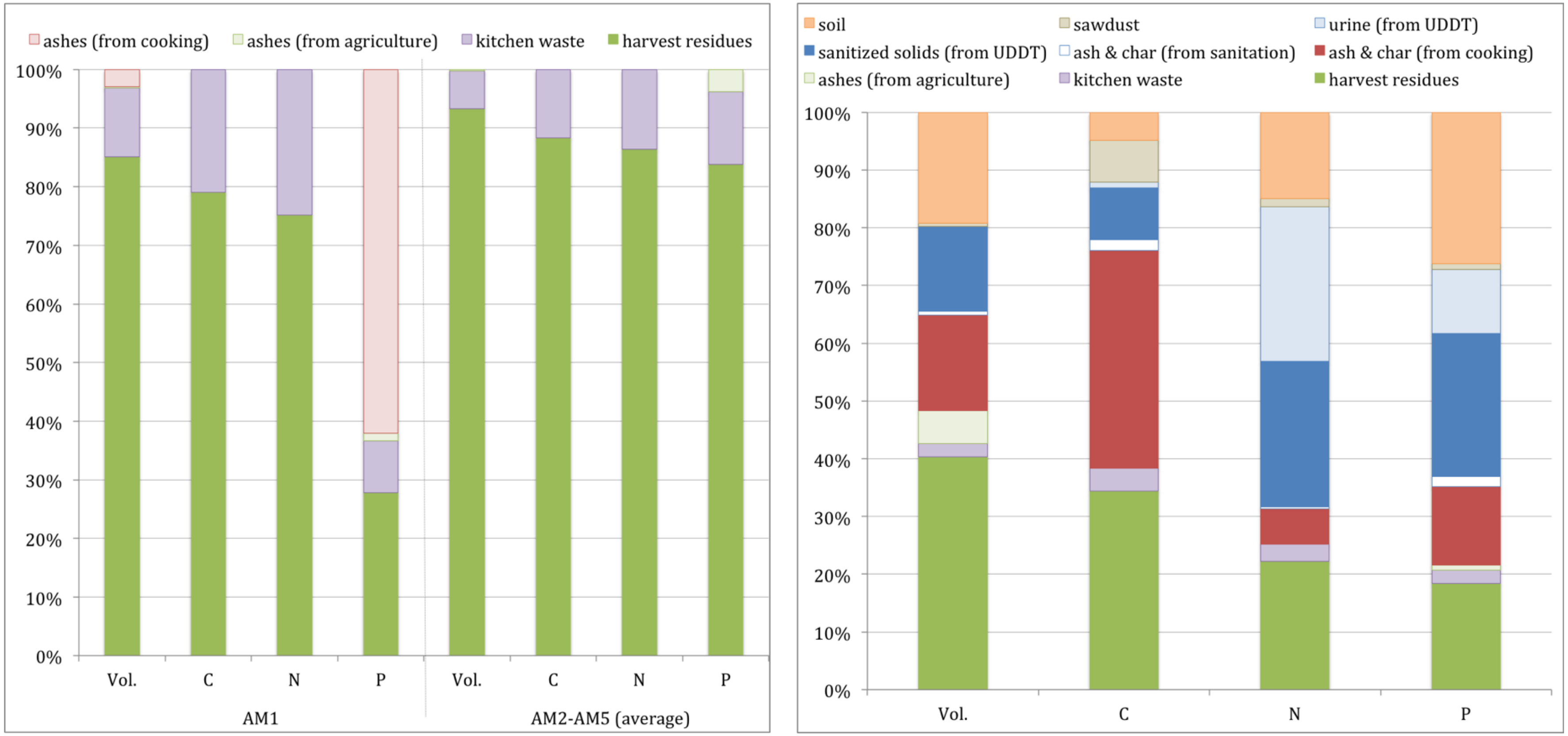
The total amount of CaSa-compost produced is comparable in AM3–5, while quantities of standard compost prepared vary over scenarios (Supplementary Table S10). (Note that results are presented in terms of fresh matter (FM). We consider this to be the more practice-oriented unit, as it refers to the material that farmers actually need to transport when performing agricultural activities.) Annual compost production is projected to be equivalent to about 0.3–0.9 m^3 for standard compost, and 2.6–2.8 m^3 for CaSa-compost (Table 2), which is, overall, an adequate and feasible amount for annual applications [81]. The variation regarding standard compost depend (i) on the general availability of harvest residues (and thus on yield assumption, as discussed above), and (ii) whether or not the CaSa-compost is additionally produced, because then residues are divided between the two composting processes (cf. Supplementary 2.6). The average compositions of both composts in terms of relative volumes (Figure 4) fit well with local practices [39].

Recovering residues from cooking and sanitation can contribute clearly to C and nutrient contents in composts. By way of an example, P in ashes recovered from three-stone fires contributes >60% of total P in standard compost for AM1 (Figure 4a). However, in AM2–5, where a switch in cooking technology has been assumed, the use of three-stone fires and the subsequent recovery of ashes for standard composting are no longer considered in the calculation. Instead, biogas slurry from small-scale biogas digesters, and biochar recovered from microgasifier stoves are available as direct organic fertilizer in AM2, or as additive to CaSa-composting in AM3–5, respectively. Taking a closer look at the CaSa-compost (Figure 4b), it reveals that approximately 38% of total C, and 14% of the total P content originate from biochar recovered after cooking. In addition, stored urine, sanitized faeces (also referred to as "sanitized solids" (Figure 4b), as a mix of materials collected from the UDDT, which include human faeces and some sort of dry material, such as dry soil, sawdust, ash, etc., that is added after defecation to enhance the drying of faeces and to reduce smelling), and biochar recovered from sanitation, add approximately 52% and 38% of total N and of total P in CaSa-compost, respectively.

Furthermore, the total amount of biochar recovered from cooking and from sanitation, and sanitized faeces are both available in comparable amounts in terms of volume (i.e., about 1.2 and 1.0 $m^3 \cdot year^{-1}$ of FM of biochar and sanitized faeces, respectively). This fits very well with the typical composition of CaSa-compost in the CaSa pilot project, which includes approximately 0.17 $m^3 \cdot m^{-3}$ biochar and 0.15 $m^3 \cdot m^{-3}$ sanitized faeces [39]. In addition, about 0.8 $m^3 \cdot year^{-1}$, or approximately 60% of stored urine, is used for CaSa-composting. This means that the total amount of urine available as mineral IN is higher in AM2 (*without* CaSa-composting) as compared to AM3–5 (*with* CaSa-composting) (Supplementary Table S10).

Yearly application rates for standard compost are estimated at 2.0 $\pm$ 0.5 in AM4, and 4.4 $\pm$ 1.4 $kg \cdot m^{-2} \cdot year^{-1}$ of FM in AM1; those for the CaSa-compost are within the range of 1.7–1.8 $kg \cdot m^{-2} \cdot year^{-1}$ in AM3 and AM4 (Supplementary Table S5). Overall, *annual* application rates estimated for both composts are consistent with relevant literature [82,83]. The *triennial* application rates calculated in AM5, however, are significantly higher, with 11.3 $\pm$ 1.8 and 5.5 $\pm$ 0.5 $kg \cdot m^{-2} \cdot year^{-1}$ of the standard and the CaSa-compost, respectively, a figure also appropriate according to [17]. Seasonal application rates of urine vary over each of the scenarios, and range from 0.1 to 0.3 $dm^3 \cdot m^{-2}$ $year^{-1}$ for maize, and from 0.5 to 2.0 $dm^3 \cdot m^{-2} \cdot year^{-1}$ for vegetables, which is also fully consistent with common recommendations for urine fertilization [38]. Furthermore, urine application rates estimated for maize, in particular, are appropriate for one-dose fertilization per cultivation period, which ensures workloads are manageable. The appropriate timing for urine fertilization would be at week five after sowing, when crops demand most N for growing [82].

Finally, we acknowledge that not all potentials of input materials available are exhausted (Supplementary Table S11), even though nutrient deficits remain in the full SNB for N (Table 4). For example, standard compost remains available after fertilizing vegetables in most scenarios. This leftover compost could be used, therefore, to improve PB for maize and beans.



(**a**) (**b**)

Figure 4. Relative contribution of the different resources used for standard composting ((**a**); left) and for CaSa-composting ((**b**); right) to the total input flow in terms of volume (Vol.) and content of carbon (C), nitrogen (N), and phosphorus (P) prior to the composting process (values represent the mean percentage calculated for all scenarios). Scenarios are defined in Table 1. Plot data provided in Supplementary Table S18 (for Figure 4a) and Table S19 (for Figure 4b).

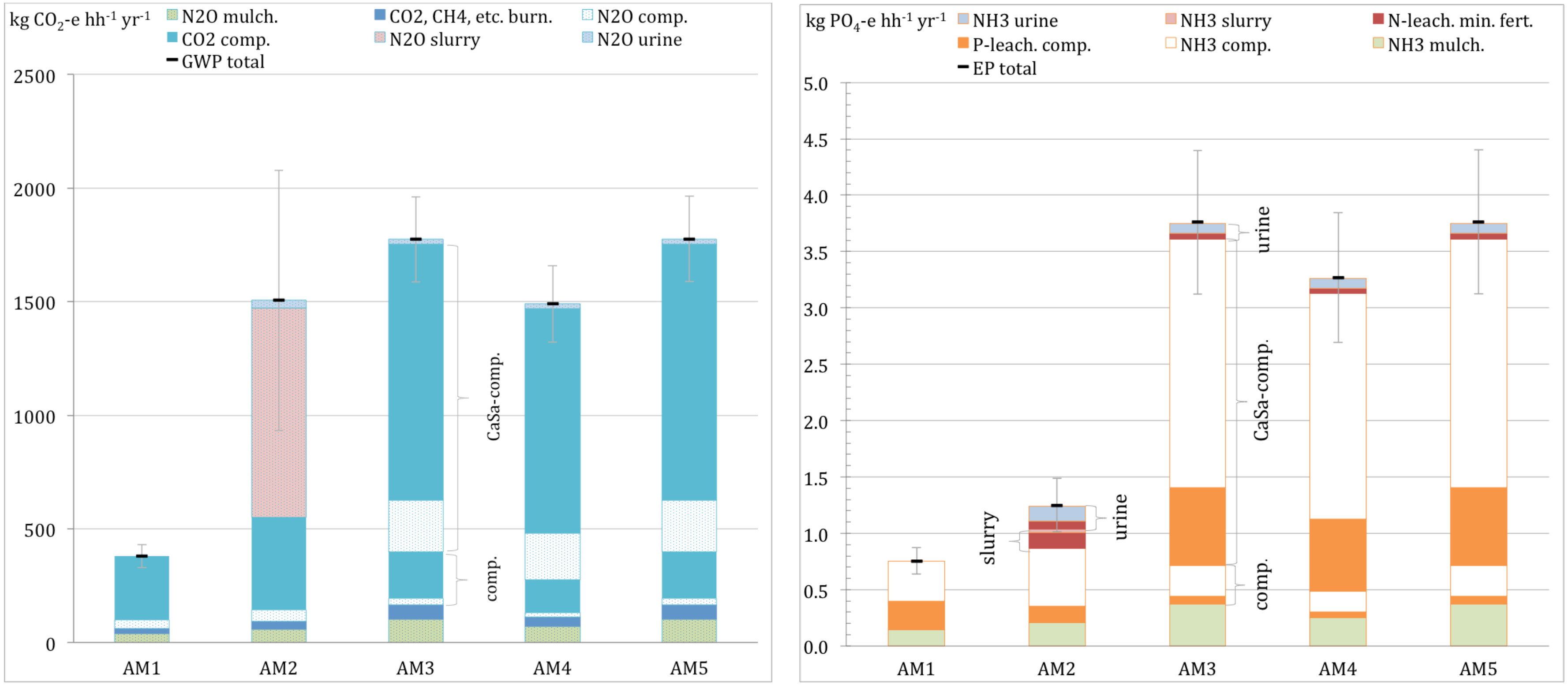
3.3. Environmental Emissions

Environmental emissions of greenhouse gases (GHG) increase in all IPNM strategies analyzed, when compared to current state practices (Figure 5a). GWPs in alternatives AM2–5 are around four to five times higher than the GWP of the current state, while the overall results of analyzed IPNM alternatives are generally comparable. The most significant contributions to GWP in AM2 can be traced back to N_2O emissions from biogas slurry application (≈60% of the total GWP assessed in AM2). In the CaSa-scenarios AM3–5, CO_2, and N_2O emissions from CaSa-composting bring about, respectively, approximately 65% and 13% of the total GWP assessed for these alternatives.

Similarly, environmental emissions with eutrophying effects potentially increase through IPNM (Figure 5b). Numerically, EP assessed in AM2, AM4, and AM3/5 is approximately 160%, 430%, and 500% of the current EP in AM1, respectively. Overall, EPs of AM1–5 correspond closely to NH_3 emissions from composting, and thus, to the intensity of the total compost production. The comparatively higher EPs estimated for AM3–5 are mainly attributable to NH_3 emissions and P leaching from CaSa-composting, contributing, on average, about 60% and 20% to the EPs in AM3–5, respectively. In AM2, those emissions assessed with EP that exceed those estimated for AM1 mainly stem from N leaching after applying biogas slurry and urine, and comprise, in total, approximately 15% of the total EP in AM2. The contribution of NH_3 emissions after slurry application to the EP assessed for AM2, meanwhile, is negligible.

Finally, we add some practical recommendations to reduce environmental emissions. For example, applying biogas slurry preferably to dry soil, and incorporating biogas slurry into soil within the first few minutes after application, can avoid nutrient leaching and N_2O and NH_3 emissions, as advised by [44,84]. Farmers may do so using a simple hand hoe. Also, [85] emphasize the importance of biogas slurry entering soil as rapidly as possible after application, and therefore, recommend a high water content in the slurry, or additional dilution of slurry with water. According to prior research presented in [39], water content of biogas slurry studied stands at approximately 95% of FM, and should thus be adequate for rapid infiltration. Likewise, [38] recommend applying urine into a furrow or hole, and closing the furrow/hole with soil afterwards, in order to reduce N_2O and NH_3 emissions after urine application. In addition, biochar additions to composting can potentially decrease N_2O and CH_4 emissions, e.g., [86–89], whilst NH_3 emissions potentially increase (e.g., [87]). Other studies [33,90] showed that biochar captures nitrate and phosphate during composting, which is promising, in order to reduce nutrient leaching. However, such potentially beneficial effects of co-composting biochar have not yet been included in our model (Section 3.5).

Before synthesizing our results, we want to shortly comment on the certainty/uncertainty of (i) data that have been collected from literature and used for the modelling, and (ii) values that have been presented as results. According to [91], a relative uncertainty (RU) of <30%, ±50%, or >90% indicates "low", "average", or "high" uncertainty, respectively. The uncertainty of most flows considered in, and calculated by our model, can be classified as low. Nevertheless, there are some flows that show average or high uncertainty, such as, respectively, atmospheric deposition, total N and P in rainfall, N in cabbage or onion (for both, food product and harvest residue), total C in kitchen waste, P in stored urine collected from UDDT, and density of (generic) organic waste or emission factor for CO from burning agricultural residues (Supplementary Table S32). Also, with respect to the results of SNB (Supplementary Table S24), the uncertainty of most flows calculated can be classified as low. Especially values estimated for the PB, i.e., nutrient requirements and nutrient supplies, show an RU of <20%. For the NB, the uncertainty is low for N in AM1–3 and AM5, and average for N in AM4 and for P in all alternatives. The uncertainty of results estimated for the full SNB in AM1 is low. For the IPNM alternatives, the uncertainties range from average (for N in AM3/5 and P in AM2/4) to high (for N in AM2/4 and P in AM3/5), which is also indicated with grey error bars for the standard errors of the means in Figure 3.



(**a**) (**b**)

Figure 5. Estimated environmental impacts of the analyzed IPNM strategies: the global warming potential ((**a**); left) and the eutrophication potential ((**b**); right). Scenarios are defined in Table 1. Plot data provided in Supplementary Table S13 (Figure 5a) and Table S14 (Figure 5b). comp.: composting; EP: eutrophication potential; GWP: gobal warming potential; hh: household; leach.: leaching; min. fert.: mineral fertilization.

3.4. Sustainability Aspects of Intersectional Resource Management

When evaluating our results, our main focus is on the potential for sustainable soil fertility management. In particular, we aim at taking the specific vulnerability of smallholders into consideration, and the importance of the soil as a basis of existence and subsistence. Hence, in order to be considered "sustainable", soil management should, among other factors, maintain or improve crop productivity and mitigate existing soil constraints, such as nutrient depletion and soil acidity (Section 2.1). In the contemporary context, it should also promote resilience in farming in the face of climate change as a local and global threat. Therefore, SOM, which contributes to the soil's water holding capacity and erosion resistance, and the restoration of SOM, are of utmost importance as climate adaptation measures. Furthermore, adequate soil P levels support climate mitigation and adaptation, due to the fact that a sufficient supply of soil P supports plants to root more deeply, which, in turn, makes crops less vulnerable to drought [92]. To sum up, the focus of our final evaluation is on the potential of IPNM practices to (i) replenish soil P, (ii) combat soil acidification, (iii) restore SOM, and (iv) sequester C. In addition, (v) we briefly discuss, integrated environmental emissions accumulated for smallholder household *and* farmland. (Effects on crop productivity, as a consequence to improved soil fertility, is not further discussed here. Estimated figures of food products for self-consumption (OUT1a) and food products sold to market (OUT1b) are displayed in Supplementary Tables S20–S22.)

3.4.1. Replenishing Soil P

In AM1–4, phosphate is applied with *annual* rates of around 20–60 kg·P·ha^{-1}·year^{-1} (Supplementary Table S6). Within this range, per hectare P applications estimated for CaSa-compost as applied to maize and beans, and those for standard compost as applied to vegetables, are very similar. When considering amendments to soil cultivated with maize and beans, CaSa-compost used in AM3–5 accounts for about 175% of total P provided in the form of biogas slurry in AM2. Compared to our results, [17] consider 10–20 kg·P·ha^{-1} as a sufficient *seasonal* P application to degraded soils in East Africa that are characterized by strong P-fixation, as is the case for Karagwe Andosols. In addition, [93] found that application rates of >25 kg·P·ha^{-1}·season^{-1} over the course of four seasons were capable of replenishing levels of P in a P deficient soil in Western Kenya. In contrast, the application of 40 or 70 kg·P·ha^{-1} in the form of biogas slurry or standard compost, respectively, was not sufficient to increase extractable soil P, as demonstrated in a short-term field trial on the local Andosol [61]. Adding about 140 kg·P·ha^{-1} with CaSa-compost, however, significantly increased levels of available P in the soil after the experiment, and thus, *immediately* contributed to mitigating P deficiency [17]. The latter P amendment is comparable to our present results in AM5, where P is supplied *triennially* in the range of around 100–200 kg·P·ha^{-1}·year^{-1} for both composts analyzed. In comparison, [17] suggests 100–500 kg·P·ha^{-1} for one large application repeated "every few years".

When considering application frequency and subsequent plant response, [94] emphasize that a seasonal and moderate application of P is more effective in increasing crop yields than a large, one-off application. This contradicts [17], who recommends both strategies. In addition, [94] reason that a lower input of P is preferable, as the residual effect of a single fertilization dose is far lower than the initial and direct effect of the seasonal fertilizer application. In other words, P-use efficiency of fertilizers is higher at comparatively lower inputs of P [17]. By contrast, a model-based simulation of [95] supports an appropriate supply of plant available P to crops originating in residual soil P pools. The authors promote substantial efforts to build up soil P, whilst being patient with respect to the known hysteric response of plants to fertilizer application [17]. The specific hysteric characteristics of local Karagwe Andosol have not, to the best of our knowledge, yet been studied. Finally, [94] argue against large P applications, as farmers often lack the capital, as well as the machinery, to apply the large quantities required for appropriate fertilization. In the present work, we have demonstrated the potential to provide P-rich inputs to agriculture on-farm, at no additional cost, and in such quantities that are feasible to apply with standard tools, such as a wheelbarrow and hand hoe.

3.4.2. Combating Soil Acidification

In order to strengthen nutrient cycling processes, acidity management through liming is an important practice [92]. Nutrient availability in the soil is, among other factors, a function of soil pH [96]. This means that an increase in soil pH through liming promotes plant uptake of P and N from organic and mineral fertilizers, and thus renders on-farm nutrient recycling more efficient. Organic material has an equivalent potential to neutralize soil acidity levels as lime (CaO) [97,98].

In an earlier study, we quantified the potential liming effect of the substrates analyzed [39]. We have integrated this data into the present study to deduce the following results: In AM1–4, the liming effects of *annual* organic INs are equivalent to around 200–650 kg·CaO·ha^{-1}·year^{-1} (Supplementary Table S7). All treatments studied, therefore, meet the *minimum* requirements of 50 kg·CaO·ha^{-1}·year^{-1} to avoid Al toxicity, and to neutralize acid deposition from the atmosphere onto agricultural soils [96]. Within the ranges presented, however, amendments with biogas slurry and standard compost have significantly lower liming potentials (≈ 200–400 kg·CaO·ha^{-1}·year^{-1}) as compared to the CaSa-compost (<600 kg·CaO·ha^{-1}·year^{-1}). In AM5, the liming effect is estimated in the range of around 1000–2300 kg·CaO·ha^{-1}, and refers to the same soil amended every three years. This treatment is, therefore, adequate to maintain, or even improve, soil pH in accordance with [82], who recommends a triennial application of 1250–2250 kg·CaO·ha^{-1}. Empirically, an *immediate* rise of soil pH within one cropping season was only possible with CaSa-compost, not with standard compost or biogas slurry, and at an application rate of about 2000 kg·CaO·ha^{-1} [61].

3.4.3. Restoring SOM

The capacity to restore SOM generally depends on the form in which C is recovered and applied to soil. Compost and biogas slurry typically provide, respectively, about 50% and 25% of total organic C content for reproducing SOM [83]. For this reason, amendments of total C with standard compost (Supplementary Table S8) correspond to SOM reproduction potentials on soil cultivated with vegetables, varying approximately 1.4–1.9 ton·SOM-C·ha–^{1}·year^{-1} in AM1–4 (Supplementary Table S9). In comparison, cabbage and onion consume approximately 2.1 and 0.7 ton·SOM-C·ha^{-1}·year^{-1}, respectively. Moreover, on soil cultivated with maize and beans, the amendment of total C with CaSa-compost is about two and a half times higher than compared to biogas slurry. Hence, inputs of biogas slurry and CaSa-compost consequently correspond to SOM reproduction potentials of about 0.3 and 1.2–1.3 ton·SOM-C·ha^{-1}·year^{-1}, respectively. Maize meanwhile consumes approximately 1.4 ton·SOM-C·ha^{-1}·year^{-1}, while beans *replenish* SOM-C at the rate of about 0.4 ton·SOM-C·ha^{-1}·year^{-1} [99]. In scenario AM5, the SOM reproduction potentials of standard compost and CaSa-compost are approximately 9.1 and 3.9 ton·SOM-C·ha^{-1}·year^{-1}, respectively, which then has to serve for three years of continuous cropping. To sum up, the potential for reproducing SOM for large applications of standard compost in AM5, or for general applications of CaSa-compost in AM3–5, is estimated at slightly higher than the accumulated C consumption of crops. This finding indicates a potential for replenishing SOM, and even for sequestering it.

3.4.4. Sequestering C

Carbon sequestration refers to long-term storage of CO_2 in the form of SOM, in order to mitigate global warming, and also, in principle, to an increase of SOM. Furthermore, the addition of phosphate and lime promotes a stable increase in SOM in deeply weathered tropical soils [76], such as the local soil. For this reason, sequestering C is possible in the present system analysis through the use of compost and, particularly, the CaSa-compost, which simultaneously promotes restoring SOM, replenishing soil P, and liming. The context of the present analysis further promotes C sequestration, as local soil is known for its outstanding capacity to accumulate organic C. Andosols tend to protect organic matter from degradation by forming either metal–humus (i.e., often Al–Fe), or allophane–organo complexes [100]. Thus, Andosols can act as a CO_2 sink [101].

Furthermore, CaSa-compost contains biochar recovered from cooking and sanitation. Biochar potentially renders C sequestration possible, because (i) it originates from renewable biomasses [102], and (ii) it is characterized by relatively recalcitrant organic compounds, which promise the long-term "stability" of biochar in the soil [29]. In regard to the latter, [103] recently criticised the traditional model of "labile and stable organic compounds" and their role in the genesis of long-term "stable" SOM. The degradation of SOM and other organic matter in the soil is rather a continuum, and depends on many factors, including accessibility of matter, microbial ecology, energy transportation processes, prevailing temperatures affecting enzymes, etc. [17]. To the best of our knowledge, however, long-term studies observing the effect of compost amendments—with and without biochar—on SOM in tropical Andosols do not exist. We are, therefore, unable to quantify the general potential for C sequestration with existing data, and any further discussion would enter into the realms of speculation.

Nonetheless, we may at least compare our modelling results for CaSa-scenarios with data available from empiric studies in the region on biochar applications and effects. According to our model, biochar is applied at rates of approximately 2.7 ton·ha^{-1}·year^{-1} in AM3 or AM4, and of about 8.0 ton·ha^{-1}·year^{-1} in AM5, which is presumably equivalent to rates of 2.0 ton·C·ha^{-1}·year^{-1} and 6.0 ton·C·ha^{-1}·year^{-1}, respectively. In comparison, [50] generally identified a minimum application rate of biochar, leading to a significant increase in SOM, and thus to C sequestration, of 50 ton·ha^{-1}. On highly degraded soil in Kenya, [58] empirically demonstrated that biochar amendments equivalent to 6 ton·C·ha^{-1}, applied in three consecutive seasons, increased SOM by 45%, as compared to the unamended control soil.

3.4.5. Integrated Environmental Emissions

Finally, we estimate the overall environmental impact of the intersectional resource management analyzed. We have, therefore, aggregated environmental emissions of the entire smallholder farming system, including MES, MSS, and AES. With respect to overall climate balance (Supplementary Figure S4a with plot data in Tables S15 and S18), integrated GWP in AM2, when shifting to a biogas system and an UDDT, and while utilizing biogas slurry and stored urine as inputs to the farm land, is more than 250% of the integrated GWP in AM1. This is caused by (i) extremely high levels of GWP identified for operating biogas systems [41] propagating into the integrated perspective, and (ii) comparatively higher levels of GWP identified for the AES (Figure 5a). By contrast, [104] estimated that overall GHG emissions *decrease* when integrating biogas digestion to organic farming systems through a lifecycle assessment methodology. However, the net reduction originates from offsetting fossil fuels consumed for producing electrical energy, which lie outside the scope of the present analysis [17]. The total GWPs of CaSa-scenarios are generally comparable to the current state. In AM3–5, GWP assessed for the MES *decreased* when shifting from three-stone fires to microgasifier stoves [41]. This is offset, however, by increased GWP assessed for the AES (Figure 5a). With respect to emissions with eutrophying effects (Supplementary Figure S4b with plot data in Tables S16 and S19), the integrated EPs for all IPNM strategies studied in AM2–5 is only about half of the total EP in AM1. This general decrease of integrated EP is attributable mainly to lower EP levels assessed for using an UDDT instead of a pit latrine [17]. In AM2 and AM3–5, a proportion of the EP reduced in the MSS are, however, offset by higher EP analyzed for biogas production, or for CaSa-compost production, respectively.

Results of the synthesis above refer to our case study in Karagwe, and are summarized in Table 5.

Table 5. Summarized effects estimated for the IPNM strategies analyzed with regard to selected sustainability aspects.

IPNM Based on the Use of	Replenishing Soil P	Liming Potential	SOM Reproduction Potential	C-Sequestration Potential	Integrated Emissions
Standard compost *	++/++	=/+	=/+	?/?	na
Biogas slurry and urine	+	=	−	−	GWP: −, EP: =
CaSa-compost and urine	++/++	++/++	+/+	?/?	GWP & EP: =

++: Strong improvement; +: improvement; =: constant; −: decline; − −: strong decline; ?: not clear; na: not analyzed. * Note that results refer only to a small share of the land, whilst the larger part of the farmland remains unamended. When two results are indicated, for example =/+, the first result refers to the regular annual amendments analyzed in AM1 and AM3–4, whilst the second result refers to the one-off large amendments analyzed in AM5. (Scenarios are defined in Table 1.)

3.5. Discussion of Methodology

Overall, we consider the combination of MFA and SNB as a highly appropriate methodology for conducting a holistic *ex-ante* assessment of soil management practices in SSA smallholdings. Both methods generally aim at a structured analysis of certain substances flowing in an arbitrary complex system, and therefore, follow comparable principles and procedures. Selecting certain IN and OUT, which are generally considered in SNB, allowed us to describe the real farming system in as simple a manner as possible, yet also in as complex a manner as necessary, for the scope of this study. MFA supplemented our analysis by providing a framework, (i) to expand our investigations, by incorporating both private households and the environment into a single system analysis, (ii) to compute our analyses with uncertainties incorporated into it, and (iii) to illustrate the results of composting processes into flow diagrams. The first point, in particular, allowed us to derive additional information, such as C content or liming potentials of the substrates analyzed, composition of composts, emissions from composting, etc.

Despite obvious strengths, we identify the following limitations in the applied methodology:

(I) Data used to assume biomass production and crop yields in AM2–5 derive from a field trial conducted in Karagwe [61]. The experiment was well adapted to local practices, *but* only lasted for one cropping season. The results still need, therefore, to be replicated for validation. Nevertheless, practical experiences from the case study underline existing scientific results so far.

(II) The time needed for mineralization, the form of applied nutrients (i.e., organic versus mineral N or P), and the transfer of the applied nutrients to the various nutrient pools in the soil (e.g., labile and stable pools of P) is not taken into account in our model. This simplification is accounted for by the fact that our model is a static one, and it was not possible to include dynamic effects. Instead, we simply assumed that the treatments analyzed would be applied repeatedly, and thus constantly release nutrients to various pools. The total nutrient uptake of plants in one season is rather the sum of contributions from different previous cultivation periods. Our model, however, suggests that plant uptake is equivalent to the contributions applied over one single season.

(III) Soil and nutrient losses through wind and water erosion are not considered in our model. We reason that (i) [27] also neglected soil erosion as a natural OUT when conducting SNB for *shamba* systems in Karagwe; (ii) available data on slopes and erosion sensitivity of the local soil are not sufficient; and (iii) many farmers in Karagwe apply erosion control measures, such as contour planting, catching water in trenches, mulching, intercropping with cover-crops, and agroforestry, to control soil erosion. According to local expert judgment, efforts to implement countermeasures are widely adopted by farmers in Karagwe. However, [69] report a possible range of 0–28 kg·ha^{-1}·year^{-1} for erosion induced N-losses from arable land in East Africa. Other SNB studies conducted for Uganda, estimated N- and P-losses with 5–14 and 1.5–10.0 kg·ha^{-1}·year^{-1}, respectively [25,79,80].

(IV) Sequestered C could have been subtracted from total GWP according to the Kyoto Protocol. However, C sequestration rates of local soils are, to the best of our knowledge, largely unknown. Hence, we excluded C sequestration in GWP accounting, which, according to [102], is valid *if* biogenic

CO_2 emissions are included in the assessment, which is the case in our model for CO_2 emissions from composting.

(V) Environmental emissions with EP are likely to be over-estimated. We assessed the EP after [74], and consequently included both total P, and total N contained in liquid emissions. Given that high levels of P fixation can be expected for the local soil [101], and given that P is relatively immobile in the soil [94], we presume that phosphate would most likely remain in the soil surrounding pit latrines. By contrast, pollution of underground water resources is *more* likely from ammonium emissions. If we were to exclude P leaching from our assessment, our EP estimations could possibly be reduced to about 70–90% of the EP (Figure 5b).

(VI) Possible biochar-related effects are not considered when quantifying GHG emissions, or nutrient leaching from the composting process. We rather assumed equal processes and emission factors for standard compost and biochar-containing CaSa-compost. We reason that existing scientific data on using biochar as a soil amendment are contradictory, cf. [105,106]. Overall, available data expose existing uncertainties in various areas, knowledge gaps in underlying principles and mechanisms, and the admission that possible effects of biochar amendments are highly site-specific [105]. For these reasons, we judge that it is not yet possible to depict biochar effects in a model such as the present one.

(VII) The model developed in this study does not yet depict soil dynamics, such as nutrient dynamics or SOM transformations. Further empiric studies are therefore required to study, for example, in situ interactions of biochar, soil nutrient pools, and SOM in long-term field experiments, and the effects of amending selected treatments, such as biochar-compost to tropical Andosols. Empiric data collected would help quantify the relationship between compost applications and replenishment rates of soil nutrients, turnover rates of SOM, and accumulation rates of SOM for C sequestration. Analytical work, such as dynamic modelling, could then follow, in order to estimate the timeframes associated with soil effects.

Despite all limitations discussed, we consider the present model to be complex enough, and therefore adequate to sufficiently answer our research questions.

4. Conclusions

By adopting an integrated perspective on farming *and* households, we draw the following conclusions with respect to the research objectives, and for the example, of smallholdings in Karagwe, TZ:

- The IPNM strategies analyzed, i.e., utilizing resources recovered from cooking and sanitation, show a clear potential to decrease currently existing soil nutrient deficits. Specifically, net P balance is reversed, giving a positive result. This means that P depletion is avoided, while depletion rates of N are mitigated, but not avoided completely.
- Biogas slurry, standard compost, or CaSa-compost, are all feasible for completely meeting P demand of crops. All organic inputs analyzed require application in combination with a mineral fertilizer, such as urine, to compensate crop N-demand.
- Recovering and utilizing residues from households for composting allows for the production of adequate quantities of compost *on-farm*. Biochar recovered from cooking and/or sanitation specifically contributes to C contained in CaSa-compost, while residues from EcoSan significantly contribute to nutrient content of CaSa-compost.
- Environmental emissions greatly increase with the production and use of organic fertilizers, whereby the climate balance declines for all IPNM scenarios analyzed. The EP also demonstrates an increase in association with intensive subsistence production of composts.

When considering the analyzed IPNM practices with respect to certain relevant sustainability aspects, we emphasise that

- Using the CaSa-compost is a suitable method for sustainable soil fertility management, due to the following factors: (i) applied P amendments are appropriate to replenish P in exhausted soils, (ii) estimated liming effects are suitable for mitigating existing soil acidification, (iii) C inputs contribute to restoring the SOM, and (iv) potentially also to C sequestration, while (v) the *overall* GWP is maintained, and total EP is reduced.
- Regarding the aforementioned benefits identified for compost amendments, the potential of the CaSa-compost is superior to the standard compost, especially with respect to liming and SOM restoration. By contrast, the use of biogas slurry is inferior in all aspects when compared to compost amendments, especially for liming, SOM restoration, and emissions with GWP.

Conceptually, combining SNB with MFA was beneficial because it enabled us to:

- Conduct an analysis from a system perspective around the nexus of energy-sanitation-agriculture, instead of focusing only on farming products and processes.
- Create a functional link between smallholder households, farming practices, soil nutrient stocks, and the environment.
- Shed light on how IPNM strategies that combine use of residues from cooking and sanitation affect local soil nutrient budgeting in comparison to the current state.

To sum up, we found that switching household technologies to locally adopted alternatives, such as biogas digesters, microgasifiers, and UDDTs, combined with the consequent recovery and use of residues, has a strong potential to improve SNBs in farming. Moreover, both of the prevailing challenges for the agricultural production in Karagwe—P-scarcity and soil acidity—can be mitigated through the use of biochar–faecal-compost. We judge that our results are transferable to comparable smallholder systems in other regions of SSA, where similar technologies are available. Moreover, estimated results from this study, which focus at the farm level, may serve as a starting point for upscaling analyses from the farm level to the community or district level. In addition, they help estimate potential positive environmental and agronomic impacts, which in turn support local initiatives aimed at sustainable farming and soil improvement. We maintain that a socio-economic assessment should follow up on this study.

Overall, we conclude that integrating residues from farming households into agricultural practices is a promising path for subsistence farmers wishing to escape the vicious circle of insufficient production of food crops, and therefore, residual matter, leading to poor soil fertility. Nevertheless, efficient recycling of *all* available domestic refuses is required to offset those local soil nutrient deficits identified in this study. Exploiting the potentials of the analyzed recycling practices therefore requires a considerable effort on the part of local farmers, affecting processes including transportation of materials, making compost, collecting and using urine (or other mineral fertilizer), etc. Smallholders need to pursue multiple practical aims, including optimizing nutrient recovery efficiency, maintaining sound composting processes, minimizing workload, reducing GHG emissions, etc. For these reasons, various (objective) criteria and subjective preferences need to be considered jointly from an intersectional and transdisciplinary perspective. We must, therefore, consider the possibility that a single "optimum solution" may not exist, but rather pursue a "best option" that measures the delicate balance of all these different objectives against one another. For example, the multi-disciplinary approach of a multi-criteria analysis (MCA) can be applied for selecting and considering the objectives of the evaluation, identifying the preferences of all the people involved, and ensuring transparency within the group of decision makers.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: Example of a *shamba*, the agricultural land surrounding farming houses, also called "banana-based home garden", used for inter-cropping of perennial crops like fruit, banana, and coffee trees, and annual crops including beans, cassava, African eggplant, etc., Figure S2: Example of a *msiri*, former grassland used for the cultivation of annual crops including maize, beans, millet, and vegetables, like tomatoes, cabbage, onion, etc., Figure S3: Proceeding of the applied system analysis combining the material flow analysis (MFA) with the soil nutrient balance (SNB) for an annual intercropping system in Karagwe, TZ, Figure S4: Integrated environmental impacts of the micro energy systems (MES/red), the micro sanitation system (MSS/blue), and the agroecosystem AES/green) for the global warming potential (a) and the eutrophication potential (b), Figure S5: Regression analysis for estimating the relationships between the N flows in the natural balance (NB) and the biological nitrogen fixation (BNF) for all of the five analyzed scenarios; values are displayed in kg of N per hectare and year, Table S1: Production of main crops in Kagera region and Karagwe district based on the national sample census of agriculture 2007/2008, Table S2: Pictures and short description of the analyzed cooking alternatives that are locally available in Karagwe, TZ, Table S3: Pictures and short description of the analyzed sanitation alternatives that are locally available in Karagwe, TZ, Table S4: Definition of the system analyzed, Table S5: Estimated application rates of the organic and mineral inputs studied in scenarios AM1–AM5 in kg of FM per household and year, Table S6: Estimated P-inputs with organic and mineral inputs studied in scenarios AM1–AM5 in kg of P per hectare and year, Table S7: Estimated liming effects of the organic material expressed in equivalent application in kg of CaO per hectare and year calculated with liming potentials presented in Krause et al. (2015), Table S8: Estimated C inputs with organic and mineral inputs studied in scenarios AM1–AM5 in kg of C per hectare and year, Table S9: Estimated SOM reproduction potentials with organic and mineral inputs studied in scenarios AM1–AM5 in kg of C in SOM per hectare and year, Table S10: Available materials for organic and mineral fertilization in kg year^{-1} of FM, Table S11: Utilization of the matter as input material in % of available FM, Table S12: Estimated SNB for N and P comprising natural input (IN3a, 4a, 4b) and natural output (OUT3, 4a) flows; organic (IN2a–2e) and mineral (IN1c) input flows; and output flows (Out1a, 1b, 2) with agricultural products; in kg of N and P per household and year; plot data for Figure 3, Table S13: Estimated environmental impacts of the analyzed IPNM strategies: the global warming potential in kg of CO_2 equivalents per household and year; plot data for Figure 5a, Table S14: Estimated environmental impacts of the analyzed IPNM strategies: the eutrophication potential in kg of PO_4 equivalents per household and year; plot data for Figure 5b, Table S15: Integrated environmental impacts with GWP of the MES, the MSS, and the AES in kg of CO_2 equivalents per household and year; plot data for Supplementary Figure S4a, Table S16: Integrated environmental impacts with EP of the MES, the MSS, and the AES in kg of PO_4 equivalents per household and year; plot data for Supplementary Figure S4b, Table S17: Evaluation SNB—regression analysis: estimated biological N fixation and estimated natural balance in kg of N per household and year; plot data for Supplementary Figure S3, Table S18: Relative contribution of the different resources used for standard composting and for CaSa-composting to the total input flow in terms of volume and content of C, N, and P prior to the composting process in %; plot data for Figure 4a, Table S19: Relative contribution of the different resources used for standard composting and for CaSa-composting to the total input flow in terms of volume and content of C, N, and P prior to the composting process in %; plot data for Figure 4b, Table S20: Material output flows of *food products* (i.e., maize and beans grains, cabbage heads, and onion bulbs) in kg of FM (after air-drying for maize, beans, and onion) per household and year, Table S21: Material output flows of *food products for self-consumption* in kg of FM (after air-drying for maize, beans, and onion) per household and year, Table S22: Material output flows of *food products sold to market* in kg of FM (after air-drying for maize, beans, and onion) per household and year, Table S23: Material output flows of *harvest residues* in kg of FM (at time of harvesting) per household and year, Table S24: Relative uncertainties (RU) of results calculated defined as the standard error in % of the arithmetic mean value. Supplementary S1: General information; Supplementary 2: Specific equations applied for modelling; Supplementary 3: Assessment of emissions to the environment; Supplementary 4: Short Discussion; Supplementary 5: Data collection of material and process values; Supplementary 6: Terminology.

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Chapter 6

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Challenges in Sustainability

Research Article

A Multi-Criteria Approach for Assessing the Sustainability of Small-Scale Cooking and Sanitation Technologies

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Abstract: To reduce the consumption of firewood for cooking and to realise recycling-driven soil fertility management, three projects in Northwest Tanzania aim to provide the local smallholder community with cooking and sanitation alternatives. The present study proposes an integrated approach to assess the sustainability of the small-scale cooking and sanitation technologies. Based on the multi-criteria decision support approach (MC(D)A), we developed a decision-specific, locally adapted, and participatory assessment tool: the Multi-Criteria Technology Assessment (MCTA). Pre-testing of the tailored tool was set up with representatives of Tanzanian and German partners of case study projects. From a methodological perspective, we conclude that the MCTA uses a set of relevant criteria to realise a transparent and replicable computational Excel-tool. The combination of MC(D)A for structuring the assessment with analytical methods, such as Material Flow Analysis, for describing the performance of alternatives is a promising path for designing integrated approaches to sustainability assessments of technologies. Pre-testing of the tool served as a proof-of-concept for the general design of the method. Future applications and adjustments of the MCTA require the inclusion of end-users, a reasonable and participatory reduction of criteria, and an increase of feedback loops and group discussions between participants and the facilitator to support a common learning about the technologies and thorough understanding of the perspectives of participants.

Keywords: Biomass stoves; decision support; development of appropriate technologies; ecological sanitation; energy-sanitation-agriculture nexus; multi-objective evaluation; sustainability assessment; technology assessment

Preliminary Note

Additional information is presented in the Appendix and the Supplements; Figures and Tables are indicated with Figure A.x and Table S.x. Additional notes are indicated in the text (e.g. [x]) and provided at the end of the manuscript, alongside a list of non-standard abbreviations and the references. We use italic letters to emphasize and indicate discipline-specific definitions, established terms upon initial use, terms applied from languages other than English, and quotations covering more than two lines.

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1. Introduction to the Context

1.1. Towards a Sustainable Anthroposphere

There is broad consensus that—from a global perspective—the excessive use of natural resources by human beings (in particular the resource consumption of the richer countries) has manifold consequences [1,2]. The anthropogenic overexploitation of natural resources results, for example, in (i) shortages of resources, such as oil, coal, sand, or rock phosphate [3], (ii) climate change [4], or (iii) decrease of soil fertility [5]. By various means, we are crossing the *planetary boundaries* [6]. With respect to biogeochemical flows and genetic diversity, the planetary boundaries are stressed to such an extent that we risk non-reversible changes of the environment and even the habitability of the earth. Agriculture, in particular—respectively the production and use of synthetic fertilizers, pesticides, or seeds—contributes to this risk [7]. How, therefore, can we change the situation? Or, more specifically: How can we meet the (human) demand for food and energy without overexploiting our planet?

Recognized recommendations for a *sustainable* use of resources include, for example [2,8–10]: (i) establishing circular economies; (ii) using effective, efficient, adapted, and affordable technologies; and (iii) utilizing locally available resources for soil fertility management. Measures to establish circular economies comprise *inter alia* (i) the concept of *bioenergy*, hence the provision and use of energy from biomass [11], respectively renewable resources or organic waste materials, and (ii) the implementation of *ecological sanitation* (EcoSan). With the latter, various material flows are collected separately, treated specifically, and, if possible, ultimately recycled to agricultural land [12]. Both topics, bioenergy and EcoSan, are well-studied and have already been brought into practical applications.

1.2. A Sustainable Approach to the Energy-Sanitation-Agriculture Nexus in Tanzania

Against this backdrop, and given that over 50% of global food products are produced by small-scale farmers [13], the sustainability potentials of smallholder communities in the Global South is of major relevance. In the Northwest of Tanzania (TZ), a representative region for Sub-Saharan Africa (SSA), the main energy carrier is firewood, mostly used for cooking on a three-stone fire, whilst pit latrines are the most common sanitation approach [14]. This pattern, alongside a steady population growth, increasingly stresses natural resources such as arable land, aquifers or other water sources, and forests [15,16].

To counteract local deforestation and soil nutrient depletion, two Tanzanian farmers initiatives have started three projects located in Karagwe, Kagera region, together with German partners and donors [17]. The main objective of the technological development cooperation was to contribute to *sustainable community development* by adapting and introducing small-scale and locally *adequate* cooking and sanitation technologies [18]. At the same time, a circular resource economy shall be implemented to improve local soils and food production. Therefore, residues from cooking and sanitation are used to increase the recycling of nutrients and the recovery of carbon for restoring soil humus.

Previous work covers how these locally adapted technologies in smallholder households contribute to environmental health by reducing deforestation, climate gas emissions, and nutrient leaching to aquifers [19]. We further showed that using residues from cooking and sanitation could stimulate the productivity of smallholder farming by improving the acidic and nutrient-depleted local soil [20,21]. Subsequently, we widened our perspective to evaluate the technologies studied according to multiple *sustainability* dimensions.

1.3. Assessing Sustainability with a Participatory Multi-Criteria Approach

The challenge of any *sustainability assessment* [22] is to translate defined and basically agreed upon principles into an operational model [23]. However, even though measurable criteria can be applied to operationalize sustainability, it is individuals or societies who evaluate the plausibility and credibility of relevant assessments. If the process involves multiple actors, differing opinions may also cause trade-offs between stakeholders. Multi-Criteria Decision Analysis (MCDA) attempts to address this challenge [24–26]. In the first instance, any assessment of alternatives against multiple criteria, irrespective of who participates in the analysis, can generally be called a Multi-Criteria Analysis (MCA) [27,28]. Moreover, MCDA indicates a specific MCA, addressing *participatory* decision-making processes [29]. Both approaches, MCA and MCDA, are applied in planning, decision, and evaluation processes and to assess likely consequences of decisions [30]. In the following, we use the abbreviation MC(D)A when referring to characteristics of both approaches.

According to [31], the MC(D)A is generally suitable for decisions related to sustainable development because the method is largely transparent, participatory, and interdisciplinary. Furthermore, the MC(D)A is often applied in environmental decision making [32,33] and strategic planning for natural resources management [34]. While the number of MC(D)A applications has clearly grown over the last two decades, the method was mainly applied in scientific communities in the Global North [35]. Among the view examples of MC(D)A-studies from SSA are (i) comparisons of different sanitation approaches in Uganda [36] and in Burkina Faso [35], (ii) an assessment of cook stoves in TZ [37], and (iii) an evaluation of appropriate farming techniques in TZ [38].

With this study, we want to contribute to advancing the applicability of MC(D)A in the regional context of SSA as well as in the topical context of technology-driven sustainable community development in the Global South and Global North alike.

1.4. Research Objectives & Questions

Based on the MC(D)A methodology, our aim is (i) to develop and propose an integrated method for a participatory sustainability assessment, (ii) to translate into an applicable tool, and (iii) to test the tool with selected stakeholders (*pre-testing*). Our specific focus addresses small-scale cooking and sanitation technologies alongside the use of residues in smallholder farming, and on the example of Tanzanian case studies.

The specific research objectives are: (i) to identify a set of criteria and applicable methods within the framework of MC(D)A; (ii) to develop and propose a handy tool for an *ex-ante*, participatory, and multi-perspective technology assessment; (iii) to conduct a pre-testing of the tool and assess the sustainability of selected technologies.

The research questions are as follows: (RQ1) What are the most relevant criteria and applicable methods for assessing sustainability of small-scale cooking and sanitation technologies? (RQ2) How did the stakeholders involved in pre-testing rated the technologies at hand with regard to relevant criteria and to overall sustainability? (RQ3) How proved specific stakeholder groups perceptions? The RQ1 thereby refers specifically to the methodological development of the tool whilst RQ2 and RQ3 refer to pre-testing of the tool.

2. Used Methodology

Firstly, in Section 2.1, we introduce the study area, the case study projects, and the technologies to be analysed. In Section 2.2, we elaborate on our specific approach to develop an integrated MC(D)A-method and tool for a participatory sustainability assessment of small-scale cooking and sanitation technologies. We introduce the main concept of MC(D)A and explain the process how we have adapted the methodology for our specific context and converted into a tool. In Section 2.3, we shortly present the process applied for pre-testing the tool. Further details on methods, computational works (including equations), and the tool are provided in the Appendix.

2.1. Introduction of the Study Area & Case Studies

The study area is the Karagwe district, in the Kagera region (lat. 01°33' S; long. 31°07' E; alt. 1500-1600 m.a.s.l.). Kagera forms a part of the Lake Victoria basin and is located about 1,500 km away from the Tanzanian capital Dar Es Salaam. The regional economy is dominated by smallholder agriculture with about 90% of households trading agricultural products grown on their farms [14].

Three Karagwe projects serve as our case studies: (i) *Biogas Support for Tanzania* (BiogaST), which aims to implement small-scale biogas digesters to use bioenergy from harvest and kitchen residues for cooking; (ii) *Efficient Cooking in Tanzania* (EfCoiTa), which disseminates advanced designs of improved cook stoves (ICS), such as microgasifier cook stoves; and (iii) *Carbonization and Sanitation* (CaSa), which works with EcoSan, including a urine-diverting dry toilet (UDDT), thermal sanitation of faeces, and composting of human excreta mixed with other organic wastes including *biochar*. The latter material is a residue from cooking with microgasifiers. Cooking and sanitation are connected through the use of residues for soil fertility management, which makes the energy-sanitation-agriculture nexus even more interesting to study. In prior publications, we introduced the case studies [17] and described the technologies [19]. All technologies shall be implemented and used in both, households and institutions (e.g. in schools or hospitals). The local non-governmental organisation (NGO) *Mavuno Project - Improvement for Community Relief and Services* (MAVUNO) facilitates the BiogaST- and CaSa-projects. The *Programme for Community Habitat Environmental Management* (CHEMA) runs the EfCoiTa-project. German project partners are Engineers Without Borders (EWB) Berlin/Germany and *Technische Universität* (TU) Berlin. Financing of the projects is provided by German foundations *BayWa* (BiogaST) and *Heidehof* (CaSa and EfCoiTa). After completing pilot studies, a strategy and a plan for implementing technologies in the smallholder community needs to be developed. Hence, the respective technologies are the subject of decisions at hand. Decision makers are either the NGOs, implementing the technologies on a project-basis, or single households, purchasing them, for example, from local manufacturers or at local markets.

2.2. Designing an Integrated Tool for a Multi-Perspective Technology Assessment

The method shall: (i) enable a systematic analysis; (ii) consider multiple perspectives related to sustainability; (iii) involve local communities and authorities in the assessment; (iv) integrate available data; and (iv) be conducted ahead of the technologies implementation in the community. Against this backdrop, we chose to follow the systematic concept of MC(D)A.

According to [34], MC(D)A consists of three pillars, which are: (i) the presence of multiple criteria; (ii) the formal approach with a set of analytical methods; and (iii) the involvement of individuals or groups of individuals in the assessment (for MCA) or in the decision process (for MCDA). The MC(D)A further combines a range of methodologies to use quantitative and qualitative data for (i) measuring sets of criteria, (ii) considering consequences of decisions, and for (iii) sequencing alternatives [29]. Applied MC(D)As often combine (i) qualitative methods for problem structuring, (ii) quantitative methods for problem analysis, and (iii) soft methods for stakeholder participation [34]. Aggregation of an assessment is possible from the level of different criteria into an overall performance of alternatives and, likewise, from the level of individual preferences into a common, average preference [29] (For the interested reader, a summary of the fundamental terms used in MC(D)A can be found in Table A.1). Based on a comprehensive literature review, especially [23,33,39–43] inspired the design of our MC(D)A approach. The dynamic process of developing the specific design of our method and tool will be described in the following paragraphs (with more details provided in Appendix Section A.2).

(A) Framing the context: Formulating the *decision problem* involved learning about the context of the decision, such as livelihood of the community, specific approaches of the case studies, and ways of using technologies in daily life. The main activities, therefore, included: participating in projects; short- and long-term stays in Karagwe; teamwork with project workers; reading project reports, governmental reports, and non-governmental reports; and communicating with scientists and practitioners in the region. Based on this, we described the environment of the decision including *driving forces* (Table 1) and *motivations* (Table 2) that represent the objectives of the projects initiators to develop and implement 'new' technologies in the Karagwe smallholder community.

In addition, two *Process Flow Diagrams* (PFD) foster a better understanding of the technologies and possible nutrient recycling approaches when interacting with people. Both PFDs indicate how the technologies analysed are integrated in on-farm resource management and how they interact with the natural environment in terms of resource consumption and emissions. One PFD is a more systematic illustration (Figure 1); the other PFD is a more pictorial illustration (Figure A.1).

(B) Creating alternatives: *Alternatives* to be analysed are either (i) discrete technologies or (ii) a mix of technologies [39]. In the present study, we decided to analyse discrete technologies that are defined by the case studies (Table 3; cf. Tables A.3–A.5 for pictures and descriptions). Currently, the most common combination of technologies for cooking and sanitation found in Karagwe smallholdings is a three-stone fire and pit latrine [14]. The alternatives assessed are further technologies that are locally available (i.e. technically and commercially) for implementation. We compared (i) technologies represented in the case study projects, and (ii) other widespread alternatives. Regarding the first point, cooking alternatives include: a system composed of a biogas digester and a biogas burner, developed and adapted to Karagwe conditions by the BiogaST-project; and two types of ICSs promoted by the EfCoiTa-project, such as the rocket stove and the microgasifier. MAVUNO endorses implementation of biogas systems at households through development cooperation projects whilst CHEMA produces and disseminates rocket stoves and microgasifiers at their workshop. Sanitation alternatives include to ecological approaches, namely, "EcoSan" that refers to using an UDDT and "CaSa" that refers to using the UDDT in combination with a sanitation oven for thermal treatment of excreta pursuant to the practices of the CaSa-project. MAVUNO is engaged in testing and promoting both approaches. Regarding the second point, charcoal stoves (also called "charcoal burners") are commonly available in Karagwe on markets and from local stove sellers and a combination of a flush toilet and septic tank can be accessed through local plumbers. The charcoal and biogas alternative also include the charcoal production and biogas digester. These processes provide the energy carrier used in households. Rocket or microgasifier stoves, in comparison, make direct use of firewood or sawdust. The latter is an available waste resource in many anthropogenic settings.

Table 1. Definition of *driving forces* behind the technology development of case study projects. These definitions had been pre-formulated by the planner and were then proofed and agreed on by participants during the design process.

Social driver	Environmental driver	Economical driver
• Provide new technologies to the community, which have progressive reputation. • Increase food security through increased soil fertility and crop productivity.	• Reduce pressure on natural forests by providing cooking technologies that use less firewood or alternative fuels.	• React on social drivers through increased agricultural productivity.
• Reduce poverty through increased farm income generation.	• Recycle nutrients recovered from residues available after cooking or from sanitation facilities.	• Provide organic fertilizers to replenish nutrients in exhausted local soils.

Table 2. Consented definition of the *motivations* behind the technology development of case study projects

Energy	Sanitation	Agriculture
Use available resources appropriately to meet the energy demand of smallholder farming households.	Improve the hygiene conditions in farming households while promoting the recycling of nutrients.	Sustain the quality and productivity of the local soil in order to ensure food sovereignty and farm income.

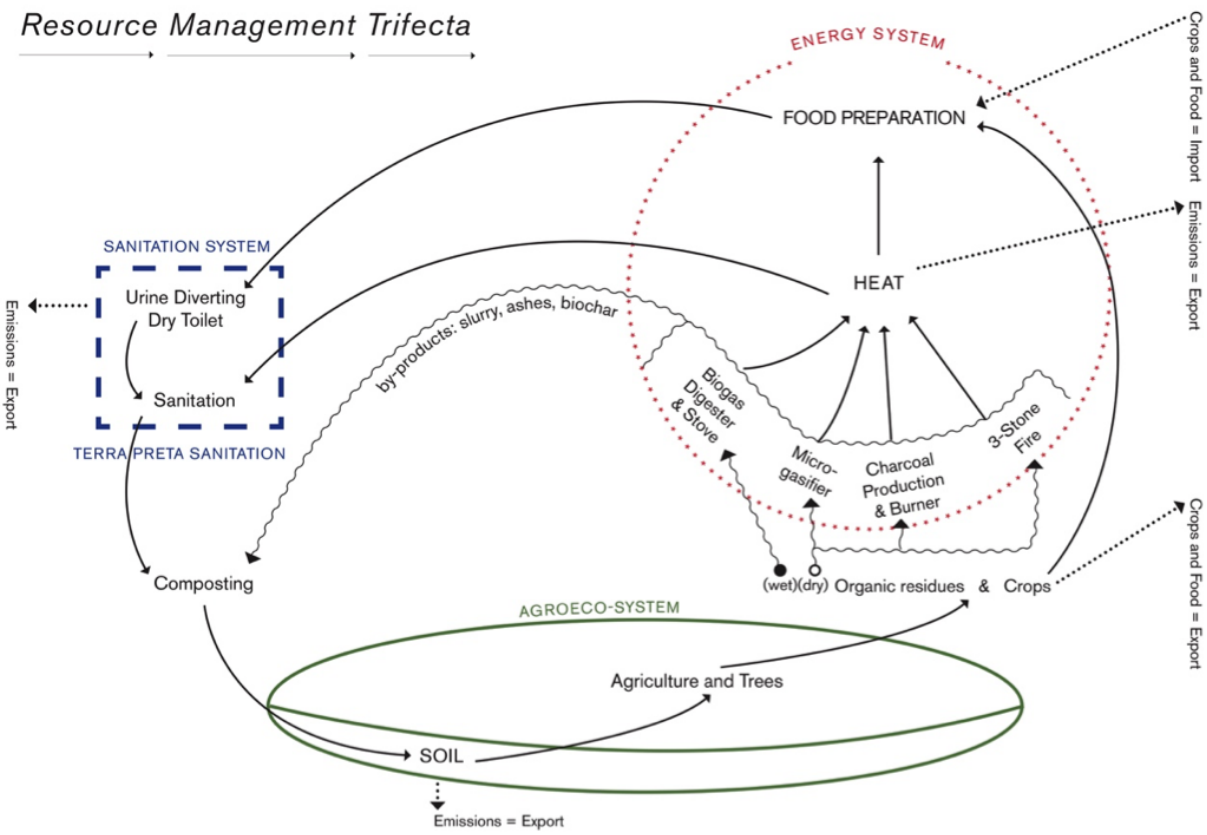

Figure 1. Systematic illustration of the analysed context featured as the “Resource Management Trifecta” [44].

Table 3. Alternatives defined for the sustainability assessment of small-scale cooking and sanitation technologies that are, technically and commercially, available to smallholders in Karagwe, Tanzania

	Cooking alternatives	**Sanitation alternatives**
Current state (not analysed)	Three-stone fire	Pit latrine
Alternatives analysed	1. Charcoal stove (incl. charcoal production)	1. EcoSan: with UDDT only
	2. Rocket stove	2. CaSa: UDDT and sanitation oven for heat treatment of solids
	3. Microgasifier	
	4. Biogas digester and biogas burner	3. Water toilet and septic tank

Non-common abbreviations: CaSa: project “Carbonization and Sanitation”; EcoSan: ecological sanitation; UDDT: urine-diverting dry toilet.

(C) Selecting criteria: In order to operationalize sustainability, relevant and feasible, thus appropriate, criteria need to be identified to describe the multiple dimensions. According to MC(D)A methodology, *main-criteria* describe the *objectives*, or highest-level criteria, and *sub-criteria* describe the *attributes*, or lowest-level criteria [29,32]. To identify such criteria, we performed a comprehensive literature review. Our focus was specifically on comparable work conducted (i) for topics such as bioenergy, EcoSan, and soil fertility or natural resource management, and (ii) in a regional context of TZ, East-Africa, or SSA. We further collaborated with practitioners, academic professionals, and other experts in bioenergy and/or sanitation in an East-African-context. Activities and methods applied include: (i) semi-structured interviews conducted in TZ and Uganda; (ii) group discussions based on the *world café method* [45] in TZ and Germany; and (iii) discussion with the coordinator of BiogaST and CaSa projects (A. Bitakwate) to conclude a final set of criteria.

(D) Collecting data: To *describe* how the alternatives performed against the criteria we needed to collect relevant data. Most data used derive from prior studies related to the case studies [17,19–21]. Additional data originate from project documents of the pilot studies, judgements of local expert, and literature as well as internet reviews. Descriptions provided to participants also include information about data sources and the estimated quality of data (cf. Table A.9).

(E) Analysing stakeholders and selecting participants: *Participants* of a MC(D)A can be split into two groups: (i) the planner; and (ii) stakeholder representatives [40]. The planner facilitates the whole MC(D)A and, therefore, pre-selects criteria, prepares the tool and descriptions of the alternatives beforehand, and moderates the assessment process. Stakeholder representatives participate, in particular, in conducting the *weighting* of criteria and the *scoring* of alternatives. According to [23], relevant *stakeholders* that should be considered when conducting a participatory MC(D)A include: (i) funding agencies; (ii) governmental authorities; (iii) specialists (e.g. stove technicians, EcoSan-experts, or strategic advisors); (iv) (future) staff for operation and maintenance; (v) end-users of the technologies and/or of the by-products; (vi) legislator and enforcement agencies; (vii) research institutions; (viii) local, national and international NGOs; and (ix) site residents (if any). In our case, local smallholders are probably the stakeholders being most affected by the technologies assessed.

(F) Preparing the assessment tool: The following requirements had been defined for the assessment tool: (i) free of charge; (ii) intuitive to use; (iii) transparent (e.g. that it is possible to see and understand also the computational model); and (iv) possible to use off-line for participants because internet access is not always reliable in Karagwe. Unfortunately, most available commercial or free software was not appropriate for several reasons. Most of them were either (i) too cost-intensive, such as V·I·S·A, (ii) too complex, such as PROMETHEE I because visualization is too scientific, or (iii) working only online, such as Decisionarium or Web-HIPRE.

As a consequence, we developed a hand-made and Excel-based assessment tool. The tool is tailored to our specific application and based on a template of [23]. In total, the designed tool comprises sheets for (i) providing information to participants, (ii) collecting judgments of participants during weighting and scoring, and (iii) calculating, summarizing, and visualizing results. The latter include so-called *Performance Matrices* (PM) that summarize weights, scores, and results for each participant and all alternatives. To elicit individual preferences from participants, we selected applicable methods for participatory weighting and scoring from [29,32,39]. The weighting further comprises *ranking* and *rating* of main- and sub-criteria. Ranking is the ordering of criteria according to individually perceived importance. Rating means assigning individual numeric weights as points ranging from 0 to 100 to each criterion in order to differentiate between the criteria.

2.3. Pre-Testing of the Tool

In order to test the developed method, we performed a pre-testing of the tool with a selected group of participants. Subjects of the pre-testing are the alternatives as described above. However, the technologies currently most used are not assessed in order to keep the total amount of alternatives manageable.

Against the backdrop in which there is a significant language gap between Tanzanian farmers and German participants, who mostly do not speak Swahili, we considered direct participation of farmers as not feasible. Furthermore, and pursuant to [46], farmers may hesitate to freely express their thoughts if *white* researchers and/or donors are present during the assessment. Overall, stakeholders participating in pre-testing the MC(D)A tool include: (i) the facilitating NGOs, represented by the management, project coordinators, and other staff members; (ii) the cooperation partners, represented by researchers, volunteers, and donor agents. In total, 10 people committed their participation and the number of participants in each group is, respectively, six (four of MAVUNO and two of CHEMA) and four (four scientists from TU; three members of EWB; and one member of the advisory board from *Heidehof* foundation; including double affiliations). Planner and moderator was A. Krause. In the pre-testing, participating staff members of local NGOs also act as representatives of the local smallholders. (The tool itself should, however, support farmers in decision-making within the smallholder community.)

Pre-testing followed a “9-steps-approach”, where the actual assessment of alternatives is conducted in a stepwise and participatory procedure, including the following nine steps:

1. *Presenting:* Introduction of the context of the assessment, of the MC(D)A method, and of different activities for participants and the facilitator in the assessment's course.
2. *Agreeing:* Presentation of pre-formulated driving forces and motivations for project initiations and request to comment, agree, or disagree.
3. *Self-assessment:* Participants disclose their role as stakeholder defined as their personal role, power, interest, and means of intervention in each of the case study projects.
4. *Weighting:* Participants express their individually perceived importance of criteria by (i) ranking and rating main-criteria and (ii) simple rating of sub-criteria.
5. *Knowledge-exchange:* Presentation and discussion of prior research work and, in particular, those data used to formulate the descriptions of alternatives.
6. *Scoring:* Participants indicate the individually perceived value of an alternative based on descriptions provided by the planner and completed by individual expertise.

7. *Calculating:* The planner (i) calculates weighted scores of all sub- and main-criteria, (ii) deduces aggregated overall results, and (iii) visualizes results.
8. *Conclusion:* Final presentation for sharing results with all participants; if possible, including group discussions and the possibility to adjust individual scorings.
9. *Evaluation:* To evaluate the process, a questionnaire is given to participants for providing feedback and criticism, and to formulate lessons learned.

Unfortunately, due to time constraints and because participants had not been in one place, rather located in both countries, Tanzania and Germany, discussion and adjustments of scoring as part of step 8, was not possible. Planner/facilitator and participants communicated in English and mainly via e-mail or by using Skype or phone calls on demand, for example to clarify questions. Presentations were shared as PDF-documents and via file hosting service. (More details provided in Appendix Section A.3).

3. Results & Discussion

This section starts with a discussion of results as far as the methodology development is concerned whilst addressing RQ1 (Section 3.1.). Thereafter, we present and discuss results of the designed tool's pre-test, and refer to RQ2 and RQ3 (Section 3.2.). Finally, we reflect on the adapted assessment process and tool (Section 3.3.).

3.1. Results from Adapting the MC(D)A Method for the Specific Context

In order to systematically assess the sustainability of small-scale cooking and sanitation technologies, we propose a tool called the Multi-Criteria Technology Assessment (MCTA). We designed the MCTA by adapting MC(D)A and developing a tool, which is adequate for the sustainability assessment of small-scale cooking and sanitation technologies. The process included activities as described in Section 2.2. Results with respect to the identification of most relevant criteria and applicable methods for assessing the sustainability of small-scale cooking and sanitation technologies (RQ1) are presented and discussed in the following paragraph.

Selection of criteria: To define the main-criteria considered in the MCTA, we merged sustainability categories of [47] with aspects from the Integrated Sustainable Waste Management approach of [48] that describes "the enabling environment of sustainability". Finally, we chose the following main-criteria as being most relevant: technological-operational, environmental, health/hygiene, socio-cultural, socio-economic/financial, and political/legal criteria. Pursuant to [23], we use a six-pointed so-called "sustainability star" (Figure 2) to visualise how we define sustainability in the MCTA. Each of the six dimensions represents one of the six main-criteria and thus reflects an objective of sustainability that is addressed in the analysis of cooking and sanitation technologies. Furthermore, the categories "acceptability", "affordability", and "reliability" are assigned to the main-criteria. Derived from Sustainable Development Goal no. 7 of the United Nations, these indicate characteristics, which feature a sustainable use of energy technologies [49].

Figure 2. The sustainability star that was used to visualize and summarize the six main-criteria considered in the MCTA.

The final selection of sub-criteria (Table A.8) constitutes a synthesis of criteria from [23,36,37,50] (cf. Table A.6). From a total of 84 sub-criteria considered in the MCTA, 80 and 75 are applied for assessing cooking and sanitation technologies, respectively (Table A.7).

Overall, we consider the chosen criteria as significant to systematically identify strengths and weaknesses of technologies and to assess their sustainability. However, criteria are not thoroughly independent from each other. Some criteria describe different objectives even though they are related to each other. For example, two of the technological-operational criteria are "preferably high use of locally available resources" and "preferably low use of industrial resources". Both sub-criteria are related to the socio-economic/financial criterion "preferably low cost for implementation" because the material use influences production costs. Another reason for preferring a substantial use of locally available resources is, however, a higher degree of independence from international markets (and main providers of industrial materials). To sum up, most of the sub-criteria applied are intermediate or so-called "means-to-an-end" objectives rather than fundamental objectives [39]. Nevertheless, according to [32] this approach is not contradicting the MC(D)A concept.

Collection of data: Overall, our study integrates quantitative data of recent scientific findings and explorative practitioners' experiences with qualitative data collected from literature, oral explanations by farmers, learning from participating in the projects, and expert judgements. Quantitative data of prior studies, where we employed Material Flow Analysis (MFA) [19] also in combination with Soil Nutrient Balancing (SNB) [21], was particularly important to describe environmental attributes. The MFA identifies and quantifies sources, sinks, directions, magnitudes, connections, dependencies, and shifts of material flows between the anthroposphere and the environment [51]. The SNB specifically measures, calculates, and balances various input and output flows of nutrients to and from agricultural land [52].

Against the backdrop that reaching environmental sustainability requires a systematic reduction of the physical degradation of nature [53], we consider MFA and SNB as highly suitable methods to be integrated in a multi-criteria sustainability assessment. By combining qualitative and quantitative methods for data collection, the MCTA realises an *integrated approach* as recommended by [24].

Data collection, however, was challenging. Available and accessible data in the given context was not sufficient to estimate and to describe performances of most technologies. In order to generate a profound basis for the MCTA, we needed significant additional efforts and approximately two years for conducting performance tests of the technologies, elaborating a field trial and MFA and SNB modelling. Hence, describing the performance of the alternatives was challenging and time-consuming, which resulted in certain shortcomings of the pre-test.

Calculations: The computational model applied in the MCTA is set up through combining the Multi-Attribute Value Theory (MAVT) and Simple Additive Weighting (SAW) out of a wide range of existing MC(D)A methods [29,34]. The MAVT basically uses multiple attributes, for comparing alternatives according to their value. SAW describes the mathematical approach to determine such values through systematic aggregation.

Computations pursue the following process: Firstly, ranking and rating of main-criteria is done by applying the SWING-method [29]; sub-criteria are then simply rated. From the *numeric weights* (i.e. points ranging from 0 to 100) given by participants during rating, the tool supports the planner in determining the *relative weights* of sub- and main-criteria (Equations A.1–A.5). Subsequently, scoring is conducted for each sub-criterion and each alternative separately. Participants therefore assign *numeric scores* in points ranging from −10 to +10 (Table 4) that should reflect their individually perceived performance of an alternative and the associated value. In the MCTA, participants also have the option to waive scoring, by indicating a * instead of assigning points, if they consider available information as insufficient and/or feel unsure about scoring. In offering this *-option, we attempt to not force participants into an arbitrary judgement.

Pursuant to the SAW, the assigned scores are firstly weighted on the lowest level of single attributes. The tool, therefore, determines the *weighted score* for each sub-criterion as the product of (calculated) relative weight and (assigned) score (Equation A.6). Computations are adapted for the *-case as described in the Appendix (Equations A.4 and A.6). Subsequently, plain addition determines the weighted scores for each main-criterion (Equation A.7). To deduce the *overall value* of an alternative, weighted scores are then further aggregated to result in a final *Sustainability Index* (SI). The SI is determined for each person (Equation A.8) along with an *average SI* of all participants for each alternative (Equation A.9). To evaluate *significant* differences between alternatives, value ranges characterised by the mean value ± standard error of the mean (SEM) are compared pursuant to [54].

Table 4. The scoring system applied in the MCTA

Scoring points	Performance of the alternative	Value of the alternative
−10	Extremely weak/poor	Strongly unfavourable
−5	Poor/fair; major improvements needed	Unfavourable
0	Good, ordinary	Acceptable
5	Very good; still needs some improvement	Favourable
10	Excellent	Very favourable
*	Not clear to me	Not assessable

Presentation of results: To understand the variety of assessments of individual participants, the visualization of results is an essential element of the MCTA. In total, the tool provides the following visualizations, which are inspired by [23]: (i) a colour-coded scatter plot showing the relative weights assigned to main-criteria; (ii) bar diagrams ranking the alternatives with respect to the average SI; (iii) colour-coded scatter plots showing the average SI for all alternatives in one graph; (iv) colour-coded scatter plots showing assessment results on the level of main-criteria; (v) colour-coded bar diagrams showing the distribution of the SI as the balance of positive and negative weighted scores on the level of main-criteria; and (vi) a summary of scoring and weighting results on the level of main-criteria. The latter three types of visualizations summarize the voting of all participants in one graph for each alternative. The colour-coded scatter plots indicate assessment results of different stakeholder groups alongside the mean of all participants in different colours. The first and fourth graphs are designed by using a net diagram and by arranging the axes that represent main-criteria according to the sustainability star. The sixth graph visualises connections between the perceived importance of a certain dimension of sustainability and the assigned performance of an alternative. The former is indicated by numeric weights assigned to respective main-criteria plotted on the x-axis and the latter by numeric scores that an alternative receives for certain main-criteria plotted on the y-axis. The area, where certain main-criteria score negatively (numeric score < 0) while, at the same time, these main-criteria are considered important (numeric weight > 50), is marked as "red area". Results are presented for all main-criteria (colour-coded symbols) and for all participants (number of signs) in one graph for each alternative.

We acknowledge that the computational approach of the MCTA is rather simple, however, in accordance with basic principles of MC(D)A modelling [29]. For example, on the one hand, the final single index makes alternatives directly commensurable [*ibid.*]. On the other hand, the applied methods, MAVT and SAW, belong to compensatory MC(D)A techniques [*ibid.*]. This means that a very bad scoring for one attribute can be compensated by a very good scoring for another and *vice versa*. Furthermore, instead of determining specific value functions for each participant, we assumed linearity. The main reason was to avoid overstraining participants. Furthermore, the statistical approach is rather simple but viable. As featured by [34], who demand a "more transparent, simple, and easily accessible participatory modelling paradigm and process", we thus consider the MCTA as a valid methodological extension of the MC(D)A. Finally, visualisations support communication of results to and between participants. Graphs are designed so that they can effectively help (i) to reveal issues that need to be addressed before considering a technology suitable for sustainable community development, (ii) to identify the specific fields where further improvements of the technology are needed, and, finally, (iii) to avoid potential project ruptures in the future.

3.2. Selected Results from Pre-Testing the Tool

In order to perceive the feasibility of the developed method and tool, we performed a pre-testing of the MCTA. In this section we firstly show how participants weighted the different main-criteria describing the overall sustainability. Subsequently, we present selected results of the sustainability assessment of cooking and sanitation alternatives. We provide additional graphical visualizations alongside plot data in the Supplements.

Weighting of main-criteria: In the course of MCTA's pre-test, the choice group of participants assigned, on average, the highest weights to the environmental main-criterion; the political-legal objective is perceived as least important (Figure 3). Second in level of importance are the remaining four main-criteria with no significant differences (Figure S.2). We further find a high variance in the distribution of weights of all participants. Weightings among participants are most divergent for socio-cultural criteria ($\Delta_{min}^{max} \approx 20\%$) and least divergent for political/legal criteria ($\Delta_{min}^{max} \approx 11\%$).

Comparing weights assigned by participants, there is a tendency that Tanzanians consider health/hygiene and environmental criteria more important in comparison to Germans. German representatives, in contrast, perceive technological-operational and socio-cultural criteria as more important compared to Tanzanians.

We explain the finding that stakeholders consider the environment to be the most important dimension of sustainability because the environmental main-criterion include many sub-criteria related to agriculture, and is consequently perceived as highly important for smallholders. On the contrary, according to [55], residents in the vicinity of Arusha/TZ do not consider environment as an important objective when choosing renewable energy technologies for electrification. Only one interviewee out of about 40 respondents, who were mainly farmers, addressed an environmental criterion as an influencing factor to purchase a solar home system [*ibid.*]. Respondents instead mentioned health and hygiene as the most important objectives for their families [*ibid.*].

Additionally, [56] state that environmental criteria are less relevant for residents when assessing sanitation systems in a peri-urban area in Burkina Faso. In order to perceive a certain sanitation system as appropriate, factors such as costs and service quality are most relevant for participants [*ibid.*]. Nevertheless, we understand our finding that environmental criteria are most relevant, by the fact that (i) our study area is a rural area farther away from urban settlements compared to the study areas of [55] or [56] and (ii) that many participants in our study are closely related to environmental settings (e.g. farmers with off-farm income, agricultural technicians, environmental scientists, and environmental activists).

In other comparative studies of small-scale bioenergy technologies from SSA, however, highest weights are assigned to the technological-operational criterion. For example, in an assessment of ICSs available on the Tanzanian market, criteria related to the construction or operation of stoves ranked highest, such as manufacturability, durability, or portability [37]. Furthermore, stakeholders participating in an assessment of a biogas system in Bahir Dar, a city in northwest Ethiopia, consider technological-operational criteria as most important dimension of sustainability [23].

In our study, lowest priority is assigned to the political/legal main-criterion. We reason that there is little governmental support in TZ and especially in the study region, which is recognized by stakeholders, and thus influences their judgements. National programs for promoting renewable energies and supporting access to such technologies especially in rural areas of TZ include the Rural Energy Fund, the Rural Energy Agency, and the Tanzanian Domestic Biogas Program (TDBP) [37,57]. However, to our knowledge, these programs have not yet reached Karagwe. For example, TBDP has not yet chosen or appointed implementation partners in the region. According to [37], Tanzanian standards for cooking technologies are only available for charcoal stoves whilst existing standards are not enforced. Furthermore, governmental initiatives, intended to support bioenergy implementation, are not coordinated and, thus, largely inefficient [*ibid.*]. With respect to sanitation, [58] also criticizes a strong lack of legislation in the sector of non-sewer sanitation service in TZ.

The finding that only average importance is given to socio-cultural aspects is comparable to studies of [23] and [37] and in the study of [56] only minor importance is assigned to socio-cultural criteria.

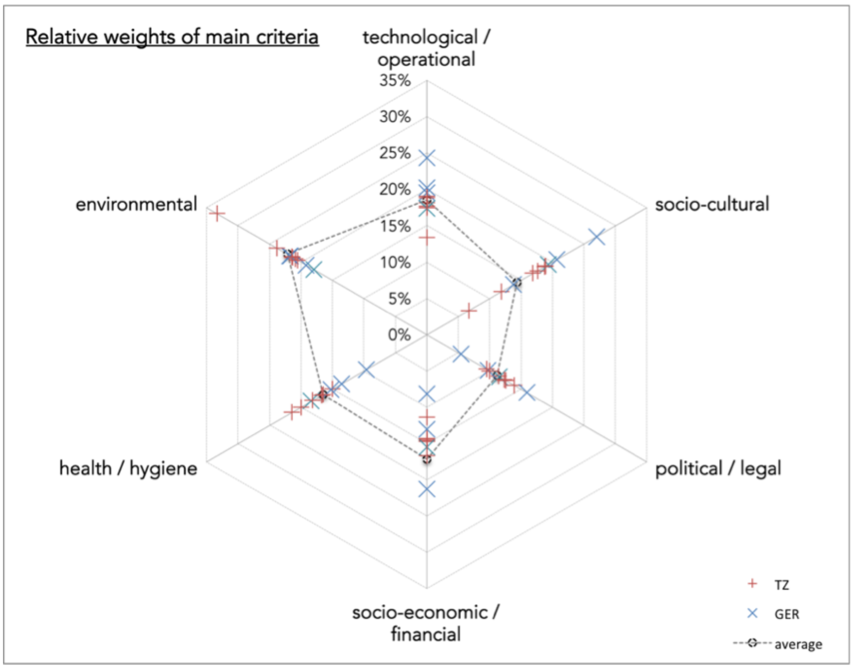

Figure 3. Colour-coded scatter plot of the *relative weights* of the *main-criteria* (in%) of Tanzanian (red) and German (blue) participants alongside the mean of all participants (grey). [The sum of all six main-criteria is 100%.]

Sustainability assessment of cooking alternatives: When pre-testing the MCTA, all analysed alternatives reach average SI-values between 0 and +1 (Figure 4). Hence, the choice group of participants perceives cooking alternatives overall as "acceptable" and attributes a "good, ordinary" performance to respective technologies (cf. Table 4). Mean values of the four alternatives, however, do not significantly differ from each other, as overlapping error bars in Figure 4 indicate [54].

Regarding the six dimensions considered to assess sustainability, all stoves receive positive (weighted score >0) assessment results mainly for health/hygiene, socio-cultural or technological-operational (except biogas system) functions (Figure 5). Negative (weighted score <0) assessment results refer to socio-economic/financial (for charcoal and biogas alternatives) and environmental (for charcoal only) criteria.

When crosschecking the assessment results with literature, we consider our findings for cooking alternatives as highly comparable to [37]. In both studies, microgasifiers and rocket stoves receive positive scores because of their potential to reduce fuel consumption and greenhouse gas (GHG) emissions.

Interestingly, Tanzanian participants in particular assigned positive scores to the biogas system and for subcriteria on GHG-emissions despite the fact that the description clearly stated that GHG-emissions would *increase* compared to cooking on a three-stone fire. We reason that Tanzanian stakeholders are aware of the minor influence of TZ on global GHG-emissions, compared to Germany, other European countries, or the United States. We further argue that there is a strong and positive pre-conception of the biogas system as an "environmental-friendly technology". Regarding the usability of cooking technologies, all stakeholders participating in the MCTA agreed that the biogas system performs the worst of all alternatives analysed. Major problems identified are thereby (i) water requirements for a sound operation of the digester and (ii) lack of robustness of the system towards changes in climate conditions and user abuse. Also with respect to costs (including costs for implementation, operation, and maintenance), the biogas technology is assessed as the most disadvantageous cooking alternative. To underline scorings of costs, investment costs of locally available alternatives in Karagwe are as follows: costs for implementing a biogas system are approximately €1,200 , which makes possessing a biogas digester a substantial investment for smallholders. In comparison, acquisition costs of charcoal stoves or ICSs range from 2 to about €25 (cf. Table A.5). Furthermore, [57] identify high installation and maintenance costs as key barriers for biogas implementation in TZ, despite the fact that households are willing to adopt the technology. Hence, [57] conclude that implementing biogas in rural areas requires financial support by national programs through subsidies and/or loans.

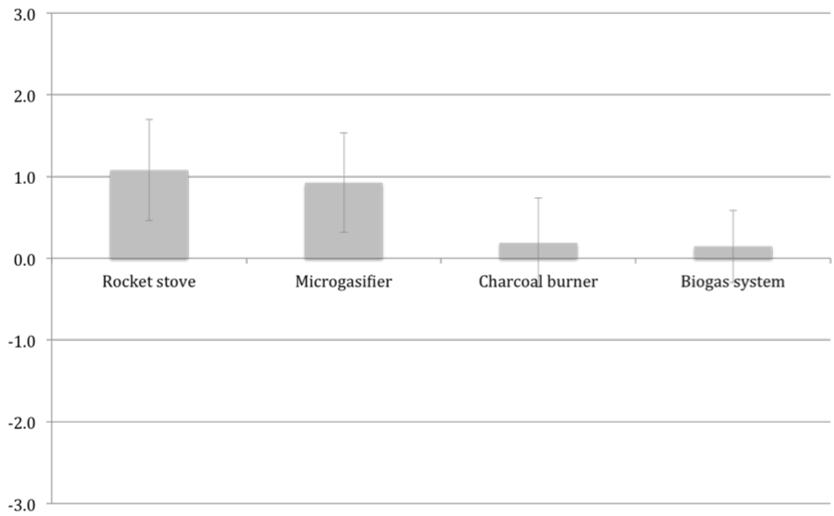

Figure 4. The average sustainability index (SI) of cooking alternatives analysed, presented as mean value of all participants and in ranked order. The SI-values range from -10 to $+10$ (cf. Table 4). Grey bars indicate the standard error of the mean (SEM).

Considering the perceptions of stakeholder groups, we find a very high variance in individual valuations of participants. On the example of the rocket stove, weighted scores of main criteria range from -5 ("unfavourable") to $+7$ ("clearly favourable") between participants (Figure 5). With respect to the SI, most Tanzanian representatives assess charcoal burners, rocket stoves, and microgasifiers negatively and below the average SI (Figure S.3). German participants, however, assess these technologies with positive and above-average valuations. A reverse tendency, however, is depicted for the biogas systems: judgements of German participants are rather negative and below the average SI, whilst Tanzanians assess the technology positively and above the average SI. Most prominently, staff members of CHEMA ascribe the highest positive points to rocket and microgasifier stoves, which are the cooking technologies that CHEMA disseminates. Likewise, staff members of MAVUNO rate ICSs with rather negative scores compared to the biogas system, which is the technology MAVUNO promotes in Karagwe.

Sustainability assessment of sanitation alternatives: Pre-testing the MCTA, all alternatives reach average SI-values in the range of about -2 to $+2$ (Figure 6). Both ecological approaches to sanitation are rated significantly better compared to the septic alternative. There is, however, no significant difference in the assessment of EcoSan and CaSa because respective error bars in Figure 6 overlap [54]. Overall, the performance of EcoSan and CaSa approaches is assessed as "good or ordinary", which means that the choice group of participants values both approaches as "acceptable" to "slightly favourable" alternatives. On the contrary, participants assess the septic alternative as "slightly unfavourable" alternative.

Regarding the six sustainability dimensions, EcoSan and CaSa receive positive assessment results mainly for technological-operational, environmental, and socio-economic/financial functions (Figure 7). Negative assessment results refer, in particular, to the political/legal criterion. Shortcomings of the septic alternative mainly refer to the environmental, health/hygiene, and socio-economic/financial criteria.

Crosschecking our results with literature, the observation that a clearly better socio-economic/financial performance is assigned to the ecological approaches compared to the septic alternatives, is in line with [56]. For the case of Burkina Faso, [56] report that in particular low- and middle-income households perceive the UDDT as more financially appropriate compared to septic tanks. Strategic thinking, which includes considering operational costs as an important factor, influences households' judgements [56]. In contrast, high-income households consider the septic system as more appropriate compared to the UDDT, because for this social group factors such as service quality are more important than costs [*ibid.*]. Farmers in Karagwe belong, however, mainly to low- and middle-income household groups [14]. (Table A.5 summarizes costs of sanitation alternatives.)

The pre-test further indicated certain doubts about the approaches, in particular on the sub-criteria "safe working conditions" and "safety in operation through avoiding risks of infection to users". In contrast, literature commonly promotes EcoSan as a *safe* sanitation alternative because of the multi-barrier approach applied [12,59]. To our knowledge, there were, however, no instances of sickness during the course of the CaSa pilot project that ran more than four years. Further investigations might follow-up this significant observation (cf. Section 4.2.). In total, the performance of ecological alternatives against the health/hygiene main-criterion is neutral. Our finding ultimately supports integrating health/hygiene as criterion when assessing sanitation technologies. This helps to identify areas of conflict, as shown in our case. Health/hygiene criteria should, therefore, not be excluded from analyses as it was, for example, the case in studies by [56] or [60].

Furthermore, we find that socio-cultural performances assessed for EcoSan and CaSa alternatives are comparable to assessment results for the septic system. We attribute this finding to the practical demonstration of UDDT-technology in the region. On the contrary, [56] identify UDDT as less socio-culturally accepted compared to a septic system and, therefore, request more alternatives and their advantages and disadvantages before assessing the technologies. This was exactly the case in the CaSa pilot project's course.

Perceptions of stakeholder groups with respect to the average SI assigned to sanitation alternatives (Figure S.4) reveals as well high variations in assessment results. The EcoSan alternative, for example, weighted scores of main criteria range from -7.5 ("clearly unfavourable") to $+6.5$ ("clearly favourable") between participants (Figure 5). Nonetheless, the characteristic patterns of stakeholders' valuations differ here. For both ecological alternatives, Tanzanian stakeholders assess negatively and below the average SI, whilst German participants rate the alternatives clearly positive and above the average SI. In contrast, most German participants assess the septic alternative as clearly more negative and below the average SI compared to their Tanzanian fellows. Only for the septic system, the assessments of all participants are rather homogenous and less differentiated compared to other sanitation technologies. In addition, the septic alternative receives an average negative SI from all except one participant. Most prominent is, however, that one German participant, who has been strongly involved in designing, developing, and testing the CaSa-approach, assigns the highest positive scores to that sanitation alternative.

3.3. Reflection and Critique of the Assessment Methodology and Process

In this section we firstly summarize experiences, insights, and lessons learned, that derived from the participatory pre-test of the MCTA regarding the assessment process and tool. Next, we discuss certain shortcomings of the methodology. Specific adjustments we recommend for future applications of the MCTA are summarized in Section 4.2.

In the first instance, the participatory design of the method we developed is a direct response to [34], who stress the need to develop more participatory elements at all levels of MC(D)A to make the method applicable in real-world practices. The relevant problem addressed is the ex-ante sustainability assessment of small-scale cooking and sanitation technologies in the exemplary context of smallholder communities in Karagwe, TZ.

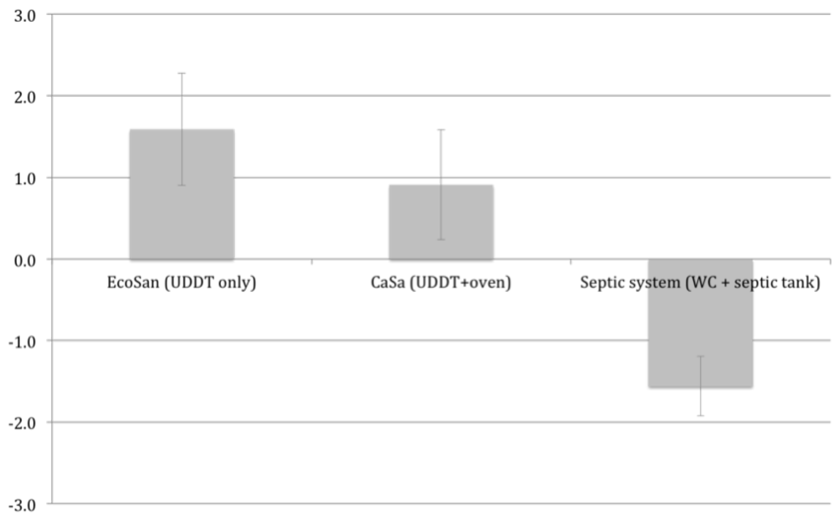

Figure 6. The overall sustainability index (SI) of sanitation alternatives analysed, presented as mean value of all participants and in ranked order. The SI-values range from -10 to $+10$ (cf. Table 4). Grey bars indicate the standard error of the mean (SEM).

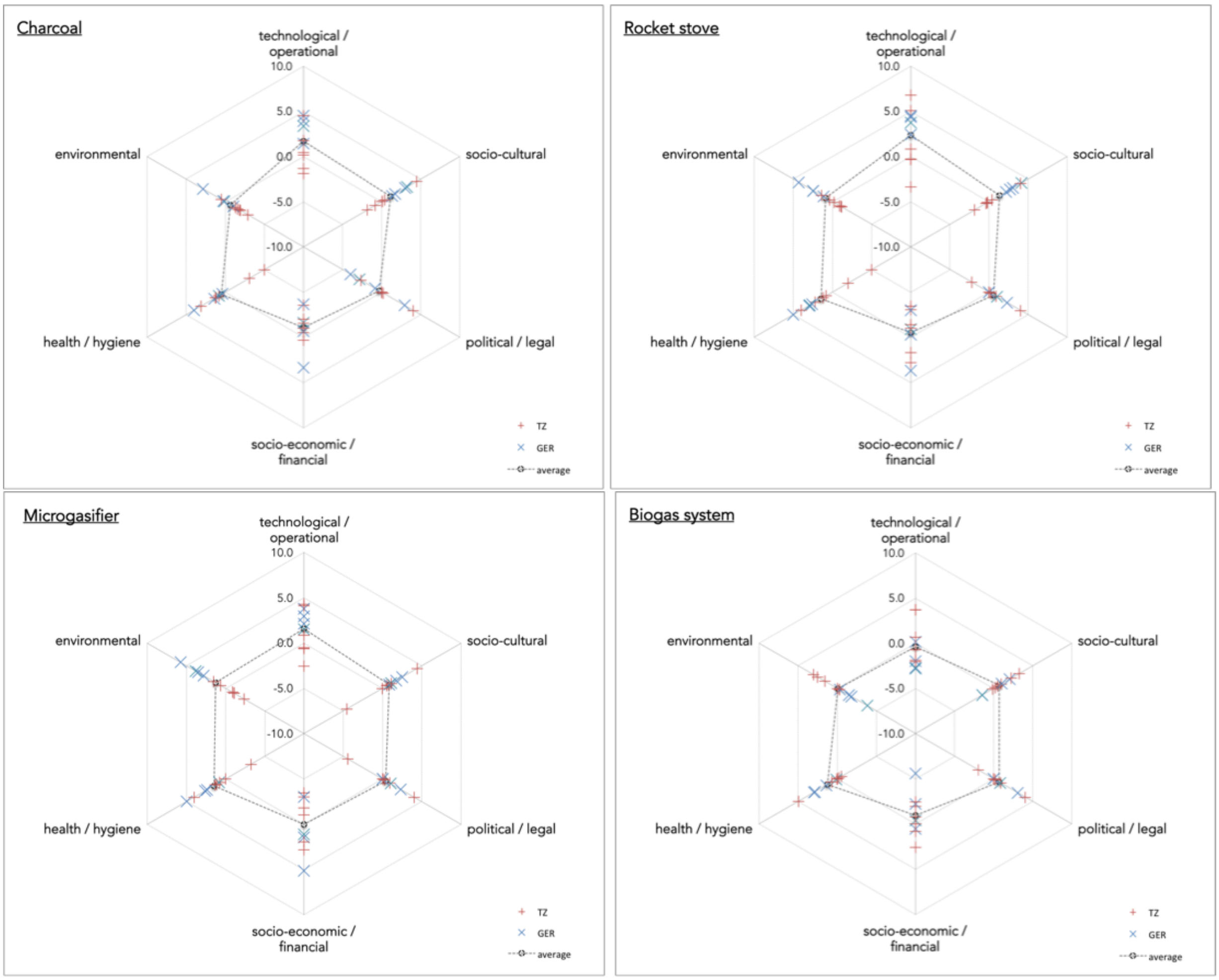

Figure 5. Colour-coded scatter plot for the four cooking alternatives analysed (charcoal stove, rocket stove, microgasifier, biogas system) indicating the assessment results of Tanzanian (red) and German participants (blue) alongside the mean of all participants (grey). Results are shown on the level of the six main-criteria. Values range from -10 to $+10$ (cf. Table 4).

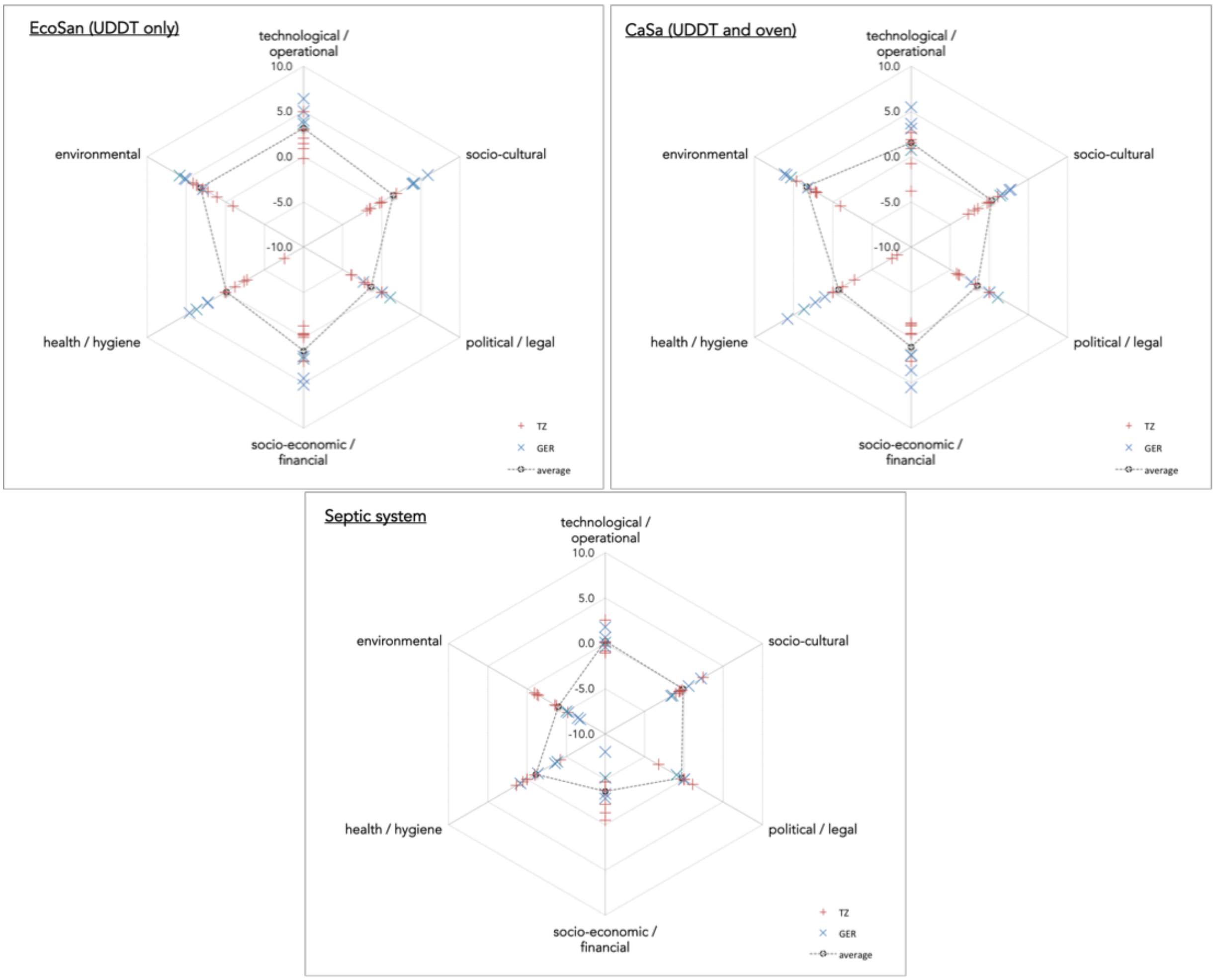

Figure 7. Colour-coded scatter plot for the three sanitation alternatives analysed (EcoSan, CaSa, and septic system) indicating the assessment results of Tanzanian (red) and German participants (blue) alongside the mean of all participants (grey). Results are shown on the level of the six main-criteria. Values range from -10 to $+10$ (cf. Table 4).

We further learned that the visualisations of results, as integrated part of the MCTA-tool, are highly supportive to shed light on individual perspectives and valuations of stakeholders for the assessed alternatives. The visualisations help to make subjectivity in scoring results transparent. Here, we agree with [40] who emphasises that showing stakeholders each other's preferences is rather one of the most relevant results of conducting an MC(D)A. The visualisations further allow for a target-oriented improvement to overcome shortcomings of the technologies. Due to the low sample size and the high variance we observed in the tool's pre-test, some visualization are not discussed thoroughly in this article. They are, however, presented in the Supplements (cf. Figures S.5–S.8).

As other benefits of the MCTA, we concluded that the assessment process promotes collaborative learning and a better understanding of the technologies assessed. Final feedback revealed that five out of six participants articulated that the MCTA supported them in forming their own opinion about the technologies (Figure S.9). Hence, our method reacts on [61] who promote "embedded learning", that is integrating recent findings and sustainability assessment. This integration also constitutes an important part of the analytical tool we developed. Information that is provided to participants during the assessment process and describe various impacts of the technologies assessed, originate *inter alia* from recent action research conducted in Karagwe.

Despite these benefits, we further experienced the challenge of "balancing three tensions: (i) maintaining scientific credibility, (ii) assuring practical saliency, and (iii) legitimising the process to multiple participants" [62]. In particular, we identify certain limitations referring to (I) the choice of alternatives and participants, (II) the realised means of participation, (III) time consumption, communication effort and complexity, and (IV) gender balance.

(I) Firstly, we acknowledge that technologies mostly applied for the time being, which are three-stone fire and pit latrine, are not among the alternatives assessed. One could further criticise the fact that farmers were not involved in the assessment even though they represent the party most concerned and that the technologies assessed were developed to improve livelihoods of smallholders. Reasons for conducting a pre-test of the MCTA-tool with local representatives limited to NGOs' staff members are disclosed in Section 2.3. Our proceeding is supported by [63] who also recommend establishing intermediaries between research institutions and farmers when evaluating agricultural projects. Culture and social standing of research and/or NGOs can inhibit reciprocal communication between researchers and farmers.

(II) We acknowledge that the MCTA process is not participatory throughout as intended. This is a consequence of additional empirical data generated and that we faced a conflict between the scope of the work and the available time budget when actually starting the pre-test. Hence, we had to adapt the 9-steps-approach. Initially we wanted to include more feedback loops during the process, for example, in order to discuss experiences after scoring, and, thereafter, offering participants the opportunity to adapt their valuations. Moreover, the assessment was conducted separately, meaning that Tanzanian participants were in TZ and German participants in Germany. This fact results, in limited insights into the individual perceptions and, thus, inhibits *joint* understanding and learning of participants.

(III) We understand that high time consumption is often reported as a problem when conducting a participatory MC(D)A [38,40]. Nonetheless, in the final feedback, most participants judged the scope of the MCTA, defined by time budget, details, number of criteria, clarity of the task, amount of information, etc., as good and to cope with (Figure S.9). Moreover, extensive communication (via e-mail and Skype) between the planner and individual participants was required to identify and solve possible misunderstandings. For example, participants scored alternatives significantly different although the performance of these alternatives was described as strongly comparable. Differing backgrounds of participants might explain this, as well as the problems they faced in understanding all (scientific and non-scientific) terms used in the descriptions. Participants might also simply not agree with the description provided, due to contrasting personal experiences and knowledge. However, because of the decentralized process we applied, it was not possible to directly address these observations, for example in individual or group discussions.

(IV) Lastly, we acknowledge that we pre-tested the MCTA-tool with in total two females and eight males; both women *white* and with academic background. Hence, we failed to reach a gender balance and, in particular, to include female representatives of Tanzanian partners. We attribute this shortcoming (i) to choosing English as working language, and (ii) to a general dominance of men at the level of project coordination and/or management in the participating NGO communities.

With regards to differences in stakeholders' perceptions, our findings are further in line with [29], who state that applying a MC(D)A-approach does not create an objective, unbiased, and value-free analysis. In a nutshell: individual perspectives and subjective judgements are "normal". It is hence a methodological challenge to make these differences visible instead of neglecting them. For example, we found that assessments of participants in the pre-test seem substantially biased towards the technology they promote. Visualizing these differences expediently is only the first step. The lack of group discussion (as part of the step 8; cf. Section 2.3.) is a clear shortcoming. For example, we have no specific insights into *why* differences exist and which arguments underlie the variations observed. Interpretation of results (by participants and the authors) is thus largely based on guesswork.

According to the final feedback, two thirds of participants believe that the MCTA is also applicable within their community if further adapted (cf. Section 4.3). In particular, the tool can help (i) to clarify existent doubts and expected benefits, (ii) to stimulate discussions, and (iii) to compare varying assessments of projects facilitating NGOs and local communities.

4. Conclusions & Recommendations

In this section, we firstly summarize overall conclusions from the work presented with respect to developing the MCTA (Section 4.1.) and the pre-test (Section 4.2). We close the article with a summary of recommendations to adapt the tool for future real-world applications in Karagwe or elsewhere (Section 4.3).

4.1. Scientific Relevance of the Methodological Work

With respect to the objective to develop an integrated method for a participatory sustainability assessment, we conclude the following strengths and benefits of the MCTA method and tool:

- Inclusion of a set of relevant criteria for assessing sustainability of small-scale cooking and sanitation technologies, which can also serve as a catalogue from which specific criteria for a given context can be chosen.
- Adequate organization of available data that describe various effects of technology implementation in relation to sustainability and to a particular objective-driven decision, such as sustainable community development.
- Realization of a transparent computational approach with a combination of applicable methods and a replicable Excel-tool.

- In-depth exploration of different alternatives with respect to their sustainability and in an iterative effort and moderated process.
- Instructive presentation of the current understanding of the analysed technologies by aggregating judgements of individual participants into a ranking of alternatives.
- Target-oriented mapping of individual perceptions in order to effectively track conflicting stakeholder opinions and to react to conflicts at an early stage, for example, *before* a decision for implementation is made.
- Target-oriented identification of the most relevant aspects where improvements of the analysed technologies are still needed.

From a methodological perspective, combining the MC(D)A with analytical methods is a viable *integrated approach* to sustainability assessment. On one hand, MC(D)A helps to structure the assessment. On the other, the integration of results from analytical studies, such as MFA, SNB, or laboratory analysis, allows for illustrating the performance of alternatives assessed through semi-quantitative objectives of sustainability, and particularly the environmental dimension.

Finally, the developed method provides hands-on support through a decent set of criteria and a basic assessment tool. Basic skills in Excel are the main requirement for using the MCTA-tool. Nevertheless, conducting an MCTA is an extensive process that demands considerable time budgets and a strong commitment from all participants.

To summarize, we conclude that the MCTA is an appropriate and applicable method to analyse potential effects and interrelations of different cooking and sanitation technologies on household levels. The method also indicates contradictions with respect to different sustainability goals. In addition, the MCTA enhances transparency about individual preferences, values, doubts, and objectives among all participants, respectively stakeholders.

4.2. Practical Relevance of Pre-Test Results

Even though the number of individuals participating in the pre-test of the MCTA was rather small, we conclude:

- All cooking and sanitation alternatives need further improvements before considering the technologies as appropriate and viable options for sustainable community development.
- Further improvements include enhancing the technological-operational and socio-economic/financial performance of the technologies and pushing political/legal actions that support the implementation of cooking and sanitation technologies on household levels.
- Valuations of alternatives clearly differ between participants and, in particular, with respect to different groups of stakeholder representatives.

With respect to the latter, representatives of the German project partners generally tend to be more enthusiastic about the analysed technologies while representatives of the Tanzanian partners are more sceptical. This observation holds true especially for the ICSs technologies, such as microgasifier and rocket stoves, and the EcoSan and CaSa sanitation alternatives. Technologies that are more common and established in both countries, such as biogas or septic systems, are assessed more similarly among participants. Another example for varying assessments is that representatives of the implementing NGOs and of the technology-developers or scientific partners tend to favour the alternative that they have supported and accompanied, and, likewise, rate competing technologies below average.

From our hands-on experience in facilitating the MCTA pre-test, we finally hypothesise that the higher the assessors diversity with respect to education, language, class, and scientific or practical experiences and knowledge, (i) the more difficult the process because of uncertainties about the common understanding and (ii) the more important the process and the more interesting the results. Testing this hypothesis could be subject of future scientific MC(D)A work.

Pre-testing the MCTA with a choice group of participants can serve as a basic proof-of-concept, with the method as a simple but viable sustainability assessment tool for the multi-perspective evaluation of cooking and sanitation alternatives. Hence, we conclude that, by providing a framework and a tool, the MCTA can effectively support case studies and relevant strategic planning and decision-making. Moreover, the MCTA is also practicable for other real-world applications related to small-scale cooking and sanitation technologies, such as in other regions and/or for other technologies.

4.3. Recommendations for Future Real-World Applications

If the MCTA is applied in a different setting, necessary adjustments include re-phrasing the descriptions of alternatives and adapting the set of criteria. To make the MCTA further applicable for its use in communities, methodological challenges and problems, as described in the preceding sections, need to be addressed. We thus recommend the following with respect to the choice of participants:

- Inclusion of farmers or other *end-users* of the technologies as participants while avoiding the dominance of participants representing implementers, researchers, or donors.
- Inclusion of agency representatives in order to push policy development and/or national support programs, such as subsidies.
- Realisation of a larger number of participants.
- Awareness of an adequate gender balance in the assessment team.

In addition, we recommend the following with respect to the assessment process and method:

- Reduction of complexity and workload, for example through intelligent reduction of the number of sub-criteria.
- If possible, conducting the MCTA with participants located at one spot, at least during scoring or evaluation of results.
- Inclusion of more feedback loops through group meetings and discussions at different steps of the MCTA.
- Potentially, the assessment could also be conducted in separate groups for men and women in order to allow women to speak more openly.

Reducing the number of sub-criteria could follow a participatory approach comprising, firstly, a moderated discussion about the existing catalogue of sub-criteria and, thereafter, a selection of those criteria considered as the most relevant. Methodologically, the "silent negotiation" could be applied in a moderated workshop, which helps to cope with power-imbalances in the consortium [24]. If practitioners do not aim at running through a whole assessment process, the existing catalogue of criteria could also serve to structure focus group discussions or community assemblies. Moderated discussions between participants can help to enhance the joint understanding of arguments that underlie and explain differences in the quantitative assessments. For example, a group discussion after reading the descriptions can help to ease a common understanding about the information provided *before* scoring the alternatives. At the same time, such a discussion could help to alleviate the time budget of the facilitator for clarifying open questions from participants. With more time available, another option could be to firstly conduct scoring of alternatives without description, secondly with description prepared by the planner, and finally to compare and to discuss results together. Finally, and with respect to the alternatives, we recommend the inclusion of technologies that are most commonly applied so far to support a comparison of alternatives to the actual real-world situation.

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[25] According to [24], MCDA is *"an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter"*.

[26] We use the abbreviation MCDA for referring to *Multi-Criteria Decision Analysis*. Other established names for the method include multi criteria decision aid, multi attribute decision making, multi objective decision making, or multi criteria decision making [91].

[27] According to [29], a Multi-Criteria Analysis (MCA) "establishes preferences between options by reference to an explicit set of objectives that the decision making body has identified".

[28] The abbreviation MCA refers also to Multi-Criteria Assessment [32].

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[83] The conceptual and analytical work was supported by Dr. L. Scholten.
[84] 'Stakeholder' is defined as: "actors who have a stake, an interest in the issue under consideration; who are affected by it, or who -because of their position - have or could have an active or passive influence on the decision making and implementation processes".
[85] 'Power' is defined as: "the extent to which they (i.e. the participants) are able to persuade or coerce others into making certain a decision or following certain courses of action".
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Chapter 7

Synthesis

This final and concluding chapter starts with a summary of the main findings from my work (Section 7.1), presented in Chapters 2 to 6. Subsequently, I discuss the relevance of my results for practice (Section 7.2) and potential opportunities and challenges identified for real-world applications (Section 7.3). The final conclusions begin with a brief reflection on the methodologies applied (Section 7.4). Thereafter, I present fields of interest identified for future research (Section 7.5). This chapter closes with a formulation of my overall conclusions (Section 7.6).

7.1 Summary of main findings

In this section, I summarize the main findings from the five publications (P1 to P5) with respect to my research questions presented on page 35.

7.1.1 Laboratory-based characterization of locally available substrates (P1)

This first paper introduces the case study projects and assesses locally available biogas slurry, standard compost, and CaSa-compost for their fertilization potential. The analysis of total element concentrations has revealed the following initial findings for answering RQ 1:

- Nutrient concentrations:
  - All treatments analyzed are characterized by (i) sufficient nutrient concentrations for appropriate plant fertilization (Table 1 in P1) and (ii) adequate nutrient ratios to avoid immobilization of nutrients in the soil.
  - The CaSa-compost shows an outstanding fertilization potential with highest concentration of all analyzed nutrients; for example, P-concentration in CaSa-compost is 1.7 g dm^{-3} compared to 0.5 and 0.3 g dm^{-3} in standard compost and biogas slurry, respectively.

- Potential impact on availability of nutrients in the soil:
  - All treatments tested show good liming potentials compared to other soil amendments, such as poultry or cattle manure, ammonium sulphate, urea, etc. (Table 2 in P1).
  - CaSa-compost is outstanding with a liming effect of 7.8 kg CaO kg^{-1} N compared to 2.6 and 3.4 kg CaO kg^{-1} N of the standard compost and biogas slurry, respectively[1].

7.1.2 Exploratory study of using locally available substrates as soil fertility improvers (P2)

After the initial characterization of substrates, I conducted a practice-oriented field trial on the local Andosol. The one-season experiment has provided empiric evidence of the following effects for answering RQ 2:

- Soil physicochemical properties:
  - Availability of nutrients in the soil improved, in particular, after amending Andosol with CaSa-compost due to (i) significantly higher addition of total P (P_{tot}) with comparable doses of mineral N (N_{min}) applied (Table 3 in P2), and (ii) a significant effect on soil pH (Table 4 in P2), which is attributed to biochar contained in CaSa-compost.
  - Levels of soil P rose significantly after the experiment, only on soil amended with CaSa-compost, to a concentration of calcium acetate lactate (CAL) soluble P (P_{CAL}) of 4.4 mg kg^{-1} compared to 0.5 mg kg^{-1} on unamended control plots (Table 4 in P2).
  - No significant effect on availability of soil water (Fig. 2 in P2), on concentrations of total organic carbon (TOC), or on CEC_{eff} for none of the amendments tested.
- Biomass growth and crop productivity:
  - Biomass of maize increased, in particular, when using CaSa-compost (Table 5 in P2).
  - Grain yields of maize on soil treated with CaSa-compost, standard compost, or biogas slurry increased to about 400 %, 290 %, and 240 % respectively when compared to yields on unamended soil.
  - Biomass and yields of beans and onions significantly increased in the case of soil amended with CaSa-compost and standard compost only, while plant growth of cabbage clearly increased for all three amendments tested (Fig. 3 in P2).
- Plants nutrient status:
  - Total uptake of nutrients (N, P, K, Ca, magnesium (Mg), and Zn) into maize grains increased significantly for all treatments, and, in particular, for plants grown on plots amended with CaSa-compost (Fig. 4 in P2).
  - Primary response of maize plants to mitigated deficiency of soil P (*ibid.*).

[1] Liming potentials, or potential effects on soil acidification or alkalization of soil amendments, are often expressed in kg of calcium oxide (CaO) per 100 kg of DM and/or in kg of CaO per kg of total N (N_{tot}) added with the amendment.

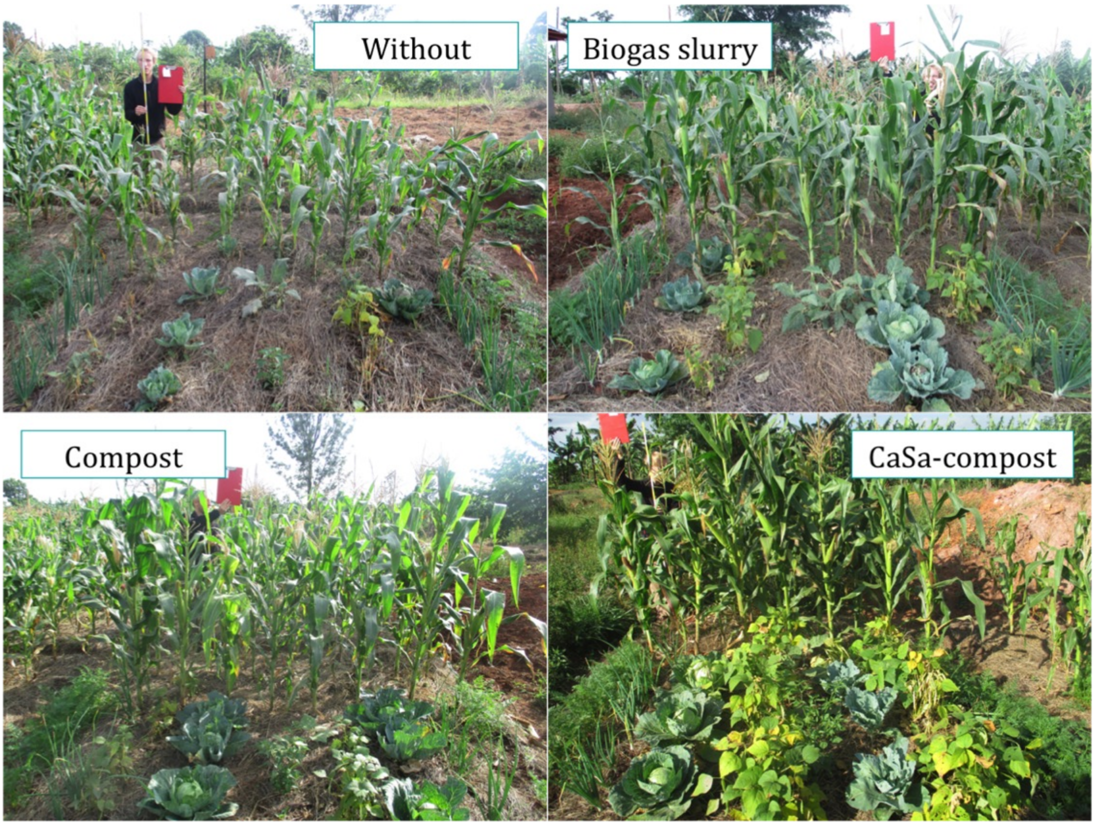

Figure 7.1: *Progress of the field experiment – 60 days after initiating the experiment with sowing of maize: an untreated plot ('without') compared to plots amended with biogas slurry, standard compost and CaSa-compost. These photographs were taken by A. Krause on June 2nd, 2014.*

7.1.3 Model-based comparison of cooking and sanitation technologies (P3)

In this next research step, I compared most commonly used household cooking and sanitation technologies with locally developed alternatives with respect to certain material flows on a household level[2]. The MFA has revealed the following findings with respect to bioenergy alternatives for answering RQ 3:

- Resource consumption[3] (Table 4 in P3):
  - The total consumption of firewood as a fuel resource when cooking on a three-stone fire is 1775 ± 128 kg per household per year.
  - When using rocket stoves or TLUD-microgasifiers, annual firewood consumption decreases to about 55 % or 75 % respectively of fuel consumed when compared to cooking on a three-stone fire.

[2] Results presented refer to matter in fresh weight, which I consider the more practice-oriented unit as smallholders deal with fresh weight, rather than dry weight, on a daily basis.

[3] Knowing the effective potential for reducing the use of firewood, when switching to either of the locally available cooking alternatives, has also been of interest to practitioners (PQ no. 1, p. 34).

  - When cooking with sawdust microgasifiers, firewood is substituted by sawdust as energy carrier and the total resource consumption amounts to about 80 % of current firewood use[4].
  - When using a system comprised of biogas digester and burner, firewood is substituted as a fuel resource by using agricultural residues as fermentation substrates. The total consumption of cow dung and banana stem, however, is about 15 times higher than fuel resources currently used.
  - Using charcoal burners reduces fuel consumed in households to 23 % of current firewood use. Producing the necessary amount of charcoal, however, requires firewood for carbonization in pyrolysis kilns in comparable quantities to current fuel wood consumption.
- Potential to recover resources (Table 4 in P3):
  - The ultimate potential to recover residues increases when operating biogas digesters or using microgasifiers, than compared to other cooking alternatives.
  - Ample content of C and nutrients in biogas slurry, with a total recovery potential for C, N, and P of approximately 570, 40, and 10 $kg\,yr^{-1}$, respectively.
  - Substantial recovery of C and P in biochar recovered from cooking with microgasifiers of about 200 to 230 $kg\,C\,yr^{-1}$ and 0.6 to 0.8 $kg\,P\,yr^{-1}$.
- Environmental emissions (Fig. 6 in P3):
  - Emissions with GWP and EP reduce through the use of ICSs, when compared to current conditions, in the range of 45 to 60 % of current values.
  - Emissions from slurry storage and biogas leakages from the digester increase GHG emissions from the biogas system, leading to about 250 % of the current GWP.
  - Ammonia emissions from digester-internal slurry storage increase the EP of the biogas system to approximately 310 % of the current EP.

Main findings from analyzing sanitation alternatives for answering RQ 4 include:

- Resource consumption (Table S.10 in Supplements S2):
  - Total inputs of sawdust and firewood as fuel are 67 ± 26 and 92 ± 34 kg per household per year, respectively.
  - High demand for flush water in the water-based septic system, with 15 to 18 $m^3\,yr^{-1}$, significantly pressures scarce water resources in households.
- Potential to recover resources (Table 6 in P3):
  - Notable recycling potential for C, N, and P from EcoSan-facilities with solid matter[5] containing about 55, 3.8, and 1.1 $kg\,yr^{-1}$, respectively, and stored urine about 11, 6.6, and 0.6 $kg\,yr^{-1}$, respectively.
  - Thermal sanitation allows recovery of C, with about 11 $kg\,yr^{-1}$ contained in biochar.
  - No recovery of resources from pit latrines or septic tanks.

[4] Sawdust is a 'waste' material, currently abundantly available in towns and villages, for example, from carpentries.

[5] 'Solid matter' comprises of a mix of human faeces, toilet paper, and dry material, which is added to the toilet after defecation. Solid matter is collected inside the UDDT and is either (i) dried in the UDDT for some months ('dried solids') or (ii) thermally sanitized ('sanitized solids') after a shorter period of drying for two to four weeks.

- Environmental emissions (Fig. 7 in P3):
  - Total GHG emissions and nutrient leaching from the UDDT decrease, when compared to the use of a pit latrine, which results in GWP and EP of about 35 % and 2 % of the current values, respectively.
  - When changing from a pit latrine to a water-based septic system, the GWP increases, whilst the EP remains at comparable values.
  - From these conventional systems, N and P is emitted to the ecosystem by 80-90 % and 70-80 % of the total input, respectively (Table S.14 in Supplements S2).

7.1.4 Model-based assessment of residue integration into soil fertility management (P4)

A subsequent study of P3 identifies the effects of switching current cooking or sanitation technologies on the local agroecosystem, with respect to soil nutrient budgets in particular. An *ex-ante* analysis compares different alternative recycling-based fertilisation practices. The study focuses on a local intercropping system of relevant nutritious crops, including maize, beans, onion, and cabbage, grown on *msiri*-land. Here, I integrate potential material flows of residues recovered from household cooking and sanitation (P3) and empirical data collected in the field trial reflecting plant responses (P2), to describe means and effects of certain IPNM-strategies. The main analytical findings for answering RQ 5 are:

- Soil nutrient balances (Table 4 and Fig. 3 in P4):
  - Under current practices, the local soils are already depleted, with existing SNBs of -54 ± 3 and $-8 \pm 1\,\mathrm{kg\,ha^{-1}\,yr^{-1}}$ for N and P, respectively.
  - All of the IPNM-strategies analyzed reverse the SNB for P to bring about a positive result.
  - Using biogas slurry or CaSa-compost[6] can clearly reduce the depletion-rate of N to approximately 20 % or 30 to 45 % of the current N-deficit, respectively.
- Availability of resources for subsistence production of compost (Table 2 and Fig. 4 in P4):
  - By using resources recovered from cooking and sanitation for IPNM, soil fertility increases, and, thus, total biomass increases, including crop yields and plant residues available after harvesting.
  - Increased levels of harvest residues, and the recovery of residues from cooking and sanitation, lead ultimately to an increased production of compost.
  - If smallholders adopt the CaSa concept, they can, presumably, produce 2.6 to 2.8 $\mathrm{m^3\,yr^{-1}}$ of CaSa-compost, as well as 0.3 to 0.9 $\mathrm{m^3\,yr^{-1}}$ of standard compost.
  - Sanitized solids, stored urine[7], and biochar from EcoSan provide significant nutrients for composting, and contribute about 50 % or 40 % of the total N (N_{tot}) or P_{tot} in CaSa-compost, respectively (*ibid.*).

[6] Biogas slurry and CaSa-compost, are used for fertilizing maize and beans, in combination with urine as mineral input, while standard compost and urine are used for vegetable production.

[7] According to the 'recipe' of CaSa-composting (P1), urine is added to CaSa-compost with 0.1 $\mathrm{m^3\,m^{-3}}$. Approximately 60 % of the stored urine from EcoSan is added to CaSa-composting. The remaining urine is available as a liquid, organo-mineral fertilizer.

  - Biochar from cooking with microgasifiers significantly contributes to P_{tot} and total C (C_{tot}) in CaSa-compost by providing about 15 % or 40 % of the P_{tot} or C_{tot} content, respectively.
- Environmental emissions assessed with GWP and EP (Fig. 5 in P4):
  - The GWP assessed for IPNM scenarios is at least quadruple that of the current state of soil management.
  - Emissions of N_2O from biogas slurry application to the soil contribute about 60 % of the GWP in the BiogaST scenario, while CO_2 emissions from CaSa-composting contribute about 65 % of the GWP in CaSa scenarios.
  - The EP increases in BiogaST and CaSa scenarios to about 170 % and 430-500 % of the current GWP, respectively.
  - Nutrient leaching and NH_3 emissions from composting contribute approximately 20 % and 65 % of the total EP in CaSa scenarios, respectively.
- Integrated environmental emissions of energy, sanitation, and agroecosystems (Fig. S.4 in Supplements S3):
  - The *integrated* GWP clearly increases to about 250 % of current levels when using a biogas system and biogas slurry as a soil amender.
  - The *integrated* GWP remains steady, when compared to current levels, when using a microgasifier for cooking, employing the CaSa approach to sanitation, and utilizing CaSa-compost as a soil amender.
  - All scenarios analyzed show only about half of the *integrated* EP of the current state of technology use and soil management.

7.1.5 Multi-objective assessment of cooking and sanitation technologies analyzed (P5)

Finally, I prepared a tool for evaluating and assessing cooking and sanitation technologies analyzed from multiple perspectives related to sustainability. The The tool integrates various criteria and methods (see below) and is called ‘multi-criteria technology assessment’ (MCTA). This final step also included the pre-testing of the integrated tool in a participatory manner. The main findings from a methodological perspective, and with respect to answering RQ 7, include:

- Most relevant criteria:
  - Criteria chosen systematically consider multiple perspectives of sustainability as the overall aim of case study projects is to develop appropriate technologies for SCD.
  - Six dimensions are employed for operationalizing sustainability, described as (1) technological-operational, (2) environmental, (3) health/hygiene, (4) socio-cultural, (5) socio-economic/financial, and (6) political/legal ‘main criteria’ and visualised in a six-pointed so-called ‘sustainability star’ (Fig. 2 in P5).
  - As practical bases for comparing alternatives, > 80 ‘sub-criteria’ are chosen (cf. Tables A.7 and A.8 in Appendix A3).

- Applicable methods:
  - The computational model applied in the MCTA is set up through combining the 'multi-attribute value theory' (MAVT) and 'simple additive weighting' (SAW). The MAVT basically uses multiple attributes for comparing alternatives according to their value. SAW describes the mathematical approach to determine such values through systematic aggregation.
  - Ranking and rating of main-criteria is done by applying the SWING-method; sub-criteria are simply rated.
  - The computational work is realized in Excel®.

The main findings from pre-testing MCTA in a participatory 'sustainability assessment' of small-scale sanitation and cooking alternatives locally available in Karagwe, and for answering RQ 8, include:

- With regard to different relevant criteria:
  - The choice group of participants assigned, on average, the highest weights to the environmental main-criterion; the political-legal objective is perceived as least important (Fig. 3 in P5).
  - All cooking stoves receive positive assessment results mainly for health/hygiene, socio-cultural or technological-operational (except biogas system) functions; negative assessment results refer to socio-economic/financial (for charcoal and biogas alternatives) and environmental (for charcoal only) criteria (Fig. 5 in P5).
  - Sanitation alternatives EcoSan and CaSa receive positive assessment results mainly for technological-operational, environmental, and socio- economic/financial functions; negative assessment results refer, in particular, to the political/legal criterion. Shortcomings of the septic alternative mainly refer to the environmental, health/hygiene, and socio- economic/financial criteria (Fig. 7 in P5).
- With regard to overall sustainability:
  - Stakeholders participating in the pre-testing of the MCTA perceive all technologies analyzed, both cooking and sanitation, on average, as 'acceptable' rather than 'favourable' alternatives.
  - Rocket and microgasifier stoves are generally assessed as being slightly more 'sustainable' than charcoal burner and biogas system. There is, however, no clear 'winner' among the cooking alternatives assessed (Fig. 4 in P5).
  - The two EcoSan approaches to sanitation (i.e. UDDT only, and UDDT in combination with pasteurization) are rated as significantly more 'sustainable' than water-based septic systems, which was the only alternative to receive a negative assessment result (Fig. 6 in P5).

Looking at the individual perceptions of stakeholders, MCTA reveals the following findings for answering RQ 9:

- Common opinions of different stakeholders:
  - All stakeholders participating in the MCTA agreed that the biogas system performs the worst of all of cooking technologies alternatives analysed with respect to costs and the usability.
  - Results from pre-testing the MCTA further indicate certain doubts about EcoSan and CaSa approaches, in particular on the sub-criteria 'safe working conditions' and 'safety in operation through avoiding risks of infection to users'.
  - Overall, all participants tend to assign comparatively higher scores to alternatives when they have been involved in designing, developing, or distributing the technologies.
- Diversities or similarities identified:
  - Considering the perceptions of stakeholder groups, I found a very high variance in individual valuations of participants. Weightings among participants are most divergent for the socio-cultural criteria, and least divergent for political/legal and health/hygiene criteria (Fig. 3 in P5).
  - There is further a tendency that Tanzanians consider health/hygiene and environmental criteria more important in comparison to Germans. German representatives, in contrast, perceive technological-operational and socio-cultural criteria as more important compared to Tanzanians.
  - Most Tanzanian stakeholders assess alternatives as being below the average of scores, while German participants, meanwhile, rate them above average; this holds true in all cases except biogas and septic systems.

7.2 Relevance for practice

The potential of the substrates studied to increase crop yields and to improve soil fertility, as practically demonstrated in the field experiment (P2), could be an essential driver for farmers to adopt certain IPNM practices. In this section, I reflect on the relevance of my findings for practical applications by evaluating the extent to which those recycling practices analyzed contribute to (i) food sovereignty and income generation (Section 7.2.1), and (ii) 'sustainable' soil fertility management (Section 7.2.2).

7.2.1 Consumptive and productive uses of the substrates analyzed for food production

Approach.

To assess the agronomic value of recycling-based soil fertility management for smallholders, I focus on the following aspects:

1. The 'consumptive use' of substrates in order to produce food crops for household consumption and, thus, to contribute to subsistence food supply and to food sovereignty.
2. The 'productive use' of substrates to produce food crops for sale and, thus, to generate farm income.

The evaluation considers several parameters, including[8]:

- Extent of available land[9]:
  - The total available arable land is, on average, 0.625 ha per farm (Tanzania, 2012).
  - Of this total, 0.125 ha is typically allocated to the *msiri* and 0.5 ha to the *shamba*.
- Food production[10]:
  - The *msiri* is used for growing annual crops such as maize, beans, cabbage, and onions during two seasons per year (Table A5.2 in Appendix A4).
  - The *shamba* is used for cultivating banana as a perennial crop and beans as an annual crop during two seasons per year (*ibid.*).
  - Crop yields vary depending on various fertilizer applications (Table 7.1).
  - Yield assumptions are based on data from literature combined with empirical data collected over the course of the field experiment (Tables A5.5-A5.11 in Appendix A4).
- Allocation of harvest products[11]:
  - As is customary for farmers of MAVUNO, approximately 56, 38, and 66 % of the total production of banana, beans, and maize, respectively, is used for own consumption (Table A5.2 in Appendix A4).
  - The remainder is sold on local markets or to intermediaries to generate farm income.
  - Vegetables are exclusively produced for own consumption.
- Food demand[12]:
  Six individuals of a smallholder household [hh] have, on average, the following basic nutritional needs per year (Table A5.4 in Appendix A4):
  - 780 kg hh^{-1} yr^{-1} of staple foods, such as rice, wheat, and starchy maize or banana;
  - 130 kg hh^{-1} yr^{-1} of pulses, such as beans, peas, soybeans, etc.; and
  - 350 kg hh^{-1} yr^{-1} of vegetables, such as cabbage, onion, tomato, etc.
- Local producer prices:
  - Local producer prices for maize and beans are, on average, 400 and 720 TZS kg^{-1}, respectively (MAVUNO, 2014)[13].

[8] Further details, such as yield assumptions, equations applied, references, etc. are documented in Appendix A4.
[9] As both *msiri* and *shamba* contribute to total crop production of smallholders, the final evaluation includes both types of land-use, while the work presented in P4 focuses only on *msiri*.
[10] Crop production on the *msiri* has been quantified as part of the SNB (P4).
[11] Identified in pre-studies conducted by myself in Karagwe in 2010, based on questionnaires.
[12] Basic requirements presented refer to a vegan diet. To avoid deficits of energy, proteins, fats, iron, calcium, vitamins, etc., a varied diet should further include a variety of vegetables, fruits, pulses, nuts, oil, salt, and possibly also food supplements (DGE, 2011). If eating meat is desired, the German Association for Nutrition recommends a *weekly* consumption limited to a maximum of 300 to 600 g of meat (DGE, 2010).
[13] There is no data of the FAO available on Tanzanian producer prices for maize and beans. Average producer prices in neighbouring Kenya or Rwanda were, in 2014, 0.37 EUR kg^{-1} or 0.34 EUR kg^{-1} for maize and 0.81 EUR kg^{-1} or 0.54 EUR kg^{-1} for dry beans, respectively (FAOSTAT, 2016). Local producer prices presented are thus relatively moderate for East Africa. Local producer prices for maize are comparable to German producer prices of 0.19 EUR kg^{-1} in 2014 (*ibid.*).

- In Euros (EUR), these prices are equivalent to about 0.17 and 0.30 EUR kg^{-1}, respectively[14].

The evaluation compares, in total, four scenarios (Table 7.1)[15] reflecting (i) the 'current state' of soil management with limited fertilizer application (A1), and (ii) 'improved' soil fertility management with fertilizer applications based on using residues from cooking and sanitation (A2-4). Table 7.1 summarizes variations in fertilization strategies considered for *msiri*. For *shamba*, I simply assume that soil fertility management and crop production also improve in A2-4. Practices applied might include using remaining biogas slurry, which is abundantly available, or adding human excreta directly to planting holes of bananas (cf. Section 7.3).

Table 7.1: *Scenarios analyzed in the final evaluation of food production: scenarios A1-4 reflect differences in soil management practices by different substrates used as fertilizers in the msiri.*

Abbr.	Name	Fertilizer application for...	
		maize and beans	cabbage and onion
A1	'Current state'	none	standard compost (for cabbage)
A2	BiogaST scenario	biogas slurry and urine	standard compost and urine
A3	*Optimistic* CaSa scenario	CaSa-compost and urine	standard compost and urine
A4	*Pessimistic* CaSa scenario	CaSa-compost and urine	standard compost and urine

Results and discussion.

Table 7.2 summarizes the total food production estimated, which is either used to supply food crops to householders or to generate farm income.

Table 7.2: *Total annual food production estimated from msiri and shamba in kg per household and year.*

Scenario	Banana	Maize	Total staple food	Beans	Cabbage	Onion	Total vegetables
			$kg\,hh^{-1}\,yr^{-1}$				
A1	480	245	725	225	258	24	282
A2	800	525	1,325	315	258	88	346
A3	800	880	1,680	615	258	88	346
A4	800	640	1,440	540	258	88	346

(1) Figure 7.2 presents the 'consumptive use' of substrates analyzed with respect to food production, which is in opposition to estimated basic food requirements. In the baseline scenario A1, subsistence production of banana/maize, beans, and cabbage/onions supplies about 55 %, 65 %, and 80 % of household demand for staple foods, legumes, and vegetables, respectively. However, changing fertilization strategies in favour of using residues from cooking and sanitation shows significant potential to increase farm productivity. The use of biogas slurry and urine,

[14] Prices are converted with an exchange rate of 1000 TZS to 0.42 EUR and 1 US Dollar (USD) to 0.94 EUR (February 2017) (BV, 2016).

[15] The abbreviation part 'A' reflects the 'agroecosystem' of a smallholder farm including *msiri* and *shamba*. The two CaSa scenarios (A3 and A4) differ in regard to yield assumptions. I contrast (i) the more *optimistic* scenario A3 with comparatively *higher* yield assumptions based on empiric results gained with CaSa-compost (P2) to (ii) the more *pessimistic* scenario A4, with comparatively *lower* yield assumptions based on empiric results gained with the standard compost (P2).

as simulated in scenario A2, allows for the production of sufficient staple food, legumes, and vegetables to cover almost all household needs, with approximately 100 %, 90 %, and 100 % of the household's demand for basic nutrition, respectively. The use of CaSa-compost and urine, as simulated in scenarios A3 or A4, further increases on-farm food production to about 130 % or 110 %, 190 % or 155 %, and 100 % of the benchmark for food requirements with staple food, legumes, and vegetables, respectively.

Overall, these findings reflect imminent food insecurity for smallholders in the current state. In fact, approximately 65 % of the households in Kagera Region suffer from food insecurity at different levels[16] (Tanzania, 2012). The results further indicate the need to adapt the share of food crops commonly used for income generation. Ensuring a sufficient food supply to smallholders requires that selling crops is halted, or at least decreased, in the current situation. For example, *if* 100 % of the harvest estimated for maize and banana is used for household consumption, then the farm could supply (just) enough for the basic nutritional needs. By using the entire harvest for its own needs, however, farm income decreases, the impacts of which I discuss in the following paragraph. In contrast, soil management based on using biogas slurry or CaSa-compost with urine entails a strong potential to produce sufficient, or more than sufficient, food for household consumption. As a consequence, selling of crops could be intensified, meaning that the share of the harvest used for own consumption can be decreased in scenarios A3 or A4. Finally, in all scenarios, the size of land used for vegetable cultivation needs to be increased if farm income is to be generated from selling vegetables.

(2) When assessing the 'productive use' of the substrates analyzed, and estimating monetary values of farm production, I adapted the allocation of harvest products for household consumption and for income generation in such a way that the need of food for farm members is sufficiently met (Table A5.3 in Appendix A4). Table 7.3 presents the valorization of the productive use of substrates analyzed and utilizing them for soil management, expressed in TZS and EUR. Results are not compatible with an annual income from crop farming, as it is typical for the region according to Lwelamira et al. (2010). Monetization only refers to maize and beans[17]. Overall, results indicate a significant productive use of the substrates analyzed with outstanding results for CaSa-compost.

[16] According to the agricultural census of Tanzania (2012), agricultural households in Kagera Region experience problems in satisfying the household food requirement at the following levels: 39 % of households suffer from food insecurity 'seldom', 12 % 'sometimes', 9 % 'often', and 5 % 'always'.

[17] It was not possible to assess banana production due to data gaps for local producer prices for banana. Given that the focus of my work has rather been on intercropping of annual crops on *msiri*-land, this limitation is acceptable.

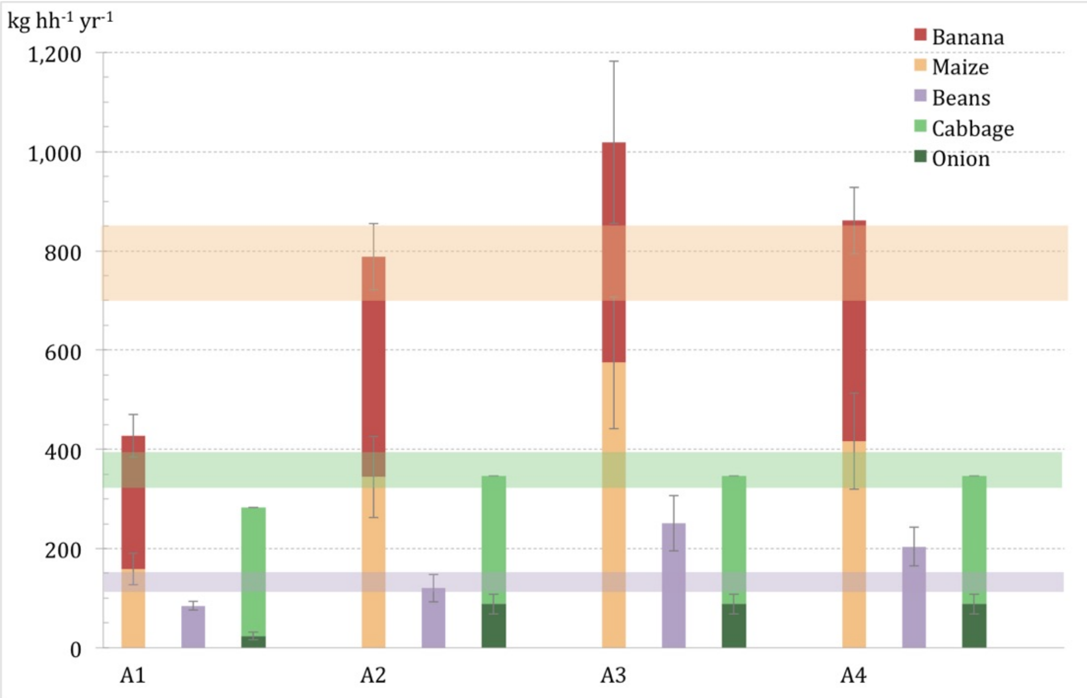

Figure 7.2: *The 'consumptive use' of substrates analyzed to achieve food sovereignty for smallholders: food production on msiri and shamba estimated for own consumption in the farming household and compared to food requirements for staple food, vegetables, and pulses, indicated with the orange, green, and purple rectangles, respectively. Reference values are provided with a range of the mean ± 10 % of the mean according to recommendations of BMELV (2009), PAHO (n.d.), and UNHCR (2002). Grey bars indicate the standard error of the mean production.*

Table 7.3: *The 'productive use' of the substrates analyzed to generate farm income from selling maize and beans grown on msiri and shamba on local markets. Values given in TZS and EUR per household and year and in % of an average farm income in the region of 1 million TZS according to Lwelamira et al. (2010).*

Scenario	Maize	Beans	Total income	Maize	Beans	Total income	Share of average farm income
		TZS hh^{-1} yr^{-1}			EUR hh^{-1} yr^{-1}		%
A1	0	55,000	55,000	0	22	22	5 %
A2	70,000	135,000	205,000	30	56	86	20 %
A3	200,000	380,000	580,000	85	160	245	60 %
A4	105,000	290,000	395,000	44	122	166	40 %

7.2.2 Long-term effects of recycling practices studied on crop yields and soil nutrients

Approach.
To evaluate the feasibility of the substrates analyzed for 'sustainable' soil fertility management in Karagwe, I focus on the following aspects:

1. Crop growth for estimating whether it is possible to reach comparable yields to the field experiment when cultivating twice a year in the long-term.
2. Soil nutrient statuses for examining the timespan needed to replenish soil nutrients and to reach 'optimal' levels of soil P, depending on the fertilizer regime applied.

The assessment of lasting soil implications is based on modelling the long-term use of local soil amenders. I therefore cooperated with the Potsdam Institute for Climate Impact Research (PIK - *Potsdam-Institut für Klimafolgenforschung*), that developed the so-called 'Soil and Water Integrated Model' (SWIM) (Krysanova et al., 2000). The SWIM is a process-based, eco-hydrological model, which integrates impacts of climate and land management, or the 'way of farming', with hydrological processes, soil erosion, nutrient dynamics, and vegetation (Fig. A6.1 in Appendix A5). Thus, all spheres – atmosphere, anthroposphere, biosphere, hydrosphere, and pedosphere – are interconnected in SWIM. The model works on a regional scale and has already been calibrated for TZ, including Kagera Region (Gornott et al., 2015; Gornott et al., 2016). The timeframe of the simulation is usually two decades, exemplarily depicted by the period from 1993 to 2012.

The evaluation considers several output parameters[18]:

- Annual crop yields of maize grains removed from the field during two seasons [$t\,ha^{-1}\,yr^{-1}$].
- Soil P [$kg\,ha^{-1}$] comprising labile P (P_{lab}) as mineral P in the soil solution readily available for plant uptake.
- Soil N [$kg\,ha^{-1}$] comprising organic N (N_{org}) that is readily mineralizable, and NO_3^- as N_{min} in the soil solution that is readily available for plant uptake.

The evaluation compares in total four scenarios (Table 7.4)[19] reflecting (i) the 'current state' of soil management with limited fertilizer application (AM1) and (ii) 'improved' soil fertility management with fertilizer applications based on using residues from cooking and sanitation (AM2-4). In addition, and in accordance with local practices, carpeting with grasses and mulching with harvest residues is applied as a 'basic practice' in all scenarios.

[18] Appendix A5 provides a summary of relevant details on the basic structure of SWIM (Section A6.1) based on the SWIM-manual of Krysanova et al. (2000), and lists data used for model calibration (Section A6.2) and input parameters (Section A6.3). For example, the specific characteristics of the local soil and the local climate conditions from my own data have been used for model calibration (Table A6.1) and applications of N_{min}, N_{org}, and P_{tot} have been estimated as input data prior to the simulation (Tables A6.3-A6.8). In addition to the results presented here, I also analyzed and evaluated certain soil-related stress factors as growth constraints (cf. Section A6.6).

[19] The abbreviation part 'AM' reflects the 'agroecosystem' of a *msiri*. Scenarios are comparable to those scenarios studied in P4. The two CaSa scenarios (AM3 and AM4) differ regarding the yield assumptions. I contrast (i) the more *optimistic* scenario AM3 with comparatively *higher* yield assumptions based on empirical results gained with CaSa-compost (P2) to (ii) the more *pessimistic* scenario AM4, with comparatively *lower* yield assumptions based on empirical results gained with the standard compost (P2).

Table 7.4: *Scenarios analyzed in the final evaluation of long-term effects on soil fertility: scenarios AM1-4 reflect differences in soil management practices through the use of the analyzed substrates as fertilizers in the msiri.*

Abbr.	Name	Fertilizer application for maize
AM1	'Current state'	none
AM2	BiogaST scenario	biogas slurry and urine
AM3	*Optimistic* CaSa scenario	CaSa-compost and urine
AM4	*Pessimistic* CaSa scenario	CaSa-compost and urine

Results and discussion.

In the following paragraphs I present and discuss the results from SWIM.

(1) With respect to crop growth, SWIM predicts that annual maize yields would slightly, but continuously, decrease over a period of two decades under current soil management, as the linear trend line in Fig. 7.3 indicates for AM1. Likewise, yields calculated for the BiogaST scenario decrease over the timeframe simulated, while grain yields estimated for the case of CaSa scenarios clearly increase over two decades. Furthermore, according to SWIM, yields of maize grains more or less double in scenarios AM2-4, compared with the baseline scenario AM1. However, (long-term) yields estimated with SWIM for BiogaST and CaSa scenarios increase to a lesser extent when compared with (short-term) empirical findings[20]. Mean values of scenarios AM2, AM3, and AM4 are about 85 %, 45 %, and 60 % of annual yields projected from empirical data, respectively (Table 7.5). Yields simulated for AM1 are, meanwhile, comparable to those realized on unamended soil during the field experiment (P2), and fit with average grain yields reported for the region (FAOSTAT, 2012; Kimaro et al., 2009; Mourice et al., 2014)[21]. Yields simulated for IPNM scenarios AM2-5 are comparable to approximate yields required to reach world food security by 2025-2050 (Lal, 2009)[22].

Table 7.5: *Comparison of yields of maize grains per year estimated by SWIM to results of the short-term field experiment.*

Scenario	Yields calculated by SWIM $\Delta^{max.}_{min.}$ (mean value) $\mathrm{t\,ha^{-1}\,yr^{-1}}$	Yields projected from empiric data mean value from P2 $\mathrm{t\,ha^{-1}\,yr^{-1}}$
AM1	1.7 - 2.6 (2.1)	2.2
AM2	3.8 - 5.5 (4.7)	5.6
AM3	3.2 - 4.7 (4.1)	8.8
AM4	2.9 - 4.2 (3.7)	6.0

[20] In SWIM, yields of maize grains increase to about 225 % or 175-195 % of the current production when using biogas slurry or CaSa-compost (each combined with urine), respectively. Compared to that, grain yields increased to, respectively, about 240 % or 400 % of the production on unamended soil when using biogas slurry or CaSa-compost (*without* urine) in the field experiment.

[21] According to FAOSTAT (2012), the average national grain yield is $1.2\,\mathrm{t\,ha^{-1}}$ *per season*. Kimaro et al. (2009) produced a *seasonal* grain yield of about $1.0\,\mathrm{t\,ha^{-1}}$ from unfertilized plots in a field experiment in the Dodoma region of TZ. Mourice et al. (2014) yielded approximately $1.2\,\mathrm{t\,ha^{-1}}$ from untreated soil in Morogoro region during one season.

[22] According to Lal (2009), cereal production of 3.6 to $4.3\,\mathrm{t\,ha^{-1}\,yr^{-1}}$ is required to reach world food security by 2025-2050.

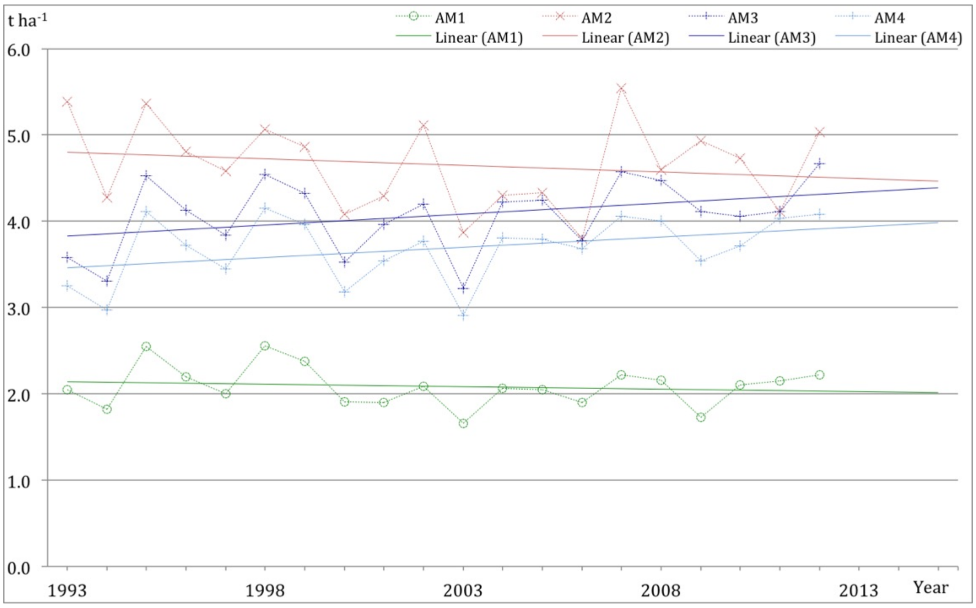

Figure 7.3: *Temporal shifting of annual crop yields from the SWIM analysis: calculated annual crop yields from the SWIM for the period 1993 until 2012.*

Overall, according to SWIM, yields are higher for the case of using biogas slurry compared to using CaSa-compost, which is inconsistent with my empirical findings. I assume that SWIM overestimates higher inputs of N_{min} with biogas slurry compared to CaSa-compost[23]. On the contrary, residual effects of N_{org} applied and higher inputs of P_{tot} with CaSa-compost compared to biogas slurry are probably underestimated[24]. Nonetheless, I observed empirically that maize plants directly react, in particular, on improved P fertilization (Fig. 4 in P2; cf. discussion p. 189).

(2) With respect to soil nutrient statuses, time series for P_{lab} in the soil (Fig. 7.4) show a slight decrease of contents in AM1, which means that P is continuously depleted under current state conditions. However, in the BiogaST scenario, the content of P_{lab} in the soil slightly increases, while the increase is clearly superior in both CaSa scenarios. SWIM further projects a clear increase of N_{org} in the soil for CaSa scenarios whilst in the BiogaST scenario, N_{org} only slightly increases over two decades (Fig. 7.5[25]). Under current soil management practices, however, the level of N_{org} in the soil remains constant over time. Simulated concentrations of NO_3 in the soil fluctuate widely over the two decades, as was to be expected pursuant to Finck (2007). The mean over two decades, simulating BiogaST and CaSa scenarios, is nearly seven and four times higher compared to the current state, respectively (Table A6.10). Hence, according to SWIM, amending the soil with CaSa-compost bears an outstanding potential to continuously replenish soil nutrient statuses of N_{org} and P_{lab}.

[23] The addition of N_{min} was 80.6, 17.8, and 12.5 kg ha^{-1}, respectively, in AM2, AM3, and AM4. Reductions of N_{min} through gaseous N losses after slurry application are, however, not considered in the data input or by SWIM.

[24] The addition of N_{tot} (= N_{min} + N_{org}) was 125.0, 145.5, and 121.4 kg ha^{-1}, respectively, in AM2, AM3, and AM4. The addition of P_{tot} was 30.5, 50.8, and 45.4 kg ha^{-1}, respectively, in AM2, AM3, and AM4.

[25] Please note that the different starting values for N_{org} in Fig. 7.5 derive from data evaluation as it is cut for an initial period of about 10 to 15 years until the simulation runs more stably (cf. Section A6.5 in Appendix A5).

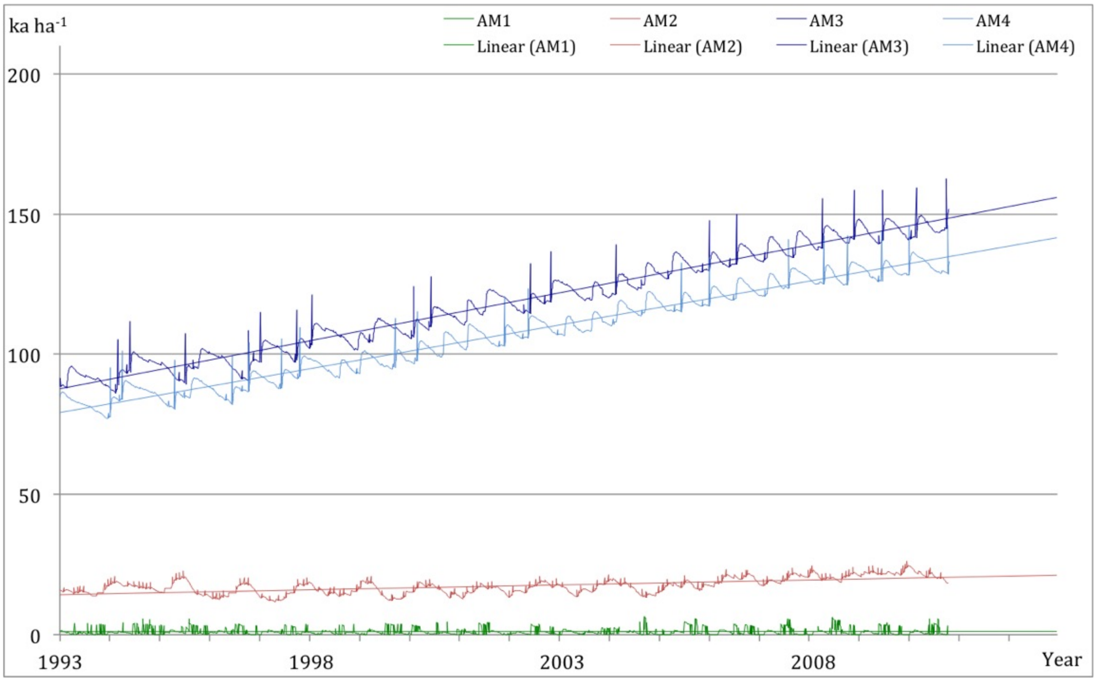

Figure 7.4: *Temporal shifting of content of P_{lab} in the soil from the SWIM analysis: calculated content of P_{lab} in the soil from the SWIM-analysis for the period 1993 until 2012.*

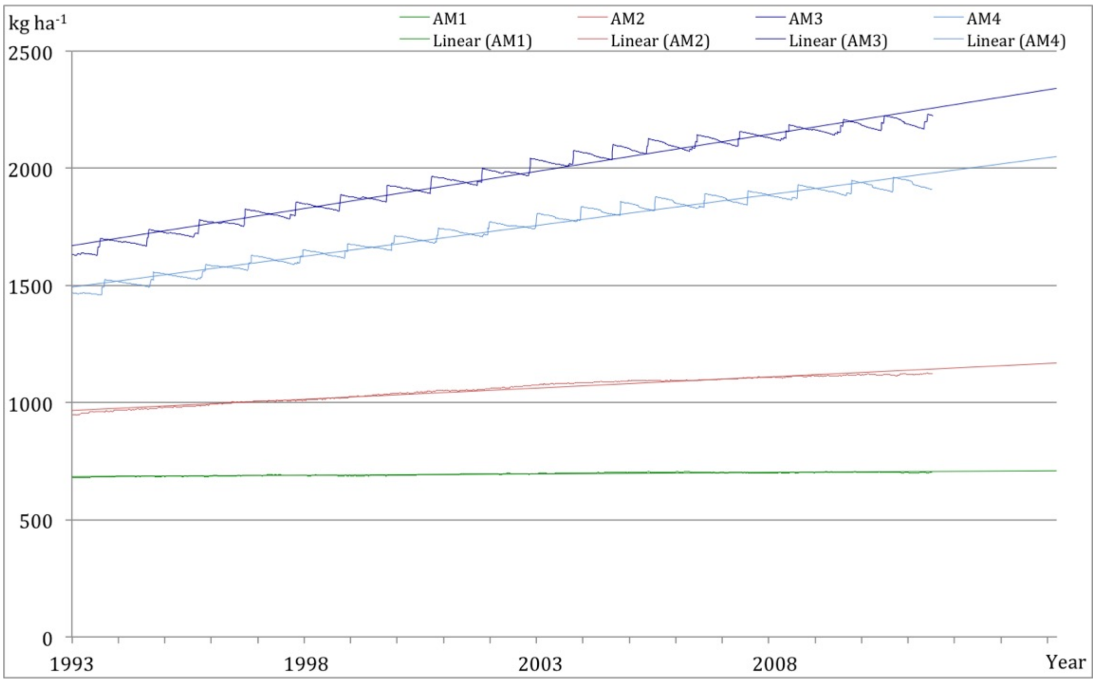

Figure 7.5: *Temporal shifting of the content of N_{org} in the soil from the SWIM analysis: calculated content of N_{org} in the soil from the SWIM analysis for the period 1993 until 2012.*

With annual depletion or replenishment rates[26] on the one hand, and certain target values of soil P[27] on the other, it is possible to estimate potential timeframes for P replenishment. Table 7.6 shows, that a period of 30 to 300 years of continuously amending the local soil with CaSa-compost is required for reaching ordinary target values of soil P[28]. Meanwhile, more than 700 years of constant CaSa-practice are required for reaching *Terra Preta*-like concentrations. However, when using biogas slurry, the timeframe expands from several centuries to several millennia depending on the target value.

Table 7.6: *Years required for replenishing soil P in the local Andosol by considering ordinary benchmarks of extractable soil P ranging from 100 to 800 kg ha^{-1} (Finck, 2007; Landon, 1991) and extremely high, Terra Preta-like concentrations of about 2500 kg ha^{-1} (Falcão et al., 2009). Contents refer to a 1m-layer of topsoil.*

	Benchmarks for P_{lab} in the soil [kg ha^{-1}]				
Target value	100	200	400	800	2500
Scenario	Number of years required for replenishing				
AM2	825	1,684	3,402	6,839	21,445
AM3	27	55	112	225	706
AM4	36	73	147	295	926

Finally, Table 7.7 summarizes the main findings from evaluating the feasibility of the recycling practices analyzed and clearly indicates the outstanding performance of using CaSa-compost as compared with biogas slurry.

Table 7.7: *Summary of main findings with respect to the practical relevance of using CaSa-compost or biogas slurry as soil amenders [++: outstanding; +: adequate and feasible; o: not yet adequate but improved compared to current state of affairs; -: not feasible, and deterioration compared to current state of affairs].*

Practical relevance	CaSa-compost	Biogas slurry	Section no.	Aspect no.
Reaching food sovereignty	++	+	7.2.1	(1)
Increasing income generation	++	+	7.2.1	(2)
Increasing crop growth	+	+	7.2.2	(1)
Replenishing soil nutrient statuses	++	o	7.2.2	(2)

[26] Annual depletion or replenishment rates of P_{lab} predicted for AM1, AM2, and AM3 and AM4 are -0.1, +0.1, +3.5, and +2.7 kg ha^{-1} yr^{-1}, respectively.

[27] Finck (2007) figures 44 to 88 mg kg^{-1} of extractable, and thus potentially plant-available, P in dry soil to ensure an adequate supply of P for plants. Landon (1991) suggests that 13 to 22 mg kg^{-1} of extractable P in dry soil are an adequate P supply for most African soils. Extremely high P concentrations of >250 mg kg^{-1} are found in *Terra Preta* soils, as reported by Falcão et al. (2009). Data on target values of soil P was collected as mass concentrations [mg kg^{-1}] and subsequently transferred to areal data [kg ha^{-1}] (cf. Section A6.5 and Table A6.9 in Appendix A5).

[28] No estimation made for scenario AM1, as P is depleted under current conditions.

7.3 Opportunities and challenges identified for real-world application

This section summarizes important 'lessons learned' with respect to real-world applications of the technologies analyzed and the recycling practices studied. I, therefore, merge (i) my own scientific findings, with (ii) insights gained from reviewing literature, and (iii) the perspectives of practitioners[29].

I firstly present the opportunities and challenges identified in the case of cooking alternatives (Section 7.3.1), then for sanitation alternatives (Section 7.3.2), and, finally, for recycling-based soil fertility management (Section 7.3.3). In all three parts, I emphasize potential means for minimizing environmental emissions[30]. The demand for further research, as deduced from this evaluation, is presented in Section 7.5.

7.3.1 Opportunities and challenges of the energy alternatives analyzed

In the following paragraphs, I elaborate on the specific opportunities and challenges of the biogas system and microgasifier stoves, and of using biogas slurry and biochar in agriculture.

Implementing and operating a biogas digester

Potential opportunities and challenges identified for the biogas digester include:

1. High investment costs can be a barrier for low-income households.
2. Successful implementation of biogas technology requires an adequate provision of services.
3. Sufficient feeding substrates are only available on farms with animal husbandry.
4. Transportation of substrates required for operation increases workload of farmers.
5. Extremely high GHG emissions from the system biogas burner *and* digester.
6. Implementation of the technology may be more appropriate to the community level.

(1) The cost of a locally-available biogas digester[31] is around 3.6 Million TZS or 1,500 EUR. This high investment compares unfavourably to the alternatives (i.e. ICS, charcoal burner), that cost between 5,000 to 30,000 TZS or 2 to 12 EUR (Table A.5 in Appendix A3). In order to access biogas digesters, farmers have to invest labour and materials to the value of around 1.3 Million TZS or 530 EUR[32]. Installation of a biogas digester, thus, consumes the total annual income of households mainly living from crop farming[33]. Households earning money from off-

[29] During the course of the present research, the implementation of technologies and the promotion of using residues in agriculture began with the case study projects. Accordingly, relevant information and updates from each of the projects are included in this section. Unstructured interviews with A. Bitakwate, F. Schmid, and S. Bissett (team members of case study projects) are a major source of information.

[30] An assessment of the possible benefits and burdens for the environment was among the open and relevant questions which were communicated by practitioners at the outset of the present research project (PQ no. 6, p. 34).

[31] Costs refer to a digester with 9 m^3 total volume. The design of the digester, however, is no longer a plug-flow fermenter as introduced (Fig. 1.11), but rather a fixed-dome digester (Fig. S5.1 in Supplements S5).

[32] Farmers and other clients of the BiogaST project are responsible for local materials and unskilled labour equivalent to about 35 % of total costs. The remaining 65 % is financed by donors (Fig. S5.2 in Supplements S5).

[33] The average income from crop farming is about 1 Million TZS per household and year (Lwelamira et al., 2010), which classifies those households as 'low-income' or 'poor' pursuant to Sussex (2004).

farm businesses or employments can more easily afford a digester[34]. Previous clients of the BiogaST project pay about half the costs directly from savings, and raise the other half through community loans[35]. These high installation costs, in combination with ongoing maintenance costs, are often seen as key barriers for the widespread dissemination of biogas technology in SSA (e.g. Rupf et al., 2015; Tumwesige et al., 2011). In the case of TZ, Rupf et al. (2015) emphasize that acquisition of a biogas digester is often unaffordable, even though households are willing to adopt the technology. National programs for promoting renewable energies and supporting access to energy technologies especially in rural areas, include the Rural Energy Fund, the Rural Energy Agency, and the Tanzanian Domestic Biogas Program (TDBP) (*ibid.*; Rajabu and Ndilanha, 2013). These programs have not yet reached Karagwe, however. For example, the TDBP has not yet chosen or appointed implementing partners in the region. Furthermore, the country lacks its own programs to provide subsidies or other financial support, including loans (Rupf et al., 2015). Past and existing biogas programs in TZ have, thus, been mainly driven by 'development cooperations', including the BiogaST project. As a practical opportunity to ease access to a donor-supported BiogaST system, farmers can cover their costs with non-monetary value. For example, they can prepare bricks, collect sand, dig the hole, etc. Moreover, flexible planning of purchasing materials can drastically reduce total costs, as local prices of, for example, sand, cement, or steel, vary significantly over the year. Finally, IPNM practices can help to increase the production of banana, beans, coffee and other crops, and thus raise farm income (Section 7.2.1). However, further preconditions to this are that farmers (i) are experienced in food budgeting, (ii) have access to local or regional markets, and (iii) receive adequate producer prices.

(2) Knowledge transfer among project partners, skill-building for local craftworkers, and user training have been challenges within the BiogaST project. The first two of these challenges were met through tailored training programs conducted by MAVUNO and EWB, in cooperation with an independent consultant (C. Kellner) and the Tanzanian Centre for Agricultural Mechanisation and Rural Technology (CAMARTEC). The Centre has been working with biogas in TZ since 1982 (Rupf et al., 2015) and is based in Arusha. After taking part in skill-building training, a team of four local craftworkers were then fully trained in construction and maintenance. To promote user training, MAVUNO plans to implement 'biogas clubs' where farmers owning digesters can meet on a regular basis. Their objective is to overcome the challenges of the initial phase of biogas implementation in Karagwe collectively by sharing and discussing individual experiences. Such experiences may include challenges met with feeding and/or operating the digester, or

[34] Business incomes, wage salaries, and other casual earnings contribute cash income to approximately 16 % of households in Karagwe (Tanzania, 2012). According to an estimation from A. Bitakwate, the average budget available to these households is about 3.6 to 7.2 Million TZS per year, which means 'that income is not only used for covering basic needs, but also for other social and family needs'.

[35] Loans in Karagwe are usually provided from within the community through 'social groups', which work as a form of combined saving and credit scheme. Micro credits through 'micro finance institutions' (MFI) or bank loans are less common. These two options usually charge higher interest compared to community loans. Moreover, MFIs or banks often demand a deposit, excluding poorer households. Accessing capital through social groups is, therefore, cheaper and easier, especially for resource-poor farmers. When part of a social group, members pay a monthly or annual fee, which forms the basic financial stock of the group. This money is used for providing loan services for group members on a revolving basis. Interest rates are between 5 to 10 %.

observations made when using biogas slurry in agriculture, etc. Rupf et al. (2015) identify adequate user awareness and training, as well as sufficient follow-up services, as essentials for successful biogas dissemination in TZ. To provide knowledge transfer to users, local craftworkers, manufactures, and potential biogas service providers Rupf et al. recommend implementing training centres with specialized programs.

(3) For steady operation, locally available biogas digesters require a daily input of 31 ± 9 kg and 45 ± 12 kg of cow dung and banana stem in FM, respectively (P3)[36]. To provide sufficient banana stems, approximately 0.13 ha of *shamba* are needed[37], which is equivalent to about 30 % of the typical Karagwe *shamba* (Tanzania, 2012). In addition, households would need to possess at least three cows[38]. It is, therefore, generally feasible to provide the input matter required for sound operation of the biogas digester. However, this means that only those households that possess cattle can also possess a biogas digester. Such households account for less then one fifth of Karagwe households[39]. Also Yousuf et al. (2017) report that, on a global scale, a majority of households are commonly excluded from access to small-scale biogas programs due to the fact that they do not have access to sufficient animal manure to feed the digesters.

(4) Operating a biogas system demands a markedly higher effort on the part of household members compared to cooking on a three-stone fire or with an ICS (P3). This extra workload includes transportation and preparation of feedstock, as well as carrying biogas slurry to the fields. In total, farmers would need to carry feeding resources and biogas slurry with a weight of around 70 times the total weight of firewood and ash for a three-stone fire for cooking. In contrast, the distances covered for collecting fuel are likely to be reduced, as cow dung and banana stems are available *on-farm*, while firewood is usually collected off-farm. In addition to material collection, banana stem material also needs to be cut manually, which requires considerable physical exertion.

(5) The GHG emissions from a system of biogas digester and biogas burner significantly exceed those of alternative cooking technologies. This is in contrast to the general perception that biogas is an 'environmentally friendly' technology, a view that is also encountered in Karagwe (P5). Biogas *burners* are comparatively 'environmentally friendly', with the lowest GWP in my analysis (P3). The *digester*, meanwhile, demonstrates exceptionally high GWP. Biogas leakages from digester-internal gas storage and CH_4 and N_2O emissions from intermediate slurry storage in the outlet basin of the digester make up about 40 % and 60 % of the GWP respectively. Practically, biogas leaching can be reduced through appropriate construction and maintenance work. For example, so-called '7-layer plastering' can improve the gas-tightness of the digester

[36] Monitoring the first six household digesters in use revealed that it is practically possible to operate the new digester, which is smaller with 9 compared to 12 m^3 fermenter volume, with 18-25 kg of cow dung per day. In addition, harvest and kitchen residues were used. These were, however, not further quantified.

[37] According to Yamaguchi and Araki (2004), the availability of residues from banana plants in DM is $0.92\,kg\,m^{-2}\,yr^{-1}$. The average moisture content in banana stems is 89.7 % of FM (Table A.12 in Appendix A1).

[38] According to Sasse (1987), the daily excretion of cows in FM is equal to 5 % of the living weight of the animal. The average weight of cows in Karagwe is $350\,kg\,animal^{-1}$ (Becker, 2008). Thus, one cow produces approximately $17.5\,kg\,d^{-1}$ of fresh dung.

[39] About 17 % of households in Karagwe keep cattle, and half of the cattle rearing households possess fewer than five animals (Tanzania, 2012).

significantly, if carried out effectively (Ullrich, 2008). Local craftworkers have been well-trained in this technique. In order to reduce emissions of GHG from slurry storage, it is important to cover the outlet of the container where the slurry is stored and to monitor the pH inside the basin, as alkalization promotes N-volatilization (Möller et al., 2008). Further recommendations refer to methods used to apply biogas slurry to the soil, and are discussed in the following paragraph. Methodologically, it is, in my opinion, vital to take a whole-system perspective when analyzing biogas systems, in order to include factors and practices relating to biogas digesters, biogas burners, the storage and the use of biogas slurry.

(6) Finally, for a number of reasons, I conclude that biogas technology is more promising for implementation on the community level, such as in schools, hospitals, and other institutions, rather than on the household level. This implementation approach proved highly successful in Rwanda, according to Rupf et al. (2015). I argue that the higher the volume of the fermenter (e.g. 30-600 m^3 compared to 6 to 12 m^3), the higher the performance and resource efficiency of the digester (Sasse, 1987), and the lower the marginal costs (Yousuf et al., 2017). Yousuf et al. recommend, in particular, to implement community-sized digesters in places with dining facilities and therefore where food 'waste' is produced on-site. Moreover, I assume that service provision is more feasible on a community level as people can be formally employed to carry out operation, material handling, proper slurry management, and maintenance works, which can prevent climate-hazardous leakages from the fermenter.

Utilizing biogas slurry as a fertilizer

For the practical use of biogas slurry in smallholder farming, I identified the following potential opportunities and challenges:

1. Biogas slurry is an adequate fertilizer, but not an 'untapped resource' in all cases.
2. Integrating biogas slurry to soil management may create 'islands of soil fertility'.
3. Fertilization benefits of biogas slurry are minor when compared to the effect of compost.
4. Biogas slurry allows for a 'target-oriented' fertilizer application.
5. Net effects on GHG-emissions after slurry application are not yet quantifiable.

(1) Locally available biogas slurry is characterized by nutrient contents (Table 1 in P1) which are adequate for fertilization, as compared to the literature (e.g. Finck, 2007; Horn et al., 2010). Ample quantities of such biogas slurry are available for those smallholders operating a biogas digester (P3). However, these material flows should not be considered as an 'untapped resource' for fertilizing *msiri* fields, as both input materials for biogas fermentation have previously been used as fertilizer input in the *shamba*, as shown by Baijukya et al. (1998). It is thus vital that biogas slurry is recycled into the banana-based homegardens in order to replace prior inputs of banana stem and cow dung, and to avoid an exacerbation of existing nutrient depletion in *shamba* systems (*ibid.*).

(2) Farmers that already possess a BiogaST digester perform slurry management as follows: Some slurry is directly removed from the digester with buckets and used as a fertilizer. Further slurry leaves the digester through an outlet hole, and flows via a small runlet into a pit filled with grasses and/or cow dung. After pre-composting in the pit, slurry is used to fertilize tomatoes in kitchen gardens, maize grown on *msiri* fields, or banana plants in the *shamba*. The latter practice is highly recommended, especially when banana stems are used as fermentation substrate (cf. prior paragraph). When taking the high level of exertion required to transport *wet* biogas slurry (P3), it is likely to be used near the digester. This practice potentially creates 'islands of soil fertility' in the vicinity of farm houses, and, at the same time, accelerates existing 'discrete patterns of soil fertility', as described by Tittonell (2016) (cf. Fig. 1.9, p. 29). According to practical experience, a significant share of biogas slurry remains in the pit as the total amount available is too much for farmers to manage. This means, however, that the fertilizer effect of slurry is untapped, while GHG emissions and nutrient leaching both increase.

(3) When experimenting with biogas slurry as a soil amender, bean and maize plants did not respond as well to biogas slurry as compost or CaSa-compost (P2). In addition, MAVUNO has observed that tomato plants developed bigger plants but rather small fruits when fertilised with biogas slurry[40]. Also Komakech et al. (2015) did not find a specific advantage to using *fermented* matter compared to *composted* matter when studying biomass growth and crop yields of maize plants in Uganda. One possible explanation is that the comparatively high levels of NH_4^+ and organic acids in biogas slurry are phytotoxic for plants (cf. Möller and Müller, 2012; Salminen et al., 2001). Composting of biogas slurry with other organic matter could, therefore, reduce these phytotoxic substances as demonstrated by Abdullahi et al. (2008). Farmers may directly exchange their practical experiences of using either liquid or composted biogas slurry for growing various local crops when meeting in 'biogas clubs'.

(4) A specific opportunity and supposed advantage of biogas slurry, compared to compost, is the possibility to synchronize nutrient applications with crops' nutrient demands (Möller and Müller, 2012). This 'target-oriented' fertilizer application is particularly relevant for crops with increased N demand (*ibid.*). Taking maize as an example, plant nutrient requirements are at their highest levels between 28 and 42 days after sowing (KTBL, 2009). Applying biogas slurry is, therefore, most highly recommended during this maturing stage (Fig. S5.3 in Supplements S5).

(5) When using biogas slurry as a soil amender, N_2O contributes significantly to GHG emissions from the agroecosystem, whilst N leaching and NH_3 contribute marginally to EP (Fig. 6 in P4). Incorporating biogas slurry into the soil shortly after application potentially avoids N_2O and NH_3 emissions, pursuant to Möller et al. (2008) and Möller and Stinner (2009)[41]. Farmers may use a hand-hoe for covering the slurry, or apply the slurry directly into a hole/furrow, which they then fill in immediately after. Biogas slurry should further preferably be applied to dry soil (*ibid.*) and Amon et al. (2006) recommend a high water content of the slurry, or additional dilution of the slurry with water, to allow for rapid infiltration. The water content of

[40] MAVUNO implemented several demonstration plots ('demo plots'), including greenhouse gardening, to test and monitor the use of biogas slurry, urine, and CaSa-compost for several crops. These demo plots are located on the grounds of a girls' secondary boarding school run by MAVUNO.

[41] According to Möller and Stinner (2009), NH_3 is particularly emitted during the 12 hours after sub-surface application of biogas slurry.

local biogas slurry is approximately 95 % of the FM (P1) and should thus be adequate for this purpose. When comparing the environmental impacts of using biogas slurry, compost, or mulch, existing literature is ambiguous. In *stockless* organic cropping systems, for example, more than one third of N_2O emissions could be avoided by digesting crop residues before reallocation to the fields, compared to using the same residues for mulching (Möller and Stinner, 2009). In organic cropping systems *with animal manuring*, NH_3 and N_2O emissions or leaching of NO_3^- after application of biogas slurry are, meanwhile, comparable to those associated with applications of compost or mulching (Möller, 2015). Overall, the major effect on environmental emissions after using biogas slurry, compost, or mulch, can be summarized as follows: on the one hand, high levels of N in biogas slurry from co-fermentation of cow dung[42] *increase* N_2O emissions as nitrification is promoted (Möller and Stinner, 2009). On the other hand, comparatively *low* levels of organic C in biogas slurry[43] potentially *decrease* N_2O emissions as the activity of C decomposers (bacteria and fungi) is inhibited. This, in turn, reduces the availability of NH_4^+ for nitrification, and, thus, denitrification (Möller, 2015). Overall, according to Möller (2015), field applications of biogas slurry primarily affect soil microbial activities, not GHG-emissions.

To sum up the major effects of using biogas slurry as a soil amender, I quote Möller (2015), who concludes that '*most of the direct effects of anaerobic digestion on soil properties and soil fertility are of a short-term character'* whilst '*the direct effects of anaerobic digestion on (. . .) soil fertility and environmental impact at the field level are of minor relevance*'.

Implementing and operating a microgasifier stove

I identified the following potential opportunities and challenges for the microgasifier technology:

1. Costs for microgasifiers are moderate and affordable.
2. Stoves are perceived, and proven, to be comparatively 'ecological sustainable'.
3. Microgasifiers are especially valued for their specific cooking features.
4. Wide-spread commercialization requires human resources and time.
5. Substantial recovery of biochar requires adequate treatment of the heated matter.

(1) The cost of a locally-available microgasifier is around 30,000 TZS or 12 EUR (Table A.5 in Appendix A3). This price is in line with the prices of other ICSs, such as the rocket stove, which is also sold by CHEMA, and other microgasifiers available in the region, such as the sawdust gasifiers sold in Bukoba town. The local price for a microgasifier is also comparable to the prices of a higher quality charcoal stove, but clearly more expensive than a simple charcoal stove, which is readily available for 6,000 TZS or 2.50 EUR. Finally, buying a microgasifier is clearly cheaper than installing a combined biogas digester and burner system (cf. first paragraph of this section). Operational costs depend on whether firewood or sawdust are available on-

[42] Biogas slurry contains, on average, about 2 to 3 % of N_{tot} in DM (Table 1 in P1; Table A.12 in Appendix A1). The content of N_{tot} in DM of cow dung is approximately 1.7 % compared to 0.9, 0.5, or 0.2 % in banana stems, standard compost, or grass cuttings, respectively (*ibid.*).

[43] According to Wendland (2009), about 55 % of C in biomass is decomposed in biogas digesters.

farm or can be collected at no cost, or need to be purchased[44]. Overall, stakeholders of the case study projects perceive microgasifiers as more 'financially sustainable' than other locally available cooking alternatives, such as charcoal stoves or biogas systems (P5).

(2) Stakeholders further value microgasifiers for their 'ecological performance', including the potential to reduce fuel consumption and GHG emissions (P5). Compared to cooking on a three-stone fire, using a TLUD-microgasifier for cooking reduces annual fuel consumption by a quarter (P3). Cooking with a sawdust gasifier completely substitutes firewood, while the quantities of sawdust required for fuel weigh only around 80 % as much as the firewood consumed annually by a three-stone fire (P3). Furthermore, GHG emissions can be reduced to about 40 to 60 % of the GWP associated with current cooking methods (P3). The short lifespan of microgasifiers, of just two to three years, is seen as a disadvantage of the technology from an ecological perspective, however, and represents a challenge for the developers[45]. The shorter lifespan of the microgasifier is due to direct exposure of the metal sheets to the hot embers and corrosion. Using more robust materials is impractical, however, as stainless steel, for example, is only available in Dar Es Salaam, is very expensive, and requires working with special tools. Galvanised metal sheets are also impractical as when they are heated, the zinc coating vaporizes and poses a health risk to people in the direct vicinity of the stove during cooking.

(3) The specific cooking features of microgasifiers are perceived as an advantage. With respect to 'usability', stakeholders assessed microgasifiers more positively than either charcoal burners or biogas systems (P5). In practice, microgasifiers are more fuel efficient for high-power cooking phases, such as bringing water to the boil, than during longer lasting, low-power cooking phases, such as simmering (Fig. A.10 in Appendix A1)[46]. The stove is thus more suitable for fast and quick cooking (P3) such as deep-frying, making sauces, preparing tea, heating water for bathing, boiling water before drinking, etc. For longer lasting tasks, such as cooking beans or maize, microgasifiers are only slightly more fuel efficient than three-stone fires, while charcoal burners, rocket stoves, or biogas burners, show clear advantages. Microgasifiers are fed with fuel in batches, and it is possible to continue cooking for around two hours per batch. Previous local users of microgasifiers have especially emphasized fuelling in batches and reduced smoke emissions as the most desirable advantages of the technology[47]. Furthermore, most ICSs are flexible in the kinds of fuel used: sawdust gasifiers can also be operated by using coffee shells[48]; the TLUD also works with maize cobs, briquettes, or wood chips; and rocket stoves can be fired

[44] Initial experiences suggest that most users do not have to pay for sawdust, at it is a 'waste' material available for free from carpentries. However, given that only a limited number of households live close to a carpentry, households hire motorcyclists to deliver bags of sawdust to their homes. This service costs around 1,500 to 2,500 TZS, or roughly 1 EUR, per week.

[45] In comparison, the lifespan of a rocket stove is four to five years.

[46] Findings are based on an evaluation of empirical data from 'water boiling tests' (WBT). The WBT is a simplified simulation of a cooking process for stove testing, which follows a standardized, internationally recognized, and established procedure (WBT, 2014). I used WBT data from various sources to characterize the stoves analyzed, and to derive data for a MFA. Results of this data evaluation are presented in Section A.4.1 in Appendix A1.

[47] This finding comes from an evaluation of the data collected during 'kitchen performance tests' (KPT) conducted in Karagwe by the EfCoiTa project in 2016 and 2017 with 50 participating households in five villages in Karagwe.

[48] Coffee shells are an abundantly locally available 'waste' material from coffee factories.

with firewood or charcoal. The concept of using multiple fuels and/or having different stoves for different cooking tasks is quite common in TZ, as reported by Grimsby et al. (2016). A common disadvantage of microgasifiers, rocket stoves, and the three-stone fire when compared to biogas and charcoal burners is, however, that soot blackens the underside of cooking pots requiring much effort in cleaning.

(4) Despite all the advantages and opportunities, selling the stove is still a challenge. In consultation with the EfCoiTa team, I ascertained the following factors: Firstly, microgasifiers are too expensive for low-income households, *but* the stove is not 'modern' enough for middle-income households, as it still uses biomass as a fuel. The first group, which are mainly or partly subsistence farming households, currently suffer from lack of financial resources as the region faced extreme drought in 2016, and, as a consequence, loss of harvests and farm income. The latter group, which also have significant off-farm income, prefer fossil gas stoves, which recently penetrated local markets[49]. Secondly, some local people remain sceptical about using a 'new technology', such as gasification, and solid biomasses, such as sawdust, coffee shells, or briquettes[50], instead of firewood. Important reactions to these initial challenges have included the improvement of local recognition and availability of microgasifiers, and increased effort into advertisement and logistics. To this end, the EfCoiTa team delivers market presentations and radio broadcasts to inform local people about ICSs and resource protection, and also to demonstrate cooking methods. Retail points have been established through cooperations with general stores and carpentries[51]. The latter shops also distribute sawdust to customers, mainly at zero cost. Finally, those households who were among the initial users of microgasifiers in the region are mostly satisfied with the technology, promote the stoves locally, and would consider re-buying a stove at the end of its life[52]. Potential clients tend to be highly interested in paying in installments or with community loans, as described earlier for the biogas system. A cooperation between micro crediting projects and the stove project within CHEMA could follow in order to address this desire.

(5) The potential of microgasifiers to co-produce biochar has been among my research interests. The amount of biochar *actually recovered* from the microgasifier depends, however, on stove handling (P3). In practice, leaving the hot char inside the stove for several hours, for example overnight, has a marked effect on the total quantity of biochar, the recovery of C, and on GHG. Precisely, the recovery potential of *cold* biochar collected several hours after cooking, diminishes

[49] Fossil gas stoves are available in towns, at prices ranging from 90,000 TZS or 38 EUR, up to 260,000 TZS or 110 EUR for a burner and gas cylinder (Fig. S5.4 in Supplements S5). Gas bottle refills cost 20,000 TZS for 6 kg of gas, or 50,000 TZS for 21 kg of gas – 8.50 or 21 EUR respectively.

[50] During promotion activities, the earliest customers decided to buy rocket stoves instead of microgasifiers. These are more similar to the well-known three-stone fire in terms of handling, firing processes, and the kind of fuel used, but also reduce fuel consumption and GHG emissions. Rocket stoves are, however, heavier than microgasifiers due to the presence of insulation bricks.

[51] The first retail points were established in the first half of 2017, more will follow. Distributors are important as most people do not buy directly during a marketing presentation even if they are interested. They need time to think about a significant buying decision, and also to organize the money required.

[52] This information was collected during the evaluation of the KPT performed by the EfCoiTa team. One household in a rural village, for example, maintained their stove themselves and repaired a hole in the stove by buying, cutting, and fixing a new metal sheet. For the EfCoiTa team, this was taken as a clear sign that they were extremely satisfied with cooking with the sawdust gasifier.

to about 30 to 60 % of total FM of *hot* residues that are recoverable directly after cooking with a sawdust or TLUD microgasifier, respectively. Likewise, *actual* C recovery rates decrease to approximately 10 to 40 % of the *potential* C recovery rates (Table 4 in P3), respectively, and GHG emissions increase (Fig. 6 in P3). I therefore recommend removing biochar residues from the stove *directly* after cooking, and extinguishing the hot matter with sand, water, or some other means of depriving it of oxygen. These measures stop further thermo-chemical reactions, halt emissions, and thus the loss of mass, and so allow for the maximum potential for biochar recovery from microgasifiers to be harnessed.

Utilizing biochar for composting

In regard to the practical use of biochar for composting, I identified the following potential opportunities and challenges[53]:

1. The total recovery potential of biochar from households is sufficient for CaSa-composting.
2. Biochar applications promote liming and, thus, improve the efficiency of nutrient recycling.
3. The effects of composting biochar on environmental emissions are not yet quantifiable.

(1) Smallholder households cooking with microgasifiers potentially 'produce' biochar in FM of 270 to 300 $kg\,yr^{-1}$, respectively, depending on whether a sawdust gasifier or TLUD is used (P3)[54]. In addition, a potential of 15 ± 4 kg of fresh biochar is available from thermal sanitation. Both recovery potentials decrease, however, if biochar is not managed appropriately (cf. previous paragraph). Finally, total potentials to recover (maximum) biochar on the one hand and sanitized solids on the other, result in comparable annual material flows in terms of volume (P3). This, in turn, fits very well into the practices required to produce CaSa-compost (P1)[55]. After composting, about 2.6 to 2.8 m^3 of CaSa-compost is available to smallholders each year (P4). This amount is generally adequate and feasible for handling, carrying, and amending compost to the soil (Sanchez et al., 1997).

(2) Nutrient availability in the soil is, among other factors, an outcome of soil pH (Horn et al., 2010). The optimal topsoil pH range for cropping is 5.5 to 6.5 (*ibid.*). To buffer acids in soils and, thus, to neutralize soil acidity, common measures include the use of lime ($CaCO_3$) (*ibid.*) and/or the addition of organic material (e.g. Wong et al., 1998). The addition of biochar is also associated with soil liming (cf. Biederman and Harpole, 2013; Jefferey et al., 2011; Liu et al., 2013). In this respect, I found that biochar-containing CaSa-compost is characterized by a higher liming potential (per kg of N added to the soil) than biogas slurry, standard compost, or other organic or synthetic fertilizers (P1). This theoretically assessed liming potential is further practically effective to significantly rise the soil pH to 6.1 within one season, compared with just 5.3 on unamended soil (P2). In comparison, highly productive *Terra Preta* soils,

[53] I add one personal experience from my scientific experiments. During the field trials, I observed that CaSa-compost aided workability of the soil by making it more friable, presumably due to the biochar content. However, I did not make any scientific analysis to follow up on this anecdotal observation.

[54] This amount is equivalent to a daily 'production' of 0.7 to 0.8 kg of FM of biochar, respectively (P3).

[55] The total recovery potential per household per year is approximately 1.2 and 1.0 m^3 of FM of biochar and sanitized solids, respectively (P3). According to applied CaSa practice, biochar and sanitized solids are mixed with about 17 and 15 $dm^3\,dm^{-3}$, respectively (P1).

that are particularly rich in biochar, are characterized by a pH of 5.2 to 6.4, a comparatively higher rate than surrounding soils as shown by Glaser and Birk (2012). The annual production of CaSa-compost is sufficient for application over a total area of $> 1{,}000$ m^2 per year, and to maintain, or even improve, soil pH sustainably within this area (P4). As a consequence, liming improves nutrient availability in the soil and renders nutrient-cycling through organic residues more effective[56].

(3) Emissions from composting contribute significantly to overall environmental emissions from the agroecosystem (P4). In particular, CO_2 and N_2O add to the GWP, while NH_3 and P leaching contribute to the EP. The fact that biochar captures NO_3^- and PO_4^{3-}, as shown, for example, by Agyarko-Mintah et al. (2016), Gronwald et al. (2015), and Kammann et al. (2015), is promising in order to reduce GHG emissions and nutrient leaching during composting, and also, after compost is added to the soil. There is also empirical evidence that adding biochar to composting can decrease N_2O and CH_4 emissions (e.g. Agyarko-Mintah et al., 2016; Sonoki et al., 2013; Vandecasteele et al., 2013; Wang et al., 2014). When co-composting biochar with urine, as it is practiced in CaSa-composting, NH_3 emissions still rise, but the increase observed is lower than after solely adding urine to compost (Larsen and Horneber, 2015). Similarly, N_2O and CH_4 emissions also decrease, when adding urine and biochar to compost, while those emissions increased when only urine was added (*ibid.*). Results from observing changes in soil-borne emissions after using biochar are more ambiguous. According to Cayuela et al. (2014) and Zhang et al. (2012), N_2O emissions are lower from biochar amended soils than unamended soils. Additionally, net fluxes of CH_4 from managed soils decrease after biochar amendment (*ibid.*). This depends, however, on soil moisture levels and oxygenation (Van Zwieten et al., 2015). In contrast, other research found increased emissions of N_2O (Singh et al., 2010), as well as of CO_2 and CH_4 (e.g. Spokas et al., 2009; Zhang et al., 2012), after amending biochar to soils. Overall, existing scientific data still exposes uncertainties in various areas and knowledge-gaps on the underlying principles and mechanisms at play (cf. Mukherjee and Lal, 2014; Van Zwieten et al., 2015). It remains, therefore, a challenge to quantify changes in net emissions from an agroecosystem which utilizes biochar for composting and soil fertility management (cf. Section 7.4).

7.3.2 Opportunities and challenges of the sanitation alternatives analyzed

In the following paragraphs, I elaborate on those opportunities and challenges specific to the technologies that form part of the CaSa concept for sanitation, and on using faeces for composting and urine for fertilization.

[56] According to Hammer et al. (2015), biochar additions further lead to increased uptake of P by plants due to the symbiotic relationship between nutrient-charged biochar, plants, and AM fungi. According to Hammer et al. (2014), AM fungal hyphae enter micropores (<10 μm) of biochar, which are usually too small for plant roots to enter. In the soil, AM fungi can thus access nutrients that have been adsorbed into biochar particles, and deliver them to plants, which promotes effectively closed nutrient cycles. Despite the interesting potential of this line of enquiry, studying effects on mycology or soil microbiology was beyond the scope of the present work.

The CaSa concept for sanitation

For the specific EcoSan approach employed within the CaSa concept, I identified the following opportunities and challenges:

1. Implementation costs for UDDT and sanitation ovens are moderate and affordable.
2. Pasteurization is effective, quick, early, and, thus, 'safe' for sanitizing faeces.
3. Resource consumption for thermal sanitation is proportional to needs of smallholders.
4. Implementation of EcoSan on a household level requires further planning.

(1) According to the CaSa pilot project, constructing a UDDT costs around 0.9 Million TZS or 380 EUR (Table A.5 in Appendix A3). Costs for UDDTs are, therefore, comparable to the costs for constructing a stonewalled pit latrine[57]. Total costs for implementing a CaSa oven are around 1.1 Million TZS or 450 EUR. The total investment for implementing a UDDT and a CaSa oven is, therefore, comparable to the cost of installing a system of water toilet and a septic tank[58]. Given that pit latrines and septic systems are commonly private acquisitions for households, it should also be affordable for local smallholders to install a UDDT and/or sanitation oven without donor support. Middle-income households can cover implementation costs from household cash income, possibly supplemented by a community loan, as is common when installing a septic system. In order to make UDDTs affordable and accessible for low-income households, costs can be reduced by using alternative material solutions such as, leaving the brickwork of the toilet walls plain instead of plastering with (expensive) cement, or replacing the wooden door with a linen curtain, etc.

(2) In case of the CaSa approach, sanitation is realized via pasteurization. The main opportunities presented by this thermal treatment are: (i) pasteurization is an effective measure[59], (ii) it can be easily controlled, and (iii) pathogens are destroyed swiftly and at a very early stage of the process. In regard to the first point, I note that, during the field experiment, I tested samples of CaSa-compost for faecal bacteria *E. coli* and *enterobacteriaceae*[60]. Neither potential pathogens was detectable in the samples analyzed[61]. The effectiveness of pasteurization as sanitization method has been further proven in an experimental series conducted in a CaSa oven in

[57] Total costs for a pit latrine made of bricks and roofed with roofing tiles are about 0.9 Million TZS or 360 EUR; total costs for a pit latrine made of mud/grasses and roofed with iron sheets are about 0.25 Million TZS or 100 EUR (Table A.5 in Appendix A3).

[58] Total costs for a septic system, including flush toilet and septic tank, can range from about 1.6 to 2.0 Million TZS, or 650 to 800 EUR, depending on the materials used (Table A.5 in Appendix A3).

[59] To recycle nutrients to agricultural fields, pasteurization is also considered an effective treatment for sewage sludge in Germany (Klages et al., 2009). However, the costs involved and the availability of 'innovative', small-scale sanitation plants are major challenges (*ibid.*).

[60] *E. coli* and *enterobacteriaceae* are two microorganisms which are typically used as indicators for detecting faecal pollution in water (Esrey et al., 2001). For testing, I used medium sheets of RIDA (R) COUNT *Enterobacteriaceae* and RIDA (R) COUNT *E. coli* / Coliform from R-Biopharm AG, Darmstadt, Germany. The CaSa-compost was mixed with NaCl and shaken manually for 15 minutes. A sample of the dilution was applied to indicator sheets, and then put into an incubator oven for 48 hours at a temperature of 35° C. Finally, the indicator sheets were thoroughly examined by eye to count colonies. No colonies were detected either for *E. coli* or for *enterobacteriaceae*.

[61] Knowing that thermal treatment effectively removed any health hazard was also very important to the field assistants and myself when preparing the field trial, and during the experiment. Hence, it was not unpleasant to handle the matter even though we knew that CaSa-compost contains human excreta.

Berlin, Germany (Lettow and Holzgreve, 2014)[62]. In regard to the second point above: time and temperature can be easily measured throughout the process until pasteurization is completed and pathogens are inactivated in accordance with Feachem et al. (1983) (cf. Fig. 1 in P1). In regard to the final point: pasteurization is an appropriate technical barrier to destroy pathogens *before* diseases get transmitted through flies and fluids during (aboveground) composting[63]. As a consequence of early sanitation, the composting period can be shortened to only three to six months. In comparison, the WHO (2006) recommends faecal matter is composted for at least one to two years, depending on the surrounding temperatures, if composting is applied as the main process in order to inactivate pathogens.

(3) The 'costs' of such 'safe' sanitation are, however, extra workload for farmers and the consumption of resources[64]. The total resource consumption for thermal sanitation is about 10 % of the fuel required annually for cooking with a three-stone fire, an amount I consider to be generally appropriate and acceptable. Resource consumption may, however, decrease, depending on further adaptations of the technology (cf. next paragraph).

(4) Finally, there are still uncertainties around the technical and organizational aspects of implementing EcoSan or the CaSa approach on a household level. Firstly, technological development is ongoing. Despite the fact that the loam oven proved to function adequately, another test series began in 2016 to examine the use of a *Kon-Tiki* cone kiln (Schmidt and Taylor, 2014). The Kon-Tiki design is augmented with a swivel grate, which can hold three to four pots with 80 dm^3 each (Fig. S5.5 in Supplements S5) to make it suitable for sanitation purposes. The main objective remains, namely, to combine *carbonization* of organic material to co-produce biochar with thermal *sanitation* of human excreta. An additional aim, however, is to realize thermal sanitation on a larger scale (i.e. larger mass throughput per batch) and potentially more efficiently (i.e. less fuel consumption in mass per mass unit of treated excreta). Secondly, it remains an open question whether, in future, each household should possess an individual sanitation facility or whether such a facility is better installed and operated as a community resource. For a six-person household, thermal sanitation in a loam oven needs to be performed approximately 34 times per year, or about every ten days (P3). Installing a storage facility, increasing the size of the loam oven, or switching to Kon-Tiki-technology can allow for the treatment of three to five pots in one batch operation. Ten or more households could, therefore, share one sanitation facility. Several aspects of the process, such as basic self-organization, costs, resource consump-

[62] In the Berlin experiment, a treatment of one hour at 70° C reduced indicator organisms, *E. coli* and *enterococcus faecalis*, effectively as no bacterial count was detectable in samples taken after the treatment (Lettow and Holzgreve, 2014).

[63] Esrey et al. (2001) note in this context: '*Although there are certain health risks if an ecological sanitation system is improperly managed and maintained, it was pointed out that the same is also true of any sanitation system, where by definition, at the outset we are dealing with a dangerous substance - untreated human faeces. A difference between ecological sanitation and conventional systems is that in ecological sanitation, we try to sanitize and make excreta safe at the place of excretion, whereas this is not the case in conventional systems*'.

[64] Inside the gasifier stove, sawdust is thermo-chemically decomposed into wood gas and biochar. The wood gas is subsequently oxidized. During operation, one frequently adds pieces of firewood, so-called 'firing sticks', to enhance the firepower of the microgasifier stove and to accelerate heating. Estimating the input of the resources required for thermal sanitation of faeces according to the CaSa concept has been among the questions raised by local practitioners (PQ no. 2, p. 34).

tion, transportation effort, etc., need to be considered for such an approach, and evaluated by community members[65].

Utilizing faeces as a compost additive

For the practical use of faeces for composting, I identified the following potential opportunities and challenges:

1. Human faeces contribute significantly to the nutrient contents of compost, especially P.
2. Faecal blended compost increases crop growth, but its use is not recommendable for all crops.
3. Human excreta can alternatively be used for growing perennial crops or for reforestation.
4. Mixing human faeces with other organic matter ensures adequate composting.

(1) An important aspect of CaSa-compost is its comparatively high nutrient content (P1). Contents of P_{tot} and N_{min}, for example, are about three times higher in CaSa-compost than in standard compost (P1). My findings are supported by considerable P_{tot} and N_{min} concentrations in composts blended with faeces, as compared to compost without the addition of faeces, as per an experiment I took part in at the IGZ (Krause and Klomfaß, 2015). Given that faeces are characterized by significantly higher P content than, for example, grass cuttings or kitchen waste[66], the remarkably high P content in CaSa-compost can be attributed to co-composted human faeces. My model-based analysis showed that human faeces contribute about one quarter of the P contained in CaSa-compost (Fig. 4 in P4)[67]. In view of the fact that P scarcity is a major soil constraint threatening farmers in Karagwe, this is a highly significant and beneficial aspect of utilizing human faeces in agriculture.

(2) I tested the viability of CaSa-compost to effectively increase biomass growth and yields for maize, beans, cabbage, onion, and carrots (P2). The benefits observed for CaSa-compost, which uses locally available nutrients, match those of significantly higher inputs of synthetic N-fertilizer (P2). Likewise, a higher increase in maize grain yields has been observed when using faecal-biochar compost, in comparison to synthetic fertilizers or animal manure in Moldova by Andreev et al. (2016). Finally, and as a consequence, maize plants grown on soil amended with faecal matter blended compost take up a significantly larger amount of P and N than plants grown with using standard compost (P2; Krause and Klomfaß, 2015). Adequate concentrations of those macronutrients can, therefore, be found in plant tissue and seeds (*ibid.*). Meanwhile, composts which contain human faeces should, in general, *not* be used for crops which grow *underground* (e.g. Richert et al., 2010). In my experiment, however, I still included onion and carrots as (i) these crops are an important part of the local intercropping design[68] and

[65] The process of discussing, planning, and designing an appropriate strategy and organization for future implementation began in 2016 and is ongoing.

[66] Total P content in DM of human faeces ranges from about 6 g kg^{-1} in plain faeces to about 14 g kg^{-1} in faeces collected in a UDDT (i.e. mixed with urine); P_{tot} in DM of grass cuttings or kitchen 'waste' ranges from about 1 to 3 g kg^{-1} (Table S5.1 in Supplements S5).

[67] In addition, biochar from composting adds another 15 % of P_{tot} to CaSa-compost.

[68] For example, onions are known for their repellent effect and are commonly intercropped in 'companion planting' methods as applied in organic gardening.

(ii) human faeces added to CaSa-compost have been pasteurized prior to composting to destroy pathogens[69]. I emphasize, however, that practitioners should rather follow the recommendations of Richert et al. (2010) and omit faecal compost for onion, carrots, beetroot, and potatoes, etc. Nonetheless, as shown in the field trial, CaSa-compost was especially beneficial for cultivating maize and beans, while standard compost performed equally well in the case of cultivating onion and cabbage (P2). The demo plots of MAVUNO further indicate the appropriateness of CaSa-compost for growing tomatoes.

(3) If the use of human excreta for the production of annual crops is undesirable for farmers, there are other options for its agricultural use. For example, faecal compost could be applied to fields used for growing bamboo, fodder grasses such as elephant grass (*pennisetum purpureum*, *miscanthus fuscus*, or *miscanthus violaceus*), or other grasses, which can be used as a fodder or energy crop. Another option for utilizing human excreta is for growing bananas in the *shamba*. This practice is called *omushote* in Swahili, and was common in Karagwe until pit latrines were installed in the region through 'development cooperations' in the 1940s (Rugalema et al., 1994). It would be possible to adapt this method to modern practice in the following way: Faeces are first collected in a double-vault UDDT, and then pre-composted inside the toilet for several weeks to months[70]. Pre-composted solids are then applied, on rotational basis, to planting holes for banana plant cuttings. Similarly, faeces may be applied to the planting holes for trees, including fruit trees[71], and trees for use as firewood or timber. To avoid transmission of diseases through direct contact or through flies, the hole needs to be covered ultimately with a layer of soil of about 30 to 50 cm in depth. Such reforestation could, for example, be realized on remote fields in the vicinity of settlements, and thereby contribute to ameliorating degraded soils in these areas (cf. Fig. 1.9, p. 29).

(4) Finally, however the faeces are employed, they should always be mixed with other kinds of organic residues, such as kitchen waste, harvest residues, and also biochar, or ashes. The aim of this is to sustain a well-functioning composting process with a balanced mixture out of (i) C and nutrient rich material, (ii) fractions of easily degradable organics and of stable matter suitable for humification, and (iii) dry and wet matter (e.g. Amlinger et al., 2008; Heinonen-Tanski and van Wijk-Sijbesma, 2005; Niwagaba et al., 2009).

Utilizing urine as fertilizer and compost additive

For the practical use of urine in agriculture, I identified the following potential opportunities and challenges:

1. Different means of treating urine prior to application reduce odour.

[69] The CaSa-compost was also tested for sterility prior to the experiment (cf. prior paragraph).

[70] In a double-vault UDDT, two chambers are used on a rotation basis for collecting solid matter. Once one chamber is full, it is closed. The other chamber is emptied, and then taken into use again. The duration of using a single chamber depends on: (i) the size of the chamber, and (ii) the number of people using it. A ball-park figure, however, would be around six months (Mucunguzi, 2010). Chambers are emptied with, for example, shovels and a wheel-barrow.

[71] Such an approach to EcoSan has been implemented in a girls' secondary boarding school run by MAVUNO. Figures S5.6 and S5.7 in Supplements S5 show pictures of an orchard, or 'fruit forest', created by staff members of the CaSa project in 2015 and 2016 by using faeces collected from UDDTs that are part of the school infrastructure.

2. Fertilizing with urine, in general, promotes plant growth.
3. Adding urine maintains a well-functioning composting process.
4. Enhancing compost with urine potentially decreases the efficiency of N recovery.
5. Factors surrounding pharmaceuticals and hormones in urine are, as yet, largely unstudied.

(1) It is likely that the most common method of using urine is as a liquid fertilizer diluted with water[72] (Richert et al., 2010). Urine is diluted mainly (i) to avoid excessive application of urine, and (ii) to reduce odour[73]. If urine is used undiluted, Richert et al. recommend applying it to a furrow or hole and closing the furrow/hole with soil thereafter. This can reduce odour and N losses through sub-surface volatilization. Lactic acid fermentation of urine is another option to reduce odour (e.g. Andreev et al., 2017). During the fermentation process, the lactic acid produced inhibits urease and, thus, also inhibits the formation of ammonia, whilst still conserving urea (*ibid.*). In practice, the lactic acid bacterial inoculum should be added to the empty urine storage tank of the UDDT *before* urine collection starts (*ibid.*). This increases the efficiency of lactic acid fermentation. Another approach to using urine as a fertilizer, is the addition of magnesium oxide to stored urine which results in a crystalline product called 'struvite', or magnesium-ammonium phosphate (MAP) (Winker et al., 2011).

(2) The beneficial effects of using urine as fertilizer have often been demonstrated (e.g. Andersson, 2015; Esrey et al., 2001; Richert et al., 2010[74]; Schönning and Stenström, 2004; cf. p. 11). Arnold and Schmidt (2012) found that both treatments, stored urine and struvite, show equally good fertilizing characteristics and are, thus, valid substitutes to synthetic fertilizer for cultivating maize, beans, summer wheat, or *miscanthus*. When testing the use of urine specifically for Karagwe (P2), the urine's qualities as a fertilizer were altered inside the UDDT by passing it through a deodorizer block in the urinal. For this reason, the true benefit of urine fertilization was not easy to gauge in our experiment[75].

(3) The benefits of adding urine to compost identified in this study are that (i) urine contributes to moisture levels in the mixture; (ii) urine enriches the compost product with N and P; and that (iii) adding urine to compost can reduce workload for farmers. In regard to the first point, practical experience from the CaSa case study showed that adding urine to the compost pit is highly effective in order to avoid the matter drying-out in local climate conditions in Karagwe. As water is scarce in the region, utilizing urine solves this problem without the need for extra (fresh) water. For maintaining a well-functioning composting process, and for minimizing NH_3 and N_2O emissions from the process, Amlinger et al. (2008) recommend a stable moisture content in the mixture of between 50 and 60 % of the total FM. In regard to the second point, to maintain a fast and odorless process, and also to minimize GHG emissions, C and N in the compost

[72] For example in ratios of between 1:3 and 1:5 parts urine to water.
[73] From my personal experiences during the field experiment, diluting urine with water is not an onerous task, and applying the mixture with a jug is not overly unpleasant.
[74] Richert et al. (2010) provide a valuable summary of knowns and unknowns on urine fertilization, alongside pictorial guidelines for practical application and recommendations for crop-specific application periods and doses.
[75] The deodorizer block resulted in a change in urine colour and an excessively high P content. When this urine was added to CaSa-compost, there was no evidence of any detrimental effects. However, I did not carry out a follow-up analysis on this.

mixture should be in the range of 25 to 35 (i.e. C/N-ratio)[76] (*ibid.*). Most materials added to compost tend to be rather rich in C, and so the C/N-ratio of the resulting compost is often too high (Finck, 2007), which slows down the process. According to my model, the C/N ratio in Karagwe standard compost is about 43 and in CaSa-compost about 38. Hence, the C/N ratio in CaSa-compost is lower, and therefore more proportional, presumably due to N input from urine. In regard to the third point, using urine blended compost can avoid an additional work step when compared to applying compost prior to sowing or planting, and then adding urine separately during plant growth. Furthermore, a piping system can be used to automatically transport urine from the toilet to the compost.

(4) When evaluating data from MFA and SNB (P3 and P4, respectively), I found that the overall efficiency of N recovery is, theoretically, higher for the direct field application of urine than for its use as a compost additive with approximately 70 % and 55 % of total N recovered respectively[77]. From a practitioner's perspective, there is, thus, a trade-off between optimising the efficiency of N recovery, improving the composting process, and managing or reducing workload. Finally, since biochar can capture NO_3^- and PO_4^{3-} (cf. paragraph on using biochar), the combined use of urine and biochar for composting also has the potential to reduce nutrient loss during, and after, composting, and, thus, to positively affect the turnover of N and P, and to make the practice of blending compost with urine more effective.

(5) Finally, MAVUNO staff members communicated doubts about EcoSan and CaSa in relation to 'health and hygiene' (P5). Upon request, I received feedback that the doubts expressed mainly refer to unknowns and uncertainties about *organic micro pollutants* (OMPs) contained in human excreta, such as pharmaceuticals and hormones, etc.[78]. Most OMPs are contained in urine, whilst faeces contain the larger part of pathogens (Richert et al., 2010). The eventual fate of these hazardous substances and the risk they pose to local populations is an important issue, which is, however, neither especially relevant to Karagwe, nor specifically related to EcoSan. To the best of my knowledge, it is still unclear *on a global scale* how we will deal sustainably with different OMPs that we continuously and increasingly emit to the ecosystem[79]. OMPs are also released into the environment through water toilets and pit latrines (e.g. Ngumba et al., 2016), most often in an uncontrolled manner and without any further treatment (cf. p. 8). Similarly, little is known about methods to eliminate OMPs in the environment, the prevalence of OMPs in the soil, their uptake by plants, further consequences for human health through consumption, the eco-toxicity of metabolisms, etc. It is certain, however, that simply storing urine is not sufficient to completely remove pharmaceuticals from urine. Struvite, meanwhile, is a product

[76] The optimal C/N range is determined by the need of microorganisms which require proportional content of C as an energy carrier and N for proteins (Finck, 2007).

[77] Initial N losses occur in the UDDT, and include, for both cases considered: (i) cross-collection of urine with solids due to imperfect separation (15 % of urine, and therefore, of N_{tot} content), (ii) N volatilization during collection of urine (7 % of N_{tot}), and (iii) N volatilization during storage of urine (2 % of N_{tot}). Differences in the overall efficiency of N recovery originate rather from the agroecosystem, where N is lost either (i) during the direct field application of the urine (12-13 % of N_{tot}), or (ii) during the composting process (30 % of N_{tot}).

[78] In Karagwe, OMPs mainly comprise medicines, such as malaria treatments, antibiotics (especially those given against urinary tract infection), pain killers, etc.

[79] As an example, Esrey et al. (2001) notes that 'the practice of feeding hormones and antibiotics to animals leads to large quantities of manure, hormones and pharmaceuticals polluting water supplies'.

free of pharmaceuticals and pathogens (Schürmann et al., 2012). Furthermore, according to the WHO (2006), 'the soil system is generally better equipped than watercourses for the degradation of pharmaceutical residues'. Further to this point, Arnold (2012) observed the successful degradation of hormones in the soil. With respect to pharmaceuticals, Arnold and Schmidt (2012) demonstrated that *diclophenac* (pain killer), *atenolol* (beta blocker), and *verapamil* (high blood pressure treatment) are not transferred to crops when present in urine used as fertilizer. *Carbamazepine* (an epilepsy treatment), however, can be determined in maize grains and stalks, but in relatively low concentrations[80] (*ibid.*).

7.3.3 Opportunities and challenges of using the substrates analyzed for soil fertility management

In order to be considered 'sustainable', soil fertility management should, among other factors, mitigate existing soil constraints, such as nutrient depletion and soil acidity. In the contemporary context, it should also promote resilience for agriculture in the face of climate change as a local and global threat. SOM, and the restoration of SOM, is of equal importance to climate adaptation measures, as it contributes to the soil's water holding capacity and erosion resistance. Ultimately, soil fertility management is applied in order to maintain or improve crop productivity. The evaluation of opportunities and challenges when using substrates analyzed for 'sustainable' soil fertility management in Karagwe, therefore, focuses on potentials for (1) replenishing soil P, (2) mitigating soil acidity, (3) restoring SOM, (4) sequestering C[81], and (5) increasing crop yields. In the following paragraphs, I briefly summarize the most relevant findings of my research (cf. discussion in P4).

(1) A direct increase of soil P is practically possible with the addition of CaSa-compost at a rate of about 140 kg P_{tot} ha^{-1} (P2). Adding biogas slurry or Karagwe standard compost at lower supply rates of 40 or 70 kg P_{tot} ha^{-1}, respectively, is insufficient for raising concentrations of soil P over the course of one season (P2). The theoretic potential for *annual* P replenishment (P4) rates range between 20-60 kg P_{tot} ha^{-1} (cf. Table S.4 in Supplements S3)[82]. The P application rates estimated for CaSa-compost and standard compost are similar and are in the upper half of the range presented. The potential of regular annual P applications is, therefore, sufficient for P fertilization *and* P replenishment, pursuant to the recommendations of Buresh et al. (2007) and Nziguheba (2001)[83]. Potential P applications with biogas slurry, however, barely meet the minimum demand for P fertilization on degraded soils with strong P fixation characteristics

[80] '*Comparing the amount of carbamazepine found in wheat grain with medical prescriptions, a person consuming the average German amount of 100 kg cereals yr* $^{-1}$*, would have to eat wheat for more than hundred years to reach the amount of one tablet given per day to a person suffering from epilepsy (400 mg* d^{-1} *and more)*' (Arnold and Schmidt, 2012).

[81] *Carbon sequestration* refers to the long-term storage of CO_2 in the form of SOM in order to mitigate global warming, and also, in principle, to an increase of SOM.

[82] With current soil management practices, the total application rate of P is around 2-3 kg P_{tot} ha^{-1} yr^{-1}.

[83] Buresh et al.(2007) considers 10 to 20 kg P ha^{-1} as a sufficient *seasonal* application of P to degraded East African soils with strong P fixation characteristics, such as Karagwe Andosols. Nziguheba (2001) found that *seasonal* application rates of > 25 kg P ha^{-1} over the course of four seasons are capable of replenishing levels of P in a P deficient soil in Western Kenya.

(*ibid.*). According to SWIM (Section 7.2.2), long-term amendments of CaSa-compost demonstrate the clear potential to steadily increase soil P, and therefore remedy P-scarcity. This is not, however, the case when using biogas slurry. In practice, adequate levels of soil P support adaptation to, and mitigation of the effects of climate change as a sufficient supply of soil P helps plants to root more deeply. This, in turn, makes crops less vulnerable to drought (Batjes and Sombroek, 1997).

(2) A direct increase of soil pH, i.e. after an one-off soil amendment, is only possible with CaSa-compost with a liming potential corresponding to about 2,000 $kg\,CaO\,ha^{-1}$ (P2). Amending the soil with biogas slurry or Karagwe standard compost, in application rates equivalent to liming with 300 or 700 $kg\,CaO\,ha^{-1}$ respectively, is not sufficient for raising soil pH over the course of a single season (P2)[84]. The theoretical annual liming potentials estimated (P4) indicate that both CaSa-compost and Karagwe standard compost are feasible for maintaining soil pH (Finck, 2007), while biogas slurry only fulfils the minimum requirements for liming pursuant to Horn et al. (2010). Overall, acidity management through liming is an important soil management practice in order to strengthen nutrient cycling processes (Batjes and Sombroek, 1997). This means that an increase in soil pH through liming, as demonstrated especially for CaSa-compost, promotes nutrient availability in the soil, and, thus, plant uptake of P and N. As a consequence, on-farm nutrient recycling becomes more efficient, and agricultural activities more productive.

(3) In my experiment, none of the tested soil amendments practically altered total C content of soil over the course of a single cropping season after the application of 150 or 500 $g\,C\,m^{-2}$ with either biogas slurry or composts (P2). The theoretical annual potential C contents in CaSa-compost and biogas slurry, meanwhile, are sufficient for restoring SOM[85] consumed during the cultivation of maize on a field with areas of about 0.2 and 0.1 ha respectively (P3). Using potentially available CaSa-compost or standard compost for IPNM demonstrates that it is theoretical possible to restore sufficient C to the soil to surpass the humus consumption of C of those crops grown on *msiri* fields (P4). In contrast, the C contained in biogas slurry barely balances SOM consumed during crop cultivation. To sum up, these findings indicate that only compost amendments demonstrate the theoretical potential to replenish SOM and also to sequester C in the long-term; biogas slurry does not.

(4) Among the substrates analyzed, CaSa-compost is particularly promising for sequestering C, due to the content of biochar recovered from household cooking and sanitation. Biochar has the potential for C sequestration due to the following factors: (i) it originates in renewable biomasses (Christensen et al., 2009); and (ii) it is characterized by relatively recalcitrant organic compounds which promise the long-term stability of biochar in the soil (Lehmann and Joseph, 2009). The context of the present analysis further promotes C sequestration, as the local soil is known for

[84] In comparison, minimum requirements of lime needed to neutralize deposition and avoid Al-toxicity are 50 $kg\,CaO\,ha^{-1}\,yr^{-1}$ (Horn et al., 2010). To mitigate soil acidity sustainably, and to maintain a soil pH > 6, liming requirements increase (exponentially), up to 1,000 to 2,000 $kg\,CaO\,ha^{-1}$ applied every three years (Finck, 2007).

[85] The capacity to restore SOM generally depends on the form in which C is recovered and then applied to the soil. CaSa-compost and biogas slurry typically provide about 50% and 25% of total organic C content for reproducing SOM (KTBL, 2009).

its outstanding capacity to accumulate organic C. Andosols tend to protect organic matter from degradation by forming either metal-humus (i.e. often Al-Fe), or allophane-organo complexes (Zakharova et al., 2015). Therefore, and according to Chesworth (2008), Andosols have the potential to act as CO_2 sinks. To the best of my knowledge, however, long-term studies observing the effect of biochar amendments on SOM in tropical Andosols do not exist. I am therefore unable to quantify the general potential for C sequestration with existing data, and any further discussion would enter into the realms of speculation. Nonetheless, I may at least compare my modelling results with the data available from short-term empirical studies in the region on biochar application and its effects. In the field trial, I observed that adding biochar to the local soil at a rate of around $2\,\mathrm{kg\,m^{-2}}$ had no significant effect on soil TOC content (P2). The theoretical potentials for biochar amendments on the *msiri* are estimated for *annual* or *triennial* biochar applications rates of 0.3 or $0.8\,\mathrm{kg\,m^{-2}}$ respectively, which correspond to C additions of approximately 0.2 or $0.6\,\mathrm{kg\,C\,m^{-2}}$ respectively (P4)[86]. These biochar amendments are, however, significantly lower than those recommended by Liu et al. (2012), or those in the practical experiences of Kimetu et al. (2008)[87].

(5) Finally, all tested soil amendments can directly alter biomass production and crop yields (P2). In the case of maize, CaSa-compost has the potential to quadruple grain yields in the short-term (P2). In the long-term, and according to SWIM (Section 7.2.2), CaSa-compost or biogas slurry both have the potential to roughly double yields of maize grains. The empirical and analytical findings regarding the potential effects of CaSa-compost and biogas slurry are, therefore, contradictory[88]. I argue that, firstly, the stronger *immediate effect* displayed with CaSa-compost fertilization is the possible result of a direct rise in soil pH through simultaneous liming. Soil pH, however, is not a parameter in SWIM, even though it is a highly relevant for predicting nutrient availability in the soil. Secondly, there is the possibility that SWIM overestimates N fertilization and underestimates P fertilization (cf. discussion in Section 7.2.2, p. 167). With respect to beans, I found that a seasonal biomass growth of beans in FM of at least $30\,\mathrm{t\,ha^{-1}}$ is needed to reach the break-even threshold where the balance of natural input and output flows of N turns from a net negative to a net positive result (P4). This corresponds to a crop yield of about $3.8\,\mathrm{t\,ha^{-1}}$ of air-dried beans (P4). This yield has only been possible with the use of CaSa-compost as a fertilizer (P2).

[86] The total recovery potential of biochar collected from cooking and sanitation is about $270\,\mathrm{kg\,C\,hh^{-1}\,yr^{-1}}$ (P3).

[87] Based on a meta-analysis, Liu et al. (2012) suggest amending biochar to the soil at a rate of a minimum of $5\,\mathrm{kg\,m^{-2}}$ up to $20\,\mathrm{kg\,m^{-2}}$ in order to affect, and sustainably increase, SOM content. Experimenting on a highly degraded soil in Kenya, Kimetu et al. (2008) observed a significant increase of 45 % in SOM after applying biochar at *seasonal* rates of about $0.6\,\mathrm{kg\,C\,m^{-2}}$ for three consecutive seasons.

[88] In the field trial, yields of maize grains on plots amended with CaSa-compost were about 170 % of the yields of plots amended with biogas slurry. In long-term modelling with SWIM, average yields with biogas slurry fertilization are around 115 to 130 % of the yields simulated for a fertilization strategy utilising CaSa-compost.

7.4 Critique of methodology

To realize an *integrated* system analysis of bioenergy, EcoSan, and soil fertility management, various methods have been employed. Table 7.8 summarizes the methods applied in the present study, and compares them to specific data sets of special interest to my research question. The methodologies are critically assessed and discussed as part of the publications P1 to P5 (cf. Chapters 2 to 6, respectively). For this reason, I only provide a brief critique of the methodology used in this section as an addition to the publications.

Table 7.8: *Methodological approach for addressing specific aspects of locally available technologies and soil management practices.*

	Laboratory analysis	Field trial	Modelling (MFA)	Modelling (MFA and SNB)	Technology assessment (MCTA)	Agronomic assessment	Modelling (SWIM)
	P1	P2	P3	P4	P5	Section 7.2.1	Section 7.2.2
Aspects addressed regarding the use of locally available technologies for:							
'Sustainable' cooking	-	-	A	D	A	-	-
Ecological sanitation services	-	D	A	-	A	-	-
Aspects addressed regarding recycling-based soil fertility management for:							
Replenishing soil P	A	A	D	A	I	-	A
Liming	A	A	D	A	I	-	-
Restoring SOM	A	A	D	A	I	-	A
Increasing crop yields	-	A	-	A	I	A	A

A: *Analyzed.*
D: *Discussed.*
I: Results of prior steps have been *integrated* into the assessment by using them to provide descriptions.
-: *Not considered.*

Firstly, the laboratory methods used for the characterization of locally available substrates (P1) follow international and German standards[89] and, thus, considered adequate for the present study. I recognize the fact that material samples were taken at one point in time is a limitation for this methodology. Analyzing a series of samples over time is necessary to empirically *prove* the findings in regard to the nutrient contents and the fertilization effects attributed. Nonetheless, nutrient concentrations determined have been checked against the literature, and are considered plausible and reasonable. When considered in relation to the need for research into the contribution of locally available materials to soil fertility management, this laboratory analysis has paved the way for more in-depth future research.

[89] Methods used are published by the International Organization for Standardization (ISO), by the German Institute for Standardization (DIN - *Deutsches Institut für Normung*), or by a panel of experts for forestal analytics (GFA - *Gutachterausschuss Forstliche Analytik*) from the German Federal Ministry of Food and Agriculture (BMEL -*Bundesministerium für Ernährung und Landwirtschaft*).

Secondly, the field trial conducted (P2) was strongly practice-oriented. For example, the experimental set-up includes intercropping of local, market-relevant crops for the specific context of Karagwe rather than academic testing of well-studied, but rather irrelevant grasses. Adapting the experiment to local practices promotes the transfer of results to real-world practice. This research approach further applies a methodology which satisfactorily combines soil chemistry, soil physics, and plant nutrition in one study. The study of whether significant alteration of hydraulic soil properties are present or not is often overlooked or altogether neglected in research into soil amendments. In order to adjust the experiment to the local farming practices, I used local crop species and seeds only, avoided the use of synthetic fertilizers as a control, compared locally available materials such as standard compost, biogas slurry, or CaSa-compost, irrigated only as required, for example with fresh seedlings, applied natural pest control[90], etc. Challenges faced during the experiment were (i) measuring N_{min} before, during, and after the experiment because I had no means of cooling samples when in the fields or during transportation[91], and (ii) performing the double-ring infiltration experiments, as $> 2\,m^3$ of water were required, which had to be carried with buckets from the rain-water harvesting tank to the field. With respect to the statistical analysis applied, the experimental design (a Latin Square pursuant to Richter et al. (2009)) supported randomized sampling and adequate data analysis. I had no choice, however, other than to use a block design for all laboratory examinations of soil and plant samples due to financial restrictions brought about by the cost of chemical analyses. With respect to our results, I acknowledge that the crop yields realized over the course of the experiment are comparatively high, and, therefore, cannot be expected to be replicated under all circumstances. I was lucky enough to receive sufficient rainfall over the course of the experiment in 2014. However, this is not the rule for the region[92]. Finally, I recognize that the present experiment was only short-term, which is insufficient (i) to validate results, for example on crop yields, and (ii) to enhance knowledge on the effects on SOM, C sequestration, or soil hydraulic properties, which are potential mitigation measures in order to combat climate change. A more sustained study will be needed to monitor the long-term effects of CaSa-compost or biogas slurry applications on soil fertility and crop productivity. On the other hand, it can be argued that focussing on the first season is reasonable, as the immediate 'success' of certain management practices is of high practical relevance to (subsistence) farmers in SSA.

The first model-based assessment compares cooking and sanitation technologies (P3) and considers most relevant technology-specific material flows, such as resource consumption, recovery of residues for subsequent agricultural use, and environmental emissions within one study. The method of MFA was strongly beneficial in order to structure the analysis and to be able to incorporate uncertainties into the assessment. To create an adequate database for the comparison of locally available alternatives and their application to smallholders in Karagwe, I aggregated data from various sources and disciplines, and from both the scientific and practitioner's spheres. For

[90] Insects were controlled by spraying with a mixture of ash and '*moluku*' (Swahili), which I prepared from leaves of the *Neem* tree and the *Fish Poison* tree suspended in soapy water.

[91] As a solution, I established a bicycle shuttle between the field site and on-site field laboratory at MAVUNO's compounds.

[92] For example, in 2016, the rains came very late and farmers had to cope with a severe drought. Many crops died and yields were very low or even absent.

example, data collected from literature was checked for its relevance to the given context. My own data, which includes exploratory works presented in P1 and P2, and empirical data from the case study projects, complements the database. Unfortunately, the software used (*subSTance flow ANalysis* - STAN) was not as appropriate for the task as I had expected. I needed to set up a new model for each technology analyzed, which resulted in a total of 44 flow diagrams[93]. For this reason, the visualizations of the results into flow charts were not as useful as anticipated. Nonetheless, these flow charts provide transparency on flows and processes considered in the technology assessment (cf. Supplements S2). The major contribution of STAN to my work was data reconciliation. Further adverse aspects of the present MFA application include: (i) the study lacks a sensitivity analysis in order to estimate the 'robustness' of its results; (ii) the study *applies* MFA but does not contribute to a methodological refinement of MFA; and (iii) the study rather follows a 'either-or' principle, by comparing single technologies, instead of supporting an 'as-well-as' paradigm through the formulation of scenarios reflecting specific technology mixes.

The subsequent model-based assessment of residue integration into soil fertility management (P4) combines MFA with SNB. This analysis is, thus, a contribution to developing *integrated approaches* to system analysis through multi-method applications. I further consider the combination of MFA and SNB as highly appropriate for conducting an *ex-ante* assessment of soil fertility management practices. Both methods generally follow comparable principles and procedures. Their integration allows for a *systematic* comparison of specific IPNM approaches, such as the use of biogas slurry, urine, or co-composted human faeces and biochar on a farm level. Employing SNB supports describing the real farming system in as simple a manner as possible, yet also in as complex a manner as necessary for the scope of the study. Supplementing the analysis with MFA expands investigations, as MFA incorporates private households and the environment into a system analysis. As an example, MFA delivers additional information, such as the composition of composts, emissions from composting, potential humus recovery, etc. Limitations in the applied methodology include: (i) yields assumed in the modelling derive from a short-term field trial (cf. discussion above); (ii) nutrient applications are simplified as seasonal additions of N_{tot} or P_{tot} due to the static nature of the model, which does not consider soil dynamics[94]; and (iii) effects on environmental emissions relating specifically to the use of biochar, during the composting process or after the field application of composts, are not considered in the model. In regard to the latter, I reason that the existing scientific data on using biochar as a soil amendment is contradictory, especially for soil-borne emissions (cf. Mukherjee and Lal, 2014; Van Zwieten et al., 2015). Overall, I judge that it is not yet possible to depict biochar effects in a model such as the one presented in P4. I have, therefore, assumed equal processes and emission factors for standard compost and CaSa-compost containing biochar in the model.

Furthermore, in integrating the results of P3 and P4 a functional link between smallholder households, farming practices, soil nutrient stocks, and the environment is created, which ultimately

[93] The total number of diagrams for all cooking and sanitation technologies analyzed, including the processes and sub-processes depicted and the four layers of 'goods', C, N, and P.

[94] For example, neither the form of nutrients applied (i.e. N_{min}, N_{org}, or P_{org}) nor the transfer to the various nutrient pools in the soil (e.g. 'labile' and 'stable' pools of P) are accounted for.

shows how positive and negative impacts may offset one other. For example, alongside improvements in soil nutrient balance, integrated environmental impacts with GWP and EP increase due to the employment of the technologies in households, such as the biogas system, or intensified production of compost when utilizing residues from cooking and sanitation. These findings show that a systemic perspective on the nexus of energy-sanitation-agriculture is highly recommended in order to understand the full impact of technology change. Whenever appropriate technologies that also include the subsequent recycling of residues to the agroecosystem are assessed for their environmental impacts, the analysis should, therefore, cover both the actual (domestic) use of the technology and the agricultural use of residues.

With the multi-objective assessment of cooking and sanitation technologies (P5) I widened the, so far, mainly agronomic and environmental perspective of my research out to a more holistic sustainability perspective. From a methodological perspective, combining MCA with analytical methods, such as MFA, is a viable integrated approach to sustainability assessment. On the one hand, MCA helps to structure the assessment, while on the other, the results of analytical studies (P1-P4) can be used to describe the performance of alternatives which have been assessed quantitatively. When beginning my research in 2012, I experienced challenges in regard to the availability of data for the given context. Existing literature data was not sufficient to estimate and to describe the performance of the technologies analyzed. In order to generate a broader database for the MCTA, significant additional effort was needed to collect data, such as conducting laboratory analysis and field experiments (P1, P2), estimating material flows within the agroecosystem of smallholdings in Karagwe (P3, P4), accessing the explorative data of practitioners, collecting expert judgements, etc. Two-and-a-half years later, in 2015, I faced a clear conflict between the scope of the work needed for conducting a full MCDA and the time available to carry it out. As a consequence, I simplified the mathematical model applied, excluded an in-depth analysis of sub-criteria ratings, omitted sensitivity analyses, and conducted pre-testing of the MCTA-tool in a streamlined manner that involved less participation. In regard to the latter, I would bring to the reader's attention that (i) criteria have been pre-selected and were only ranked and rated with participants input, and (ii) farmers were not involved in the assessment, even though they are the party most concerned. Even taking these limitations into consideration, conducting the MCTA was a rewarding process, that promoted 'embedded learning' by integrating recent scientific and practitioner findings into an overarching sustainability assessment. Practically, the MCTA developed has a strong potential to support collaborative learning, to deepen understanding of the technologies assessed, and to demonstrate the individual perceptions of the stakeholders by making them visible and transparent. Conducting any MCTA is, nonetheless, an extensive process that demands considerable time and a strong commitment from all participants involved. Pre-testing revealed that an MCTA is a simple but viable assessment tool that may be applied on a community level as part of decision-making processes in order to further assess locally available technologies before implementation. Before employing MCTA in Karagwe or elsewhere, however, I consider that the tool needs further adaptations, such as reducing the total number of criteria applied.

With respect to the estimation of food production in the context of food sovereignty and income generation (Section 7.2.1), I criticise the following: (i) assumptions for crop yields when using biogas slurry or CaSa-compost derive from a short-term experiment (cf. discussion above); and (ii) possible reductions of total harvest through post-harvest losses, seed requirements for the following season, etc. are not taken into account. For this reason, the results are vulnerable and may represent an overestimation of food production potential. Even so, the yields assumed do fall within a realistic scale when taking improved soil fertility and productivity into account (cf. discussion in P2).

The final model-based simulation of continuous soil fertility management over a period of two decades with two seasons per year (Section 7.2.2) further expands my investigations by taking a long-term perspective on using locally available substrates as fertilizers for intensive cultivation of local soil. The SWIM, in principal, also supports the integration of various climate change scenarios presented by the Intergovernmental Panel on Climate Change (IPCC) in the simulation[95]. Such model-based forecasting of crop production in the context of climate change would have certainly been highly interesting. However, in practice, such a simulation would have resulted in very high uncertainties, as climate data and the scenarios available for the region are scarce[96].

Finally, I reflect briefly on the average size of a smallholding assumed for the present study. To produce sufficient food for its own consumption, a farm with six people requires about 0.4 to 3 ha (Lal et al., 1989; Myers, 1999). The lower figure refers to a household eating a mainly vegetarian diet, whereas the higher figure corresponds to meat-eating households[97]. Secondly, in order to generate income in addition to subsistence farming, small commercial farms in SSA require access to around 0.75 to 1.0 ha (Mellor, 2014). Given that smallholdings in Karagwe have access to, on average, only 0.625 ha of arable land (Tanzania, 2012), the total size of land available for crop cultivation is basically appropriate for a predominantly vegetarian diet and only very limited commercial activity. To increase productive farming, it is particularly important to intensify soil management activities that both sustain soil fertility and increase land productivity. Realizing such intensification through using locally available materials and closing on-farm nutrient cycles has been the focus of the present work.

[95] Moss et al. (2008) defined four *representative concentration pathways* (RCPs) as trajectories for the increase of GHG emissions into the atmosphere and the consequent increase in radiative forcing.

[96] Based on the assumption of C. Gornott, with whom I cooperated at PIK. According to Gornott, our approach, which is based on local climate data from the past, is comparable to the IPCC-scenario 'RCP2.6', which assumes a rise in global mean temperatures of 0.3 to 1.7 °C (IPCC, 2013).

[97] According to Myers (1999), 0.07 ha per person is the absolute minimum of arable land required to support food security when a largely vegetarian diet is assumed. If meat is also consumed in quantities comparable to North American or Western European diets, the land requirements would rise to around 0.5 ha per person (Lal et al., 1989; Myers, 1999).

7.5 Future research demands identified

In my thesis, I investigated environmental and agronomic *potentials* that relate to the use of various, locally available cooking and sanitation technologies in farming households, alongside the recovery of residues in smallholder agriculture. I thereby took an integrated approach and focused specifically on smallholder systems in Karagwe. Future scientific work could follow by conducting more detailed empirical research on certain aspects of this approach, upon which I elaborate further in the following paragraphs.

With respect to biogas systems, the present study assessed GHG emissions from local biogas digesters which had been *estimated* based on existing and available data from literature. Future research could, therefore, continue to collect new data by *measuring* emissions from biogas systems. Monitoring these emissions within the context of conditions of practice in Karagwe over a period of several years would be both interesting and of ecological relevance. In practice, this could help, for example, to formulate recommendations on when internal plastering needs to be renewed to maintain gas-tightness at its highest possible level. Local practitioners also expressed an interest in continuing research and development into how the intermediate storage of biogas slurry inside the digester can be improved to reduce GHG emissions and maintain nutrient content. A further matter for future research would be a comparison study between direct fertilization with biogas slurry and composting of the slurry. A study on composting biogas slurry with other organic material, including biochar, would also enable measurement of the content of NH_3, organic acids, and other potentially phytotoxic substances therein. Preceding studies could further continue to test the applicability of locally available biogas slurry as fertilizer with respect to several nutritional and market relevant crops in order to identify 'best-practice' in terms of application technics, rates, times, etc.

To further advance EcoSan application in Karagwe and elsewhere, future research include testing an extended version of the Kon-Tiki cone kiln as a sanitation facility. Experiments could be performed to (i) quantify and evaluate material flows of fuel required, biochar produced, quench water produced, and human excreta sanitized; (ii) test operating the Kon-Tiki with a mixture of firewood and dried faeces as fuel instead of only firewood; (iii) test the use of urine for quenching the hot biochar, while measuring N_2O and NH_3 emissions; and (iv) study the use of the quench water, which is soapy and alkaline, as a 'natural pesticide' in greenhouse production[98]. Practitioners also stressed the importance of further research on the use of human excreta for tree planting. Specific research demand includes: (i) a study of the survival of pathogens and OPMs in the soil; (ii) identification of adequate application rates; and (iii) quantification of changes in failure rates after planting tree seedlings. In regard to the latter, improved performance is suggested when faecal-blended compost is added to tree planting holes as organic amendments improve water holding capacity in the soil and provide fertilization for the seedling. Proof of

[98] Further to this, Schmidt and Taylor (2014) note that the '*soapy quench water is apparently excellent for pouring on fruit and vegetable plants. It discourages snails and fungus, and generally acts as a tonic to the plants. The latter statement is based on personal observations of only two dozen plant species so far; systematic scientific investigations are still pending*'.

this hypothesis would be a strong incentive for smallholders to incorporate this EcoSan practice into their current planting regime. Irrespective of the path chosen for recycling human excreta, studying the fate of OMPs in the agroecosystem is of high importance for local stakeholders (P5) and should be addressed by future research.

Moving ahead, biochar additions to composting can have a practical influence on GHG emissions or nutrient leaching due to the fact that biochar adsorbs N and P (cf. Section 7.3.1, p. 180). Pursuant to Sun et al. (2017), biochar additions mitigate emissions of soil-borne GHGs, especially at high levels of N fertilization. These results are highly interesting with respect to co-composting of biochar and urine. Most existing biochar studies, however, have been conducted in regions with a temperate climate. This means that their results cannot easily be transferred to SSA conditions, where, for example, elevated temperatures influence microbiological and metabolic processes. Additional local experiments on co-composting biochar with urine or biogas slurry in semi-arid and tropical savanna climate, as present in Karagwe, would thus fill this research gap. In comparison to co-composting, a slurry of urine and biochar could be prepared and mixed with compost directly on the soil before seeding[99]. Future research on the combined use of biochar with urine or biogas slurry should include an analysis of input materials and compost products, and monitoring of gaseous (e.g. CH_4, N_2O, NH_3, etc.) and liquid emissions (e.g. PO_4^{3-}, NO_3^-, etc.) during composting and after amending the soil. Such a research approach would allow further assessment and evaluation of 'sustainable' biochar practices for smallholders by quantifying (i) nutrient recovery efficiencies, (ii) climate impacts, (iii) the quality of those products which are ultimately recycled to agriculture, and (iv) agroecological and socio-economic value of these products.

During my studies, I took material samples only from one site, namely, the CaSa pilot project. Likewise, the field trial was conducted only on one field site. Therefore, the empirical results from my substrate analysis and field experiment are not representative for the entirety of Karagwe. For this reason, future experiments should be conducted on different sites and include analyzes of soil and material samples. For example, local smallholders that possess biogas digesters, or microgasifiers and EcoSan facilities, could either collect biogas slurry or produce CaSa-compost at their farms, and then use them on their farmland. The design of the experiment should be planned by both researchers and practitioners, and be well coordinated and compatible for both sets of needs. There has been a precedent set for such participatory and practice-oriented experiments by, for example, Andersson (2015) in Uganda or Schmidt et al. (2015) in Nepal.

Empirical and analytical results of the present study suggest that a continuous program of amending CaSa-compost to the local soil can, over decades, fully replenish the local soil of depleted pools of soil P and mitigate soil acidification. Long-term experiments are now needed to obtain empirical evidence of this assumption, and to study other long-term effects, such as those on SOM concentrations, CEC_{eff}, or soil hydraulic properties, and effective potentials for C-sequestration when using biochar on tropical Andosols. Other possible fields of interest

[99] Such sub-seed application in the root zone has been very successful in producing fourfold pumpkin yields in Nepal as observed by Schmidt et al. (2015).

for future research on soil management practices include studies on (i) *in-situ* interactions of biochar, soil nutrient pools, and SOM; (ii) effects of soil amendments on soil mycology, soil microbiology, and erosion sensitivity; and (iii) the potential salinisation of the local soil as a result of continuous urine fertilization.

An upscaling of my analytical results from the household (*micro*) perspective, to the community or district (*meso*) levels is another avenue for future research[100]. Moreover, in the present study, I have demonstrated that certain material flows are affected by human behaviour. For example, the potential to recover biochar from microgasifiers depends on usage patterns of the stove, and nutrient recovery potentials from EcoSan hinge on the extent to which the UDDT is actually used. From a methodological point of view, the diverse behaviours of human subjects and their preferences, thus, need to be taken into consideration in future studies analyzing biomass potentials. To analytically reproduce this distinctive human 'fuzziness' in future studies on biomass dynamics, stochastic methods and statistical models could be applied to integrate a 'human factor'.

Following the discussion on implementation barriers for the technologies analyzed (Section 7.3), I see a need for future research on business models that are suitable for Karagwe, and other agricultural areas in SSA. Such socio-economic research should focus on the identification of (i) viable social business models and (ii) tangible (i.e. added) values for users. With respect to the first, it is important that business model and technological solution complement one other (Müller et al., 2009). Given that, for example, a 'lack of services' is a key barrier to implementing biogas technology, an approach incorporating 'product-service systems' (PSS)[101] might be suitable. This approach can potentially help to access services more easily and to capture value more effectively. With respect to the second point from above, further research could include a systematic mapping of the potential 'productive uses' of all the technologies analyzed alongside an assessment of the associated socio-economic opportunities[102]. Taking the example of biogas, social benefits include: (i) *direct income generation* through selling biogas as a transportable fuel[103], biogas slurry as a fertilizer, or harvest surpluses as a result of increased yields through improved soil management (as studied in this thesis); and (ii) *job creation* through construction work, stove manufacturing, and service provision, including maintenance, resource collection, or transportation[104]. As a synthesis, a cost-benefit analysis could be applied to calculate the 'net present value' of these technologies, and to evaluate the economic viability

[100] Cooperation with A. Reetsch from the United Nations University (UNU) Institute for Integrated Management of Material Fluxes and Resources, Dresden, Germany, has already been established.

[101] According to Tukker and Tischner (2006), a *producer-service system* (PSS) 'consists of a mix of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling final customer needs'. A 'product-oriented PSS' includes (i) product-related services such as financing, maintenance, supply of spare parts, etc., and (ii) advice on the most efficient use of the product (cf. Tukker, 2004).

[102] The present study contributes an analysis of the 'productive use' of residues recovered from biogas digesters, microgasifiers, and EcoSan facilities (cf. Section 7.2.1, p. 164).

[103] The company (B)energy, a social business, offers the (B)pack, a 1.2 m^3 backpack for transporting biogas from biogas producers to biogas customers (cf. Link to (B)energy website).

[104] As an example, a social business model could include the intensified use of food waste, which is a highly suitable fermentation substrate (e.g. Vögeli et al., 2014), and the following services: collection of food 'waste' from canteens in town, transportation of food waste, biogas production in small-scale digesters, and finally, transportation and sale of biogas slurry and surplus biogas (cf. Yousuf et al., 2017).

of different business models. The basic assumption is that social benefits act as incentives for users to adopt 'new' technologies. Action research from a socio-economic perspective, therefore, may help to advance access to microenergy systems for smallholders. Moreover, it can support the search for implementation strategies that make local stakeholders (more) independent from 'development projects'.

Finally, the multi-criteria approach presented (P5) proved highly effective in order to explore a set of alternative technologies against the backdrop of a multi-dimensional sustainability assessment. Over the course of this process, participants learn about the manifold effects that an implementation of technologies potentially has on the local community and on the environment. To make the MCTA applicable for decision-making processes in local smallholder communities, however, methodological challenges and problems still need to be addressed. For example, by lowering the number of sub-criteria in a participatory approach, complexity and workload will be reduced.

7.6 Overall conclusions

I have systematically identified, analyzed, and summarized the strengths and weaknesses of cooking and sanitation technologies and associated soil fertility management practices in the context of Karagwe. In doing so, I generated deeper insights into the untapped potential of the technologies that are currently implemented, or will be in the future, in the region. Overall, my work sheds light on how the applications of different locally developed technologies in smallholder households affect environmental quality, ecological health, and agro-economic outcomes. I finally conclude that a system transformation on the micro level, through implementing new technologies *and* through the effective recovery of their respective residues, shows multiple opportunities, including: (i) reducing resource requirements (e.g. firewood, flush water), (ii) reducing negative environmental impacts (e.g. nutrient leaching, deforestation), (iii) substituting finite resources (e.g. rock phosphate as fertilizer, fossil gases for cooking), (iv) reversing the fertility of degraded soils (e.g. remediation of acidified and nutrient-depleted soil), and (v) enhancing productivity of smallholders' arable land (e.g. increase of food supply to farm members and income generation).

Regarding the 'performance' of locally developed cooking technologies and sanitation facilities, I conclude the following:

- Using ICSs or the biogas system for cooking reduces firewood requirements for smallholder households, and, thus, reduces pressure on local forests.
- ICSs, such as microgasifiers or rocket stoves, are more suitable on the household level due to their lower investment costs and lower workload required for handling both input and output materials. Biogas systems are, nonetheless, promising for implementation on the community level, for example, in institutions such as schools, hospitals, etc.

- Implementation of waterless EcoSan facilities significantly promotes nutrient recovery, reduces environmental emissions, and constitutes a viable alternative to water-based septic systems, which place heavy pressure on already scarce water resources.
- Individual perceptions and evaluations of the cooking and sanitation alternatives analyzed clearly differ between stakeholders. Representatives of the German project partners tend to be more enthusiastic about new technologies, while representatives of the Tanzanian partners tend to be more sceptical.

With respect to the potentials identified for capturing residues from cooking and EcoSan for soil fertility management, I conclude the following:

- Recovering and processing residues from smallholder households provides a significant opportunity to increase access to fertilizer and soil improvers through subsistence production.
- Noticeable effort is required, however, on the part of the farmers in order to exploit the potentials of the IPNM practices analyzed (e.g. transportation of materials, making compost, collecting and applying biogas slurry or urine, etc.).
- All treatments analyzed are viable as substitutes for synthetic, commercial fertilizers, but CaSa-compost displays benefits over and above the alternatives.
- The potential of CaSa-compost for 'sustainable' soil fertility management is superior to that of standard compost, especially with respect to liming and potential SOM restoration. Biogas slurry gives inferior results in all aspects when compared to compost amendments, but especially for liming, potential SOM restoration, and GHG emissions.
- Moreover, even when the strong P retention characteristics of the local Andosol are taken into consideration, further gradual increases in soil P are possible with regular applications of CaSa-compost.
- Both prevailing challenges for agricultural production in Karagwe, namely, P scarcity and soil acidification, can be mitigated through sufficient application rates of CaSa-compost as the analyzed case studies showed. Whether, and how, CaSa practice can also serve as a mitigation measure to climate change, needs to be the focus of future research.
- The demonstrated potential to increase yields is theoretically sufficient to reach food sovereignty for smallholder households, while the corresponding nutrient requirements are adequately compensated for by locally available residual matter.
- Therefore, this practical approach of recovering biochar and human excreta for IPNM represents an exit strategy from the vicious circle of poor soil quality and insufficient production of food crops and residual matter in the context of SSA smallholdings.

With respect to the overarching RQ (p. 35), my work provides a basic 'proof-of-concept' that by using locally developed cooking technologies and EcoSan facilities, there is a clear potential to *simultaneously* improve energy and sanitation services in households *and* agricultural productivity on farmland. Microgasifiers for cooking and EcoSan facilities for sanitation constitutes a highly suitable option for simultaneously optimizing resource consumption, environmental impacts, and recycling-based soil fertility management. My results further endorse establishing a clear link between cooking, sanitation, and agriculture, and, therefore, an 'intersectional resource management' approach. This is due to the fact that recyclable matter from energy and sanitation facilities have complementary benefits. For example, biochar from microgasifiers promotes the recycling of C for restoring SOM, while those residues collected from EcoSan facilities contribute to capturing nutrients for fertilization. In the case of a biogas system, it should be noted that biogas slurry cannot be considered an 'untapped resource' for the agroecosystem in all cases. In our case study, both input materials used for biogas fermentation had previously been used as fertilizer input in the banana-based homegardens. If the larger part of the nutrient content in biogas slurry is used to fertilise *msiri* soil, than it is vital that the biogas system is combined with EcoSan. Through this link, human excreta can be used on the *shamba* to replace prior inputs of banana stem and cow dung, thus avoiding an exacerbation of nutrient depletion there. Overall, the triple nexus of 'energy-sanitation-agriculture' as a theoretical and practical approach to a SCD is superior to either of the double nexuses 'energy-agriculture' or 'sanitation-agriculture'. Furthermore, having a system-based perspective on that triple nexus is highly recommended, as positive and negative impacts may offset one other in unexpected ways, as is the case for the environmental impact of emissions.

From a methodological perspective, I further conclude that the inter- and transdisciplinary approach of combining (i) a multi-criteria approach for structuring the evaluation with (ii) empirical and analytical methods for describing the performance based on (iii) close collaboration between practitioners and researchers is highly expedient for designing sustainability assessment methods that are both integrated and participatory. A significant strength of this approach is that it enhances transparency on the assessments of different stakeholders, which helps to promote trust. And trust is absolutely crucial for the successful implementation of new ideas and solutions. Lack of transparency and trust between researchers and locals and the imposition of top-down-structures without equal participation of the locals has been a major reason for the failure of many projects.

My experiences further strongly support the importance of pilot projects with a large test group. Such practical studies help collect real-world data in order to quantify the performance of a technology and to assess whether or not the technology fulfils the objectives set out for its wider implementation. Pilot projects further serve as practical demonstrations of a given technology in a particular region, which in turn, helps to improve local understanding of the technology and, ultimately, to gain acceptance. Finally, I emphasize that Tanzanian institutions and initiatives should enthusiastically promote policy development in the field of decentralized, domestic bioenergy for cooking and waterless EcoSan services. This, in turn, will also enhance the level of security during the strategic planning stage of project implementation.

Taking all the limitations of this work into consideration, I hold that this thesis still generates transparency regarding the potential environmental and agronomic impacts associated with new technology implementation in combination with the recovery of residues from cooking and sanitation for IPNM in Karagwe. Its results, in turn, may support local initiatives aimed at implementing 'sustainable' technologies and 'sustainable' farming methods to be aware of the complex effects associated with the technologies analyzed. The results may also help improve the food security of smallholders in Karagwe and protect local natural resources (e.g. forest, groundwater reservoirs, Kagera river, etc.). The results are specifically applicable for smallholdings in Karagwe. This vulnerable region with its specific soil and climate conditions can also serve as a representation of the situation of subsistence farmers in other comparable regions in the wider context of SSA.

'Little by little, bit by bit, family by family, so much good can be done on so many levels'.

(Ostrom, 1990)

Chapter 8

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