Land-Use Change and Ecosystem Service Modeling under Conditions of Growth and Shrinkage – The Case of Berlin

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Summary

Today's political decision makers are challenged to tackle the complex interactions between human activities and the natural environment within the context of limited environmental and human resilience. This becomes especially important in urban regions, where environmental effects are particularly evident, as indicated for instance by a continuous global decline of ecosystem services (ES) due to the increase of urban areas. Future decision-making can only be effectively promoted if the multiple cause-effect relationships driving urban and ES change are understood. For this purpose, a systemic approach seems promising and was chosen in this dissertation thesis.

The aim of this thesis is to provide a combined model approach that is able to reveal the currently observed urban processes and dynamics which characterize the complex urban system. To this end, a demographically-driven residential demand and supply model is linked to a spatially explicit land-use change (LUC) model. The effects of LUC on the urban pattern and ES provisioning are analyzed using partly newly developed indicators. Additionally, the chosen model approach should serve to increase understanding of the urban system. In order to accomplish this, varying scenarios were developed to determine their respective effects on the urban pattern and ES, including both aspatial demographic shift trends such as population growth, shrinkage and population aging, as well as spatial trends such as demand preference and planning shifts. The case study presents the Berlin metropolitan region.

The combined model provides a very satisfactory reproduction of land-use change by improving the causal relations of LUC drivers within sophisticated residential choice mechanisms. It is able to reproduce the simultaneous growth and shrinkage in varying residential types, and includes the processes of reurbanization and suburbanization. Future simulations indicated that population growth and population aging—expedited by population shrinkage—increases land consumption, landscape fragmentation and ES loss. In contrast, population shrinkage and shifting preferences towards reurbanization can effectively reduce these same aspects. It could be shown which particular land-use transitions most significantly affect ES degradation or improvement, and how they relate to ES linkages in terms of synergies and trade-offs.

The thesis concludes with a detailed description of systematic linkages regarding human decisions, the urban pattern and environmental effects, resulting in a functional chain of urban system dynamics and depicting the strength of the connection between the relevant system parameters.

Zusammenfassung

Die heutigen politischen Entscheidungsträger müssen sich im Hinblick auf die begrenzte Belastbarkeit der Umwelt und die Grenzen menschlicher Belastbarkeit der Herausforderung stellen, die komplexen Wechselwirkungen zwischen menschlichem Handeln und der natürlichen Umwelt zu verstehen und zu gestalten. Dies ist besonders in städtischen Regionen, in denen die erhöhte Umweltbelastung evident ist, von hoher Relevanz, was am Beispiel des kontinuierlichen globalen Rückgangs von Ökosystemdienstleistungen in Folge der anhaltenden Verstädterung deutlich wird. Zukünftige politische Entscheidungen können nur zielführend sein, wenn sie integrativ in dem vielseitigen Ursache-Wirkungs-Gefüge städtischer Veränderungen betrachtet werden. Für solch ein Bestreben erscheint ein systemischer Ansatz, wie er in dieser Dissertation gewählt wurde, vielversprechend.

Das Ziel dieser Doktorarbeit ist es, die wesentlichen Prozesse und Dynamiken, die charakteristisch sind für das komplexe System einer Stadt, in einem kombinierten Modellansatz abzubilden. Zu diesem Zweck wird ein demographisch angetriebenes Modell zur Berechnung der Wohnnachfrage und des Wohnangebotes mit einem räumlich expliziten Landnutzungsmodell verknüpft. Die Auswirkungen von Landnutzungsänderung auf die städtische Struktur, sowie auf das Angebot von Ökosystemdienstleistungen werden mit Hilfe von zum Teil neu entwickelter Indikatoren untersucht. Zusätzlich wird das Modell genutzt um das städtische Systemverständnis unter Verwendung von Szenariosimulationen voranzutreiben und szenariospezifische Auswirkungen auf die Stadtstruktur und das Angebot von Ökosystemdienstleistungen zu ermitteln. Die Szenarien basieren auf nicht-räumliche, demographische Veränderungstrends, z.B. Bevölkerungswachstum, -schrumpfung oder Überalterung; sowie räumliche Trends, z.B. durch veränderte Nachfragepräferenzen oder veränderten Planungsvorgaben. Das Untersuchungsgebiet stellt die Metropolregion Berlin dar.

Dem kombinierten Modell wird aufgrund der verbesserten Anbindung von kausalen Triebkräften und der Nutzung eines fortschrittlichen Verfahrens zur Berechnung von Wohnstandortentscheidungen, eine überzeugende Reproduktion von Landnutzungsänderung nachgewiesen. Städtische Prozesse der Suburbanisierung und der Reurbanisierung können abgebildet werden, durch die Integration simultan ablaufender Wachstums- und Schrumpfungsprozesse in unterschiedlichen Wohnnutzungstypen. Mit Hilfe von verschiedenen Simulationsergebnissen wird nachgewiesen, dass die Zunahme der Bevölkerung, sowie die Alterung der Bevölkerung den Flächenverbrauch, die Fragmentierung der Landschaft und den

Verlust an Ökosystemdienstleistungen deutlich erhöhen. Im Gegensatz dazu können diese Kenngrößen durch Bevölkerungsrückgang und der Veränderung von Wohnpräferenzen hin zu zentraleren Wohnlagen verringert werden. Darüber hinaus wird gezeigt, welche Landnutzungsänderungen sich besonders gut, bzw. besonders schlecht auf das Angebot von Ökosystemdienstleistungen und deren Verflechtungen (wie Synergien oder Trade-offs) auswirken.

Die Doktorarbeit schlussfolgert mit der detaillierten Beschreibung der systematischen Verknüpfungen von menschlichen Entscheidungen, stadtstrukturellen Veränderungen und Umweltwirkungen, was schließlich in einer Wirkungskette städtischer Systemdynamiken mündet.

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Abbreviations

AB	Accessibility baseline scenario (cf. Table V-1)
ABM	Agent-based modeling
App.	Appendix
BB	Basic baseline scenario (cf. Table V-1)
BG	Basic growth scenario (cf. Table V-1)
BS	Basic shrinkage scenario (cf. Table V-1)
CA	Cellular automaton
ES	Ecosystem services
ESA	Ecosystem service assessment
FB	Free baseline scenario (cf. Table V-1)
FG	Free growth scenario (cf. Table V-1)
FS	Free shrinkage scenario (cf. Table V-1)
FSI	Floor space index
H2DCA	Household decision dynamics for cellular automata (model name)
HH	Household
HHT	Household type
LUC	Land-use change
OB	Overaging baseline scenario (cf. Table V-1)
OG	Overaging growth scenario (cf. Table V-1)
OS	Overaging shrinkage scenario (cf. Table V-1)
RB	Reurban baseline scenario (cf. Table V-1)
RG	Reurban growth scenario (cf. Table V-1)
RS	Reurban shrinkage scenario (cf. Table V-1)
SD	System dynamics
SDT	Second demographic transition
Sect.	Section within a chapter

Chapter I:

Introduction

1 The basic idea

For the conservation as well as the improvement in quality of life for human beings, today's political decision makers are challenged to tackle the complex interactions between human activities and the natural environment. In order to better understand these interactions—which become particularly apparent in urban settings—model approaches have come to be suitable tools for visualizing and understanding the processes and dynamics within complex systems such as cities (Batty, 2007; Haase et al., 2012a). In addition to using models to uncover the cause-effect relationships initiating urban dynamics, they also can be applied to simulate different scenario-based decision processes leading to alternative urban futures with their respective environmental impacts (Alberti, 2008; Barredo et al., 2003a). Thus, urban modelling is capable of contributing to sustainable and strategic urban planning aimed at managing potential environmental benefits and burdens (resulting in powerful legal frameworks for sustainable urban development), encouraging urban resilience and reducing environmental risks (Alberti, 2008; Rutledge et al., 2008; Van Delden and Hagen-Zanker, 2009).

This thesis intends to establish and evaluate an urban simulation model detailing human-driven land-use dynamics. This model will integrate current urban processes (cf. sect. I-2.1 and I-2.2) and reveal the consequent implications for the urban system, in respect to human wellbeing, using the concept of ecosystem services (cf. sect. I-2.3). However, before an adequate model can be chosen one has to verify the characteristics of the system in focus, including its components and the degree of abstraction acceptable for solving specific problems (Batty, 2007). The complexity of urban systems and ecosystems is very diverse, as shown in the following chapters (cf. sect. I-2). Each model approach implies a specific functional background, adapted to a specific technical approach, to represent an extract of the globally connected system (Seppelt, 2003). Thus, a combined model approach seems most suitable to answer the presented objectives in this thesis (cf. sect. I-5) that were applied to the case study, the metropolitan region of Berlin (cf. sect. I-4).

The first chapter introduces the theoretical background of this thesis, starting with the second section "The complex urban system". Here, relations between the processes and patterns of urban systems are revealed, and important mechanisms leading to current urban development trends are described. Further on, interactions between human-induced urban development and environmental change are presented, focusing on human wellbeing, by applying the concept of ecosystem services. In the third section, "Methods to investigate urban complexity", the basic methods and models are described, which systematically integrate the theoretical insights on functional relations between human decision-making, urban processes and patterns, and finally, ecosystem services. The case study is briefly described in section four, and section five introduces the objectives together with the overall structure of the thesis used to achieve them.

2 The complex urban system

The urban system is in many respects decisively different than the natural one, because it is designed by humans. It is characterized in part by natural ecosystem functions and ecological processes heavily influenced and disturbed by human activities—such as those related to housing, working or recreation—which influence the metabolism of the urban ecosystem (Alberti, 2008; Forman, 2008). Effects on resources, energy flows, soil characteristics, biodiversity and climatic conditions are just a few examples worth mentioning (Alberti, 2008). The most prominent impact caused by human activities is the alteration of natural land surface for varying urban uses, such as residential, commercial or transportation (Yang et al., 2011).

In 2011, more than half of the world population (52%) lived in cities. Assuming a continuously growing world population (UN, 2013b), this will grow to 60% by 2030 (Martins, 2012) due to the continuous trends of urbanization and rural-urban migration. According to the UN Population Division (2012) the urban population grew between 2000 and 2010 at a rate of 70 million people per year, each year of which is equivalent to the population Thailand. The total extent of the Earth´s urban land cover is less than 0.5% (in 2000), but will have more than doubled by 2030 with a growth rate of 22.145 square kilometers per year (twice the extent of the urban area of New York City every year), (Bontje and Burdack, 2005; Tavares et al., 2012; Turok and Mykhnenko, 2007). Cities physically grow and spread into natural space. In this process, natural land-uses are transferred; land-use conflicts arise and the pressure on resources and natural capital increases as ecosystem service capacity declines (Carreño et al., 2012; Costanza et al., 1997; EEA, 2010). The increase of soil sealing and degradation, loss of vegetated areas and biodiversity are just a few obvious effects mentioned here (EEA, 2010). These effects in turn have implications on human wellbeing (cf. sect. I-2.3) and increase the risk of natural disasters, such as flooding (due to surface sealing and river regulations) or landslides (due to declining vegetation cover and consequent erosions) (Mileti, 1999; TEEB, 2011). It is therefore necessary to understand current urban development trends in detail.

2.1 Urban development trends

The highest urbanization rates of more than 5% are currently observed in African and Asian due to the high migration rates into cities (UN, 2013b), which are being pushed by rural poverty and environmental degradation, and pulled by expected economic amenities which are unavailable for traditional rural lifestyles (Tarver, 1996). Together with the relatively high fertility rates of immigrants, these trends foster the emergence and the growth of megacities of more than 10 million inhabitants on these continents (UN, 2013b). Recent studies document the dramatic environmental impacts which are associated with higher risks to urban dwellers, such as air and water pollution (Douglas, 2012; Dye, 2008; Hossain Khan, 2012; Jahn, 2012).

European and North American cities are growing more slowly at average rates mainly under 1%. The recent discourse on shrinking cities reveals that, in addition to urban growth, several cities and urban regions in Europe (54%) and the US (13%) are experiencing (or have recently experienced) population decline despite the global increase in urban population (Oswalt, 2004; Wiechmann and Pallagst, 2012). The decline of the urban population is often considered to be a vicious circle, because of the reduction of tax revenues as infrastructural costs increase, which potentially leads to a decline of local facilities and utilities, resulting in deterioration and abandonment, which promotes further emigration (Schwarz and Haase, 2010). From an environmental perspective, urban shrinkage represents an opportunity for urban green development and restructuring to support human wellbeing, although this is limited due to the financial burden in shrinking urban regions (Kabisch and Haase, 2013). The two key elements of urban shrinkage are, firstly, industrial transformation caused by technical innovation, automation and globalization which led to shifts of production locations to low-income countries, and secondly, demographic shifts, described hereinafter (Oswalt, 2004; Stevenson, 2003; Wiechmann and Pallagst, 2012).

The decline in birth rates observed in western societies since the 1960s, accompanied by increased individualization and resulting in decreased household size, defines the concept of the second demographic transition (SDT), (Surkyn and Lesthaeghe, 2004; Van de Kaa, 2004). Accordingly, the concept comprises the change of life scripts within a post materialistic society towards individualization and secularization, i.e. the rejection of the church's authority, and defined by increasing consumerism and the emancipation of women, including the use of hormonal contraception (Buzar et al., 2005; Lesthaeghe, 1995). As a result, birth rates declined, while maternity age and the number of illegitimate children increased. A major consequence of this development, and one that many western societies are facing today, is the process of population aging (Davoudi et al., 2010; Długosz, 2011) . This process has to be viewed critically in terms of the increasing vulnerabilities of urban dweller towards environmental risks (cf. sect. I-2.3; Namdeo et al., 2011; Rechel et al., 2013).

Recent studies have shown that, despite population decline and urban shrinkage, urban land consumption continues to proceed for a certain period of time (Kabisch and Haase, 2013; Lauf et al., 2012c), because the number of households (smaller households with higher per capita living space consumption) increases, leading to higher residential demand and land consumption. Additionally, several authors claim that urban growth and urban shrinkage are processes that can occur simultaneously in one urban region, e.g. in different residential land uses (Couch et al., 2005; Haase et al., 2012b), as clarified below.

The post-industrial and modern urban development of Western Europe is marked by the process of suburbanization, initially starting in the nineteenth century, e.g. in London, then booming since the 1950s, especially in the US. This process has defined the growth of detached residential housing communities at the edges of cities (Champion, 2001), leading to enormous urban sprawling and associated negative environmental effects. The main contributing aspects are inefficient land consumption of low-density housing from detached family houses and the required transportation infrastructure (disturbing ecosystem functioning due to surface sealing and landscape fragmentation), together with increased traffic volume (causing vast carbon emissions and atmospheric contamination) (Martins, 2012; Ren et al., 2012; Travisi et al., 2010). Additionally, the outward movements of urban dwellers and the respective population loss in the inner-cities can be associated with inner-city decay and shrinkage (Couch et al., 2005).

This has particularly been the case for many former socialist Eastern European inner-cities after the fall of the iron curtain (Brade et al., 2009). The catching-up of the formerly limited suburbanization process, in combination with increasing unemployment (resulting in large migration to prospering regions), the second demographic transition and the poor residential conditions, amplified urban shrinkage in the 1990s. This caused alarming vacancy rates in the inner-cities, e.g. in Leipzig (Germany), of over 35% in the year 2000 (Kabisch and Grossmann, 2013; Nuissl and Rink, 2005).

Since the millennium, European urban regions have revealed new trends of inner-city revitalization, indicated by population increase and growing building activity, collectively referred to as reurbanization. This process emerged due to improved inner-city living conditions as well as the related shifts in housing preferences promoted by the amenities of central living, such as short travel distances, cultural life or the relatively better infrastructure of public and private services (Buzar et al., 2007; Champion, 2001; Kabisch et al., 2010).

Urban development with all its facets, as described above, has implications for urban structure and pattern. It is concerned with land-use change where each type (including different residential types) can be specified by, for instance, the degree of surface sealing, the share of green space, the building density, height and materials, all of which have specific consequences on ecosystem functioning (Alberti, 2008; Brade et al., 2009; Gill et al., 2008; Tavares et al., 2012). To better understand these patterns and the processes behind them, e.g. suburbanization or urban shrinkage, the driving forces of the underlying human decisions have to be considered and analyzed (Haase et al., 2012a)

2.2 Human decisions creating urban patterns

In traditional urban studies and models, the decision-making process for urban development is a top-down approach of constraints and incentives made by policy-makers and planners for controlling the urban pattern, e.g. by land-use plans (Barredo et al., 2003a; Batty, 2008; ESPON, 2004; Goldstein et al., 2004; Hall, 2001; Herold et al., 2003; Stevens et al., 2007). However, urban development is influenced by a complex decision network of multiple actors and stakeholders affecting the urban pattern, including, e.g. economists, conservationist, lobbyists, scientists or local pressure groups (Dutta, 2012; Forester, 1987; Haase et al., 2012a).
Investors, enterprises and households decide on new business or housing locations by maximizing their benefit. Their decisions are strongly linked to local economies and public finances which are linked to global markets, whereby they also depend on politics and urban planning (Hall, 2001; Orfield, 2002). Major urban change refers to residential dynamics (Batty, 2007), definable as individually-based bottom-up processes, induced by the largest group of actors, the urban dwellers. All varying actors within the urban system interact, e.g. by exchanging information, expressing competitive interests that might result in land-use conflicts, while urban planners are recognized as mediators in the decision process (Forester, 1987). These interactions need to be uncovered to be able to understand human-decision-based urban development. The UN

Sustainable development division (2013a) speaks in favor of "supporting local authorities, increasing public awareness and enhancing participation of urban residents, including the poor, in decision-making" to conserve social stability and justice (Davidoff, 1965).

To uncover residential dynamics based on individual human decision-making, one has to approach the research field of urban sociology, and in particular the field of residential mobility, to characterize the diversity of urban dwellers and behaviors. Additionally, the research field of urban economics is necessary to define the market constraints of residential choice behavior (Bramley et al., 2008; Clark and Huang, 2003; Whitehead, 1999). The latter field is expressed in local housing markets, which are characterized by a mutually dependent demand and supply side (Haase et al., 2012a).

To define residential preferences and consequent behaviors related to specific groups, urban dwellers are characterized, for instance, according to their age, income, personal living conditions, lifestyle or household membership affecting residential demand (Haase et al., 2010). Residential preferences typically concern economic factors, security, educational and infrastructural facilities, social and ethnic affiliations (Börsch-Supan et al., 2001; Haase et al., 2010). Moreover, environmental conditions, such as green space provision, air and noise pollution, have also been found to be important for residential choice (Bonaiuto et al., 2003; Gaube and Remesch, 2013). The total diverse residential supply in urban regions is the result of preceding sociological, cultural and economic factors, leading to regional and national variation such as detached houses, perimeter blocks, multi-story row houses with specific structures, e.g. regarding building density, building heights and the amount of green space (cf. Figure I-2; Batty, 2007; Forman, 2008). Besides the structural characteristics of residential land uses, they are also characterized by accessibility, price, security, green space amounts and other factors relevant to the decision-making process (Whitehead, 1999).

Residential demand driven by group-specific preferences and demographic dynamics influences the residential supply, and is inversely controlled by it through adjustment mechanisms, e.g. by increasing housing prices at increasing demand (market adjustment) or increasing environmental effects reducing the demand (Bonaiuto et al., 2003; Lauf et al., 2012c). These mechanisms reveal a closed feedback affecting future residential decisions (Irwin et al., 2009). If a critical mass is reached, changing residential decisions can invoke specific urban development patterns, such as urban sprawling due to the process of suburbanization or urban concentration due to the process of reurbanization (cf. sect. I-2.1).

In order to uncover the effects of residential decision-making on the urban system, with special regards to environmental sensitivity and potential effects for human wellbeing, the concept of ecosystem services, introduced hereinafter, has shown to be a promising instrument.

2.3 Ecosystem services affecting human wellbeing

The concept of ecosystem services (ES) describes the benefits or services that human beings gain from the ecosystem, and reaches back to the 1960s (De Groot et al., 2002; MA, 2005). It combines socioeconomic and environmental concepts and focuses on populations which profit from natural given outputs derived directly or indirectly from ecosystem functions. Ecosystem functions are defined as the biological, geochemical, and physical processes and components that take place or occur within an ecosystem (Costanza et al., 1997; Kroll et al., 2012). Examples of ES are clean water, food or raw materials. ES are understood as goods and services in an economic sense and are intended to be evaluated as such. This economic evaluation, however, presents some difficulties and uncertainties, e.g. in terms of double accounting of intermediate and final ES (Boyd and Banzhaf, 2007), or regarding the evaluation of wellbeing provided by nonmaterial cultural services such as recreation or spiritual enrichment. They represent a counterpart to traditional economic payoffs induced by human activity, and have the key objectives of promoting conservation and reducing ecosystem degradation.

The ES concept gained wide popularity with the UN initiation of the Millennium Ecosystem Assessment in 2001, an international research association involving the work of 1,360 scientists to acknowledge the relationship between ecosystem change and human wellbeing (MA, 2005). Another flagship initiative is The Economics of Ecosystems and Biodiversity (TEEB) with the aim to reach a wider recognition and integration in global to local policy making (TEEB, 2011). TEEB and MA categorize ecosystem services into provisioning services (e.g. food, fresh water), regulating services (e.g. local climate, carbon sequestration and erosion prevention), supporting services (e.g. habitats or species), and cultural services (e.g. recreation and tourism). ES can have beneficial effects on different spatial scales, from the local, e.g. in situ food provision to the global level, e.g. carbon storage that reduces globally effective CO2 emissions.

Today, there is plenty of evidence that ES are limited and still under constant threat from increasing human activities; according to the MA about 60% of 24 analyzed ES are globally degrading (MA, 2005; Raudsepp-Hearne et al., 2010). The main reason was confirmed to be land-use change. In addition, natural disasters (e.g. flooding, storms or tsunamis) and climate change were also found to contribute to ecosystem degradation (MA, 2005).

Recent studies consider multiple ES in order to reveal their complex interrelations (Butler et al., 2013; Haase et al., 2012b; Rodríguez et al., 2006). ES interactions are expressed in trade-offs, e.g. biomass for energy production versus food production on arable land, or synergies, either positive (e.g. urban green spaces regulating air quality and providing recreation), or negative (e.g. deforestation that reduces climate regulating functions and increases soil degradation through erosion). With respect to these ES interactions, the ES concept proves to be suitable for understanding the system, as cause-and-effect relationships can be assessed in a more holistic approach.

Recognizing that ES provide human benefits, ecosystem degradation can be seen as negatively affecting human wellbeing via adverse effects on human health (Douglas, 2012). Wellbeing is generally characterized as a function of health, basic materials to live (livelihood), social interaction, security and freedom (MA, 2005). Another critical factor influencing wellbeing is the psychological state of an individual, which can be affected by the environmental conditions of an ecosystem, e.g. negatively by environmental stressors, such as noise, heat or pollution (Honold et al., 2012; Ulrich, 1984) or positively by cultural services provided by urban green spaces (Kabisch and Haase, 2013). Such that ES are essential to human life, e.g. the provision of fresh water and food, a deprivation in ES reduces wellbeing per se, which becomes especially clear in case of poor rural, self-sustaining regions that are difficult to access.

Scientists found that wellbeing and particularly health is globally higher in urban areas than rural ones. Higher economic benefits in cities improve wellbeing and enhance urban hygienic conditions, and the more efficient healthcare systems provide fast access to medical care and precautionary measures (Dye, 2008; Galea and Vlahov, 2005). However, not all urban dwellers benefit in equal ways—poor people are often marginalized in areas with increased urban environmental effects (Hossain Khan, 2012; Kjellstrom et al., 2007). Moreover, it has not yet been shown that urban health benefits outweigh urban related health risks, e.g. through accidents or environmental stress resulting in urban-related chronic and mostly non-communicable diseases, such as heart disease, certain cancers, stroke or obstructive pulmonary disease (Dye, 2008; Jahn, 2012).

The demand for ES to regulate environmental (health) risk and to improve wellbeing is especially high in urban areas due to the concentrations of human beings and the high environmental burden caused by multiple human activities (Bolund and Hunhammar, 1999; Douglas, 2012). The urban ecosystem is defined by strong relations between human and ecological processes, which find expression in the linkage of environmental-related health risks and the vulnerability of urban dwellers (CBO, 2013; MA, 2005; Namdeo et al., 2011; Uejio et al., 2011). For instance, the process of population aging increases social vulnerability, and with that the social risk of the aforementioned diseases (Kim and Joh, 2006; Tinker, 2002).

On this account, demographic changes in relation to increasing ecosystem degradation have to be considered carefully, as both factors can multiply these risks and thus affect human wellbeing. Considering how social peace could be threatened by these impacts on human wellbeing, the equal distribution of ecosystem goods and services should be a prerequisite in modern urban planning (EEA, 2010; MA, 2005). However, this requires that the drivers, influences and effect of urban ecosystem change be understood in terms of their spatial and temporal dimensions, in combination with the underlying human decisions and constraints, especially in terms of land-use related activities. This is made possible within a systemic model approach.

In Figure I-1 a simplified and implicit model is presented, including the processes introduced so far, by linkages of the relevant system components pursued within this thesis in order to address urban complexity. The benefit of model approaches in uncovering complexity is introduced in the next section.

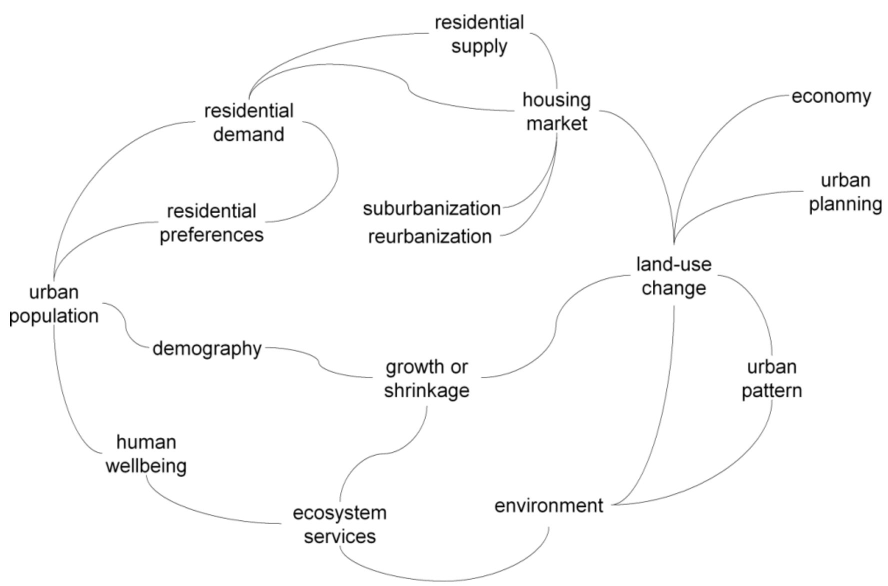

Figure I-1. Simplified conceptual model of specific urban system interrelations

3 Methods to investigate the urban complexity

This chapter describes the transformation of the above described complex processes, which drive urban system change, into suitable simulation models, and introduces the applied model techniques of this thesis. The idea for creating simulation models in order to represent complex systems, as well as for enhancing and expediting the understanding of the functional interrelations between system elements, originates from the general system theory of von Bertalanffy (1968), which acknowledges that one-dimensional cause and effects relations are insufficient to explain realistic system behavior. System theory provides a holistic consideration of a system under the assumption that “the whole is greater than the sum of its components” (von Bertalanffy, 1968). Complex systems can be characterized by the following features (An, 2012; Costanza et al., 1993; Wu and Marceau, 2002):

- they are open and exchange energy, mass, information or individuals with their environment,
- they are composed of diverse components, elements or subsystems that interact with each other nonlinearly (by feedback loops),
- they are highly diverse in terms of time and space (e.g. due to lags, discontinuities, thresholds), and
- they contain an emergent property, unexpected behavior and self-organization (with large-scale results being more than simply the sum of small-scale behavior).

Urban systems are complex, as they are affected by human activities which influence ecological processes and patterns. They are characterized by manifold interacting elements that influence their development and cause “emergent” phenomena, such as urban sprawl (Alberti, 2008). Due to the similarities between urban systems in terms driving forces and processes, it is possible to systematically translate their dynamics into generalized models (Barredo et al., 2003a).

In the last few decades, numerous model applications addressing the complex urban system have been published, from different perspectives and with different model techniques, e.g. focusing on the housing market (Smith et al., 1988; Whitehead, 1999), land use change (Barredo et al., 2003b; Engelen et al., 1997; Loibl, 2003), human decision-making and residential mobility (Haase et al., 2010; Hooimeijer and Oskamp, 1996) or ecological functioning (Grimm et al., 2000; Seppelt, 2003). However, these approaches only address specific extracts of the urban system while neglecting other system functionalities, with corresponding advantages and disadvantages.

Existing model approaches are aimed at contributing to the poorly understood, complex interrelations of human activities with other system components, while representing multiple urban processes, urban patterns and ecosystem service change as described above (cf. section. I-2). To make the appropriate choice among these models, the driving forces and effects of all relevant system components have to be understood, causally integrated and mathematically formalized. In doing so, the disciplines for each model should be considered and interlinked where appropriate (cf. Batty, 2007).

The greatest driving force of urban change is human activity (living, work, leisure), which increases relative to urban population, the key driver of urban development (Alberti, 2008; Batty, 2007). Demographic composition and dynamics define and characterize the variety of urban dwellers that are linked to specific preferences affecting decision-making, e.g. in terms of residential choice (Haase et al., 2009; Howley, 2009). Among other factors, demographic development highly depends on the economic development of an urban region, which directs the migration pattern (Couch et al., 2005).

For the implementation of decision-making within a model, it is crucial to reveal the reasoning of certain decisions (Haase et al., 2012a). Better reasoning can provide greater precision in explaining urban development, e.g. land-use change, and consequent environmental effects, e.g. ecosystem service shifts (Alberti, 2008; Batty, 2007). For instance, equal amounts of a single human activity (i.e. housing) might result in different residential types with distinct environmental effects, which should be addressed. Finally, human decision-making refers to different actors and is the result of complex processes under physical, political and economic constraints over different spatial scales (Haase et al., 2012a).

Three methods are presented in the following section in order to investigate urban complexity, which in combination seem promising to achieve the later described objectives raised in this doctoral thesis (cf. sect. I-5). The methods involve two urban model approaches, namely system dynamics and cellular automata, and are characterized according to their capability to cover human decision-making and land-use change. Furthermore, methods of ecosystem service assessment are introduced that are suitable for uncovering the environmental effects of land-use change. The combination of all three methods seems promising for holistically describing the complexity of the urban system, given the advantage of their combined strengths over their individual usage.

3.1 System analysis

One of the most promising ways to analyses complex systems is the use of system dynamics (SD), which was founded by J.W. Forester in the mid-1950s as a method to translate complex and dynamic systems into simulation models (Forrester, 1975). Within SD, the components used to describe the system are interlinked by differential equations in the form of stocks and flows, which results in nonlinear system behavior (Dhawan, 2005). Each flow variable is defined by one or more decision rules that depend on other stock variables, which can be defined as feedback loops (Haase and Schwarz, 2009; Sterman, 2000). While SD are generally not spatially explicit (which reveals their biggest disadvantage), their strength is their high nonlinear dynamic behavior due to the integration of multiple feedbacks between the system components (Dhawan, 2005; Sterman, 2000), which enables the representation of multiple and mutually dependent decision processes in regard to urban development.

SD is suitable for revealing complex dynamic system processes, based on the initial construction of a conceptual model to identify all problem-specific system elements and processes. This can be done via a graphical user interface, offered by most of the available SD software such as Modelmaker, Stella or Simile (Seppelt, 2003). Subsequently, the conceptual model network is translated into mathematical equations as functions of time to numerically derivate the stocks (states) and flow (variables).

The urban system was first addressed in the 1960s (Forrester, 1969; Lowry, 1964) with rather simple assumptions based on the interactions of population, businesses and housing; however, this pioneering work contributed to a general understanding of urban dynamics. The ability of SD to reproduce population dynamics and socioeconomically-driven decisions and behaviors makes SD models suitable for representing housing market dynamics as a basis for residential location choice. However, for the spatially explicit simulation of residential choice, SD is less suitable (Schwarz et al., 2010).

Today, SD approaches are widely applied in interdisciplinary research, connecting different aspects, such as ecologic processes, the inclusion of socioeconomic parameters and consumer behavior, resource decline and policy analysis, which are all important factors for reasonable, cause-and-effect-related human-nature interactions (Costanza and Voinov, 2004; Eppink et al., 2004; Guan et al., 2011; Rehan et al., 2013; Seppelt, 2003). Also, the representation of feedbacks between environmental effects and the driving forces of urban dynamics is currently under research (Haase and Schwarz, 2009).

3.2 Spatial pattern analysis

Since the 1980s, spatially explicit analytical methods gained importance in the study of urban patterns and land use change, after computer-based processing and remote sensing techniques became more affordable and accessible (Batty, 2007). Among these methods are cellular approaches, which are based on raster information (cells), such as the cellular equilibrium model SLEUTH (Clarke, 1997) based on spatial statistics, or cellular automaton (CA) models based on predefined cell transitions, e.g. to reproduce the allocation of land use within an urban region (Barredo et al., 2003a; Engelen et al., 1997; Van Vliet and Van Delden, 2008).

The wide and well-established group of cellular automata are defined by cells with discrete states, e.g. a land-use class, which depend on neighboring cell states in a defined neighborhood (Engelen et al., 1997). The dynamic spatial behavior of CA models result from the implemented transition rules (neighborhood functions), which are frequently implemented as distance-decay functions following Tobler´s First law of geography, “All things are related, but near things are more related than far things” (Tobler, 1970).

In so doing, all cell states are considered simultaneously to determine the probability for a cell transition at discrete time steps (Batty, 2007). In addition to the cell state, cells can be provided with contributing information (factors) to be taken into account for the final land-use decision (Barredo et al., 2003b; Van Delden et al., 2007). These factors can be physical suitability, proximity to transportation networks, or restrictions due to planning standards, either provided as specific cells values or in the form of distance-decay to integrate neighborhood effects in the form of attractiveness or repulsion (Barredo et al., 2003a; Verburg et al., 2004; White and Engelen, 1993).

Since Tobler (1979) proposed the use of CA as a tool of geography, CA has been widely used and continuously improved towards user-friendly urban simulation tools (Barredo et al., 2003a), such as the software package Metronamica (Riks, 2007). In fact, CA models today are predominantly used to simulate the spatial allocation of LUC. However, most current CA models lack a way to represent the dynamic causal relations between drivers, decision-making and LUC (Batty, 2007).

Frequently, the quantitative LUC as the main driver in CA models is based on simple trend explorations or regression-based assumptions (Ti-yan et al., 2007), while individual or group-specific behavior of city dwellers and demographic aspects are not considered in detail (Lauf et al., 2012a). Beyond that, CA do not display housing market dynamics and are mostly limited to urban growth, which does not meet the requirements of observed and proceeding urban development trends, such as urban shrinkage (cf. sect. I-2.1).

3.3 Ecosystem service assessment

Ecosystem service assessment (ESA) is a wide and interdisciplinary field dealing with the quantification, mapping and valuation of ecosystem service supply and/or demand to promote policy-related decision-making towards conservation, for instance, in the form of regulations, directives, plans, fees or other economic instruments (Seppelt et al., 2012). ESA approaches are very diverse, especially in terms of spatial and temporal scales, and reach from detailed process-oriented assessments to more generalized land-use-oriented assessments, depending on the respective research groups and their specific perspectives. Accordingly, the set of tools and models applied and available to assess ecosystem service change is rather large and continuously extended (Crossman et al., 2013; Hou et al., 2013).

Methodological approaches include causal relationships (determined by regression analysis of ecosystem service supply and environmental data), extrapolation of primary data, proxy methods, biophysical production equations, site-specific process models, probabilistic Bayesian networks (e.g. the ARIES tool) or simulation modelling (e.g. the GUMBO model), (Crossman et al., 2013). Results and units of ESA differ considerably due to the respective valuation method and the selected ecosystem service indicators. They are, for instance, represented as descriptive ranges, monetary values, biophysical values, indices or spatially related values (Crossman et al., 2013; Seppelt et al., 2012). Due to these inconsistencies as well as the lack of interfaces to existing decision instruments, e.g. environmental impact assessments, the implementation of ESA for national and regional accounts to support decision-making and policies for ecosystem protection or resource management is still limited (Crossman et al., 2013).

ES are strongly linked to natural conditions, e.g. land use, hydrology, soil conditions, fauna, slope and climate; and human impacts, such as land-use change as well as emissions and pollution (Burkhard et al., 2012). Due to the complex interrelations within the human and natural system, ESA are affected by uncertainty and generalization and are consequently sensitive to bias, potentially leading to wrong conclusions and false decision-making in the worst case (Burkhard et al., 2010; Hou et al., 2013). The three biggest uncertainties in ESA derive from, firstly, neglecting important ES originating from complex ecosystem functions; secondly, the subjective focus and selection of partly imprecisely defined ES; and thirdly, the varying methods to assess ES, revealing differing and questionable results, of which willingness-to-pay approaches are just one example (De Groot et al., 2002; Fisher et al., 2009; Hou et al., 2013). Spatially explicit ESA are additionally error prone due to the strong dependence on spatial data, e.g. land use; similarly, scale mismatches and generalizations (e.g. inadequate land use classes) or the lack of applicable spatial data are also sources of error (Haines-Young et al., 2012; Hou et al., 2013).

The main challenge of ESA is the identification of adequate ES indicators and the availability of qualified data to quantify the broad range of existing ES (Burkhard et al., 2012). For ES indicators to be suitable for ESA, they need to be quantifiable in a replicable manner, sensitive to land use and land cover, temporally and spatially explicit and they should be selected and defined using expert knowledge to address the needs of decision-makers and local authorities (Burkhard et al., 2012). The necessary components for successful ESA are suggested within a blueprint for ESA by Seppelt et al. (2012) with the aim to strengthen the political relevance of the ES concept. Accordingly, relations between ES, e.g. in terms of trade-off, should be integrated in a dynamic manner based on scenario analysis (Butler et al., 2013; Seppelt et al., 2012). In this process, environmental and socioeconomic parameters should be interactively considered over relevant spatial and temporal scales, the results should be discussed with respect to the underlying assumptions and possible uncertainties of each ESA should be critically revealed (Daily et al., 2009; Seppelt et al., 2012).

4 The Berlin metropolitan region as case study

The study area consists of the city of Berlin and its immediate surroundings within the administrative border, and involves parts of the federal state of Brandenburg in order to improve the understanding of urban to peri-urban relations (Ravetz et al., 2013), (cf. Figure I-2). The study area represents the metropolitan region of Berlin and involves almost 5.370 km², and contains a total population of 4.549.459 as of 2011 (SOBB, 2012). The color-infrared satellite scene presented in Figure I-2 shows that the region is characterized by a moderate density of built-up area (turquoise color) with large, partly central, forested green areas (red color), large agricultural areas (green colors) and a system of water bodies (black color).

The change in extent of the dominant residential land-use types (Figure I-2) is the result of the specific urban development trends observed in the region between 1992 and 2008, which was the analytical period used for calibration of the intended model (cf. sect. I-5 and chapter II).

The Berlin metropolitan region was chosen due to its diverse urban processes revealed over the last 20 years (1991-2011), including aspatial (e.g. population aging or changing household patterns), sociospatial (e.g. suburbanization, reurbanization, urban growth and urban shrinkage), and economic-driven (e.g. industrial decline and business expansion) processes, occurring semi-simultaneously. All these processes have specific implications for the urban ecosystem and its urban dwellers (Couch et al., 2005; Haase et al., 2012b; Kabisch et al., 2010; Nefs et al., 2013), (cf. sect. I-2.1). Moreover, the Berlin metropolitan region represents typical characteristics and processes of western and former socialistic urban development. Major trends are presented hereinafter.

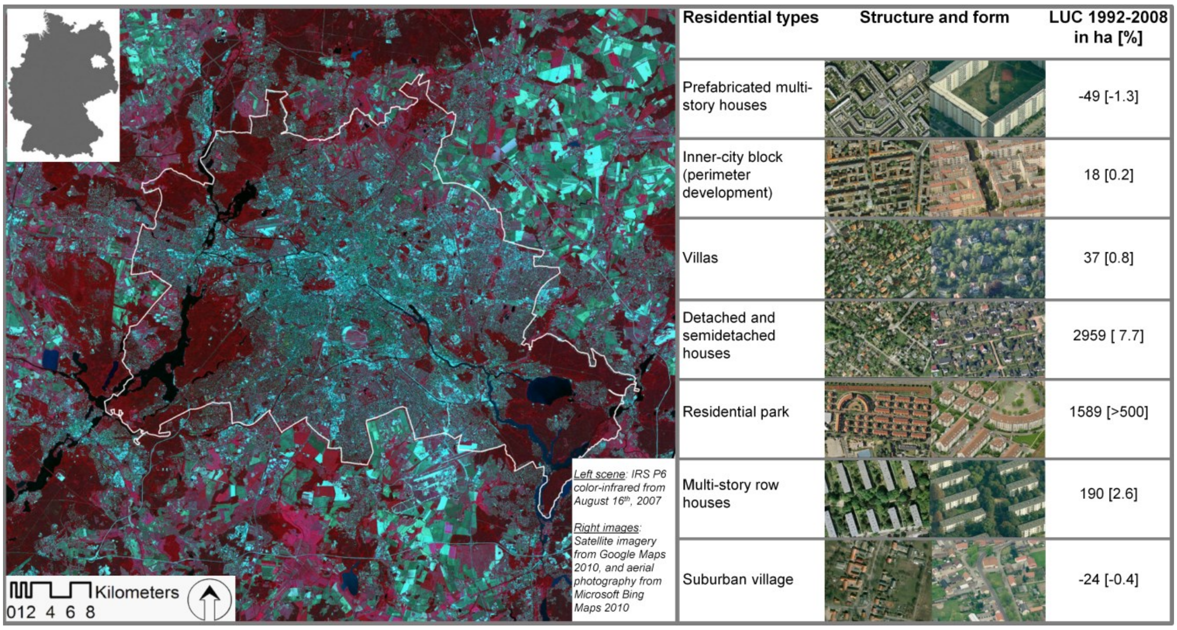

Figure I-2. The metropolitan region of Berlin and executed residential LUC between 1992 and 2008, cf. chapter II, (image sources on the right: Google, 2010 and Microsoft, 2010)

The overall population development of the Berlin metropolitan region since 1991 is characterized by a moderate, almost linear population growth with an increase of 323.429 people until 2011 (about 0.4% per year), although with notable differences when comparing Berlin with its surroundings (Figure I-3). Figure I-3 reveals that, after a short initial phase of population growth, the population development of Berlin can be characterized by three phases: (1), decline (1993-1999), (2), stagnation (2000-2004), and (3), growth (2005-2011).

After the 1990 reunification of Germany and Berlin the housing market within the region was characterized by distinctive dynamics. Negligent maintenance in the housing stock of former socialist East-Berlin and the shift in residential preferences towards "living in the green," which had been previously restricted (politically in East-Berlin and territorially in West-Berlin), resulted in relatively poor housing conditions in Berlin's inner-city blocks. This triggered a migration shift towards the surrounding areas, with an accompanied increase in the construction of detached and semidetached housing on former arable land (Haeussermann and Kapphan, 2004; Lenz, 2006), (cf. Figure I-3 and I-4).

Despite the relatively moderate increase in numbers of dwellings in detached and semidetached housing compared to apartment housing, the required land use change to achieve the new construction is remarkable, with almost 3.000 hectare between 1992 and 2008. This is due to the very low floor space index, which is the ratio of the gross floor area and the plot area and which defines the building density (cf. chapter II).

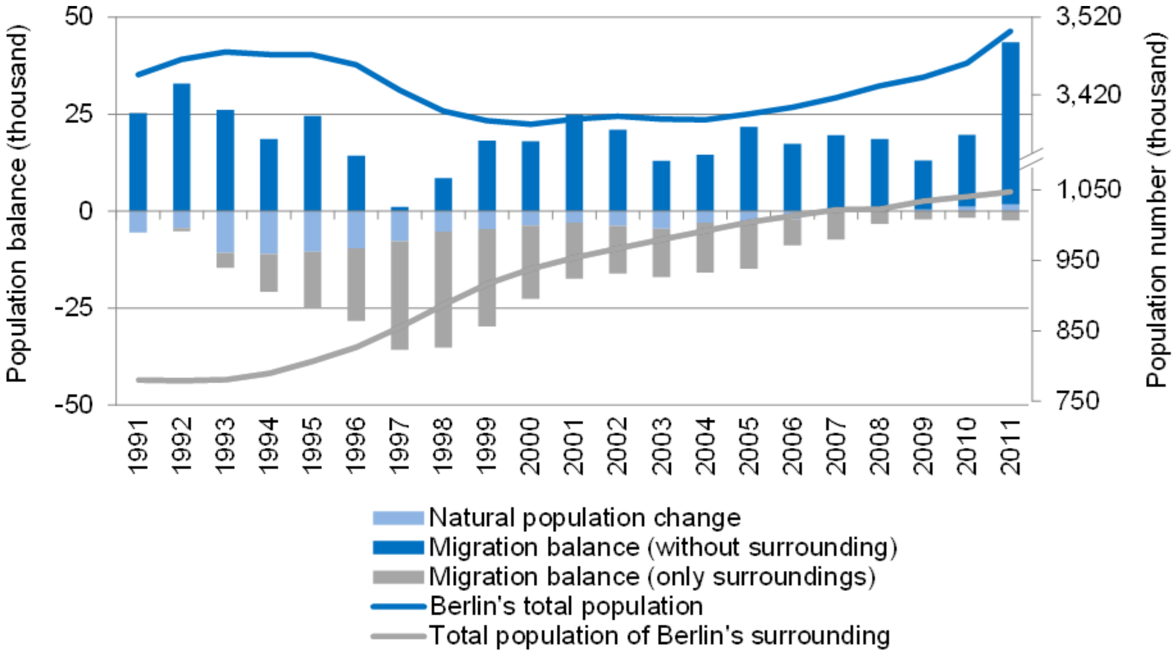

Figure I-3. Population development in the Berlin metropolitan region; data obtained from SOBB (2012)

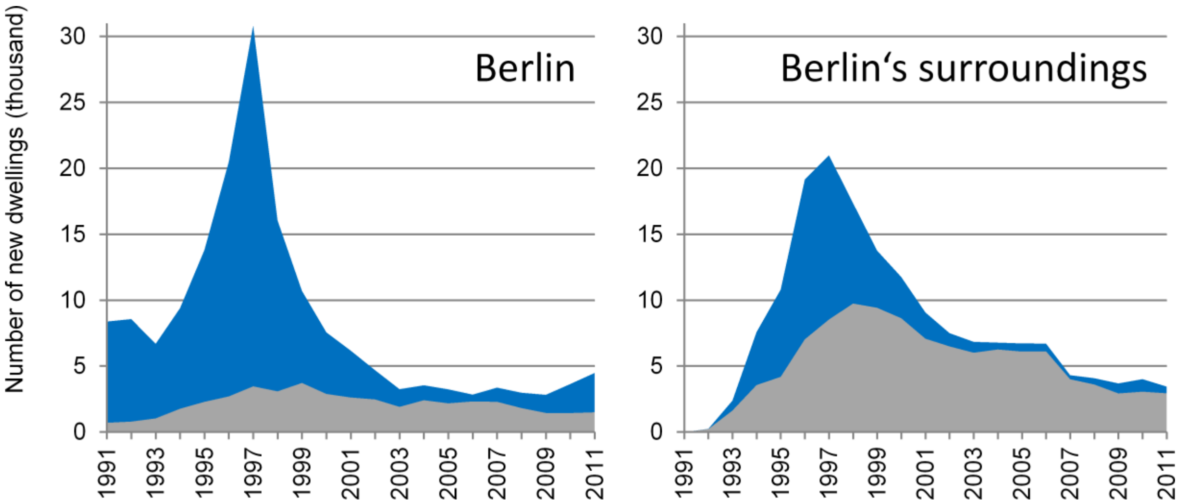

Figure I-4. Construction developments of dwellings in the Berlin metropolitan region; data obtained from SOBB (2012)

False assumptions regarding Berlin's population development resulted in a construction boom in apartment housing, especially in the inner-city of Berlin (Lenz, 2006), (cf. Figure I-4).

The declining population in Berlin due to both low birth rates and the outflow of people (especially into the surroundings) and the high rate of newly constructed apartment buildings resulted in an increase of residential vacancy, which reached a climax in the year 2001 with 7.9% adjusted long-term vacancy (SOBB, 2012), (cf. Figure I-5). Inner-city blocks and socialist-era prefabricated multi-story houses (subject to an image loss after the reunification) reached particularly high vacancy rates (Lenz, 2006; SDUDEB, 2005). Consequently, new construction declined rapidly and measures of demolition and reconstruction took place in the housing stock in order to stabilize the housing market (SDUDEB, 2005).

Another non-residential factor affecting urban development was due to the collapse of the GDR-economy, which resulted in a massive industrial decline accompanied with an increase in the unemployment rate of over 17% (Lenz, 2006). The abandonment of industrial sites and the promotion of housing demolition resulted in additional urban brownfields to those already existing (dating from the end of war and the division), while businesses from the growing service sector, especially shopping malls, grew on open land, particularly in the outer city (Lachmund, 2007; Lenz, 2006), cf. app. I, Figure A-I-1.

In the phase of population stagnation (2000-2004), the overall demographic trend of increasing single households, accelerated by the influx of young people living in small households, resulted in a decline in residential vacancy (cf. Figure I-5 and sect. I-2.1).

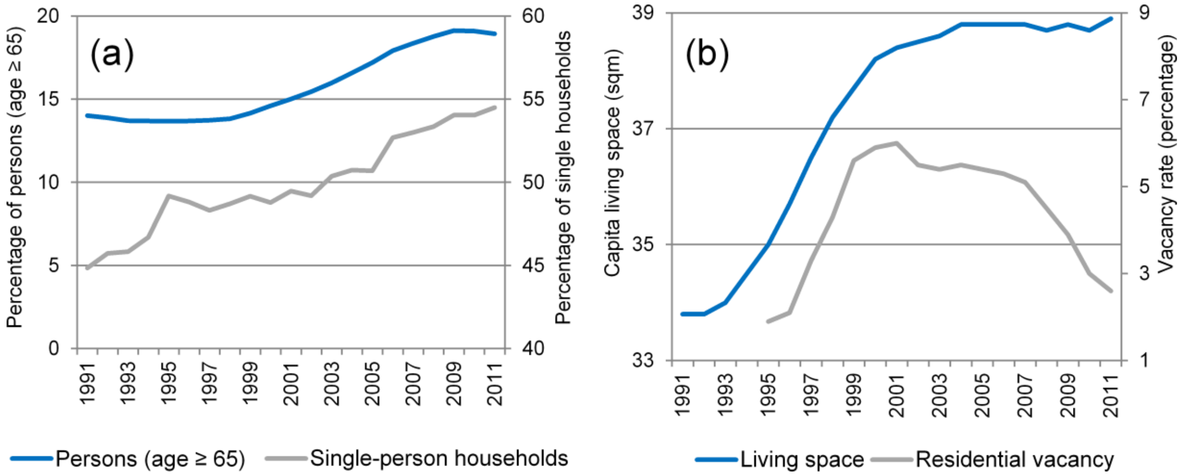

Figure I-5. Demographic and residential dynamics in Berlin; (a) demography (SOBB, 2012) and (b) residential dynamics (BBU, 2012; SOBB, 2012), with about 2% higher vacancies in whole Berlin than given by BBU (2012)

Since 2005, the city of Berlin has experienced a positive net-migration of predominantly younger people (age ≤35 years), accompanied with continuously increasing birth rates. This has almost balanced the natural population development, resulting in a moderate population growth. Since then, the city has come to be considered of international interest because of its favorable living conditions, characterized by a relaxed housing market, extensive cultural and educational offerings, an urban structure with numerous green and leisure areas combined with relatively low living costs (Lachmund, 2007; MMF, 2011; Oswalt, 2000).

This development has been accompanied by reurbanization, confirmed by the increase in the construction of new apartment buildings in Berlin, as well as lowering suburbanization with a decline in the construction of detached housing in the surrounding (cf. Figure I-4). Despite the increased influx of younger people the population continues to age, which represents one of the main challenges of future urban planning (Figure I-3 and sect. I-2.1).

5 Objectives and structure of the thesis

Distinct urban and ecological processes have been revealed through interdisciplinary research into the dynamics of urban systems and ecosystems. An interdisciplinary approach, connecting the substantial aspects of urban development and ecosystem change, is required due to the fact that urban processes are the result of complex interactions that cannot be studied separately (Alberti, 2008).

Therefore, a combined model approach is intended, using the model approaches introduced in section I-3 to integrate the existing findings of the relevant driving forces causing urban change, under given constraints and under consideration of human decision-making, land use, urban patterns and human-effective ecosystem services (cf. sect. I-2). This leads to an overall model approach integrating demographic, socioeconomic, economic, political (i.e. urban planning) and finally ecological dimensions.

Objectives:

The first objective addresses the methodological aspect of developing and applying a combined model approach, in order to join the complex processes and interactions of urban systems to an urban to peri-urban region, i.e. the Berlin metropolitan region. In order to achieve this, the model needs to cover relevant human decision-making with regard to the diverse urban processes that are currently observed in European urban regions and their causal linkage to land use dynamics, to convincingly reveal and determine the effects on urban patterns and ecosystem services. Moreover, the model needs to be validated and tested to evaluate its functioning and quality of results in respect to integrated urban processes. Finally, the model's added value when compared with other approaches should be assessed.

The second objective focuses on the model's insights regarding transferable findings contributing to a general understanding of complex urban systems, drawing special attention to the interactions of the system elements. Therefore, the functional chain from human decision-making, to land-use and urban pattern change, to ecosystem service change will be tested using scenario analysis. Scenario simulations between 2008 and 2030 are used to evaluate varying driver assumptions affecting human decision-making, according to their implications on the functional chain.

On the basis of these two overall objectives, the detailed research questions are formulated.

Research questions:

1) Is a combined model approach suitable to uncover urban system dynamics?
    a. What are the requirements to include reasoned human decision-making and current urban processes, such as urban growth and urban shrinkage?
    b. Is the model qualitatively sound?
    c. What are the benefits of the proposed model?

2) How does scenario analysis contribute to increased system understanding?
    a. Which common and deviating scenario developments can be observed between 2008 and 2030?
    b. What are the major system sensitivities and which system relationships can be drawn from the scenario analyses?

The objectives are expressed, in part, within the respective objectives of the individual chapters.

Structure and detailed objectives by chapter:

This section describes the structure of the thesis with respect to the main emphases of each chapter. Chapters II to IV present stand-alone manuscripts that deal with compartmentalized objectives. The overall research questions are answered in chapter V, considering the insights of chapter II to IV. The individual manuscripts were written originally by the author (the first author). Additional authors (co-authors) contributed to the manuscripts via several discussions and by revisions made to improve the manuscripts.

Chapters II to IV contain individual sections on the research background (introduction), the study area, the method, the results, the discussion and the conclusion, which enables one to examine individual aspects of the thesis autonomously. In this way, redundant information cannot be ruled out. Figure I-6 presents the evolution of the thesis within a process chain, as well as the intended model construction, according to the included chapters. The summarized content of each chapter helps to understand the overall context.

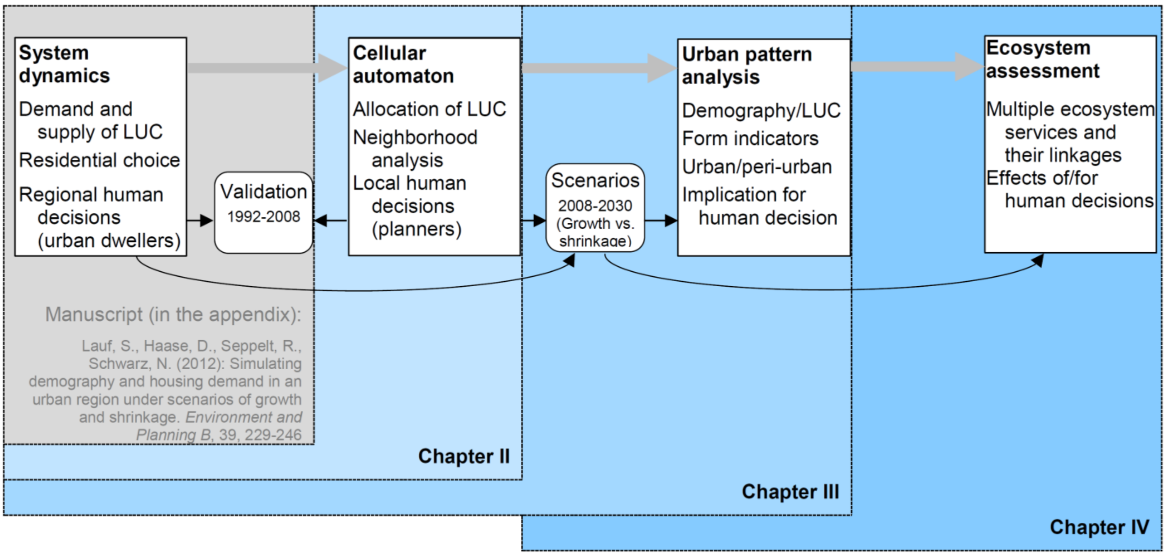

Figure I-6. Process chain of the thesis regarding the single chapters

All three manuscripts (chapter II to IV) have been submitted or published in relevant scientific journals, as presented in the chapter summary below. They are presented unchanged in this thesis, except for altered formatting. Additional publications originating in the phase of the dissertation and linked to the research results are listed in the appendix (app.). The article from Lauf et al. (2012b) is fully presented in the app. to ensure a complete understanding of the functionality and the contextual model combination presented in this thesis (cf. Figure I-6).

Chapter I: Introduction:

- Includes the research background, the case study description, the objectives and the structure of the doctoral thesis at hand.

Chapter II: Combining system dynamics and cellular automaton

(Published as)
Lauf, S., Haase, D., Lakes, T., Hostert, P. and Kleinschmit, B. (2012): Uncovering land use dynamics driven by human decision-making - a combined model approach using cellular automata and system dynamics. *Environmental Modelling and Software 27-28,* 71-82.

The objectives are:

- To provide an integrated model approach using SD for macro-scale dynamics and CA for spatial dynamics under the inclusion of causal linkages between preference-driven residential choices of household types,
- To involve different housing segments to include residential growth and shrinkage simultaneously and represent reurbanization and urban demolition,
- To simulate urban LUC more reasonably due to a more comprehensive representation of the social drivers, and
- To test the model quality in comparison to a null model.

Chapter III: Interactions of demography, preference shift and the urban development
(Published as)
Lauf, S., Haase, D., Kleinschmit, B. (to be submitted): Contrasting interactions between urban development and demographic and residential preference shifts in the Berlin metropolitan region – a spatial scenario analysis. *Applied Geography.*

The objectives are:

- To implement recent and future urban development trends of (1) population aging, (2) household and preference shifts (i.e. reurbanization), and (3) growth and shrinkage, into a spatially-explicit urban land-use model,
- To analyze and evaluate contrasting trends of population and household development (growth versus shrinkage) between 2008 and 2030,
- To assess future land consumption and loss of open land and vice versa and to detect related land-use change (LUC) in combination with exceeding trends of population aging and reurbanization, and finally
- To determine the spatial effects of contrasting and exceeding scenarios and the effectivity due to shifts in households and household decisions along the urban to peri-urban gradient.

Chapter IV: Ecosystem service assessment under conditions of growth and shrinkage

(Published as)

Lauf, S., Haase, D., Kleinschmit, B. (2014): Linkages between ecosystem services provisioning, urban growth and shrinkage – a modeling approach assessing ecosystem service trade-offs. *Ecological Indicators 42. 73-94.*.

The objectives are:

- To apply a combination of Land-Use Change (LUC) and ESA models focusing on the impact of human decisions on LUC and the consequences for ES
- To test a growth and a shrinkage scenario with regard to the prevailing position that urban shrinkage is generally positively related to ES
- To quantify and compare ES linkages using multiple ES indicators
- To create an ESA framework addressing the following issues on the local and regional scale:
    - Scenario comparison
    - Integration of ES linkages (synergies, trade-offs)
    - Multi-criteria ESA on the basis of land-use transitions
    - Contribution to support decision-making and system understanding via items 1 - 4

Chapter V: Synthesis

- Includes the summary and main conclusions of the thesis under integration of further results and provides an outlook of necessary future research related to this thesis

Chapter II:

Combining system dynamics and cellular automaton

Lauf, S., Haase, D., Lakes, T., Hostert, P. and Kleinschmit, B. (2012): Uncovering land use dynamics driven by human decision-making - a combined model approach using cellular automata and system dynamics. *Environmental Modelling and Software 27-28,* 71-82

doi:10.1016/j.envsoft.2011.09.005

Abstract

This paper introduces an enhancement of a cellular automata (CA) model by integrating system dynamics (SD) to incorporate household dynamics and housing decisions as driving forces of residential development. CA macro-models used to simulate the quantitative land-use change (LUC) for urban areas are, thus far, lacking profound dynamics driven by demographic change. The model presented in this paper focuses on household dynamics according to the concept of the second demographic transition (SDT), applying aging and population shrinkage to simulate respective effects on residential choice and the resulting LUC. Such a perspective becomes especially important for urban areas exhibiting growth and shrinkage simultaneously, as currently seen in cities in Europe and in the U.S. To analyze this simultaneity in detail, we implement the residential land use CA model Metronamica and apply it to Berlin's metropolitan region, which was selected as a typical example that displays contrasting growth and shrinkage processes. The pre-implemented macro-model has been replaced with our new SD model H2DCA (Household Decision Dynamics for Cellular Automata). For the simulation, we used empirical census data, economic data, data on residential satisfaction and numerous types of geo-information representing land-use zoning, accessibility and suitability for the time span 1990-2008. A comparison of a null model (NM) and H2DCA provides a very satisfying reproduction of land-use patterns reflected by kappa coefficient values. The causal relation of LUC drivers is considerably improved by sophisticated housing choice-feedback mechanisms. Although specific residential land-use classes exhibit shrinkage, others expand. Due to the detailed residential land-use classification, current re-urbanization processes could also be simulated.

1 Introduction

Changing land use has an important impact on the environment, particularly when it occurs in urbanized areas. Therefore, both drivers and effects must be considered systematically and reciprocally to understand their interrelations and dynamics at the local and regional levels (Abha et al., 2006; Batty, 2007). For this purpose, model approaches are highly relevant. Numerous land-use-scenario models are applied to support policy making by estimating future developments and environmental effects due to LUC (Benenson and Torrens, 2004; Koomen and Stillwell, 2007; Schaldach and Alcamo, 2006). In cities, land-use models are of particular relevance because the environment is mainly affected by human activity. With respect to land use, cities exhibit highly complex dynamics that often result in both environmental and social problems. Rising imperviousness, loss of agricultural land and green spaces, danger for human health and social segregation are among the problems to be addressed (Forman, 2008). For forward planning at the local and regional levels, processes and feedbacks of land-use change (LUC) should be analyzed using spatial urban models for scenario forecasts that will lead to early intervention policies and adaptations, thus mitigating negative effects (Petrov et al., 2009). Existing LUC models are continuously being advanced and adapted to meet current and anticipated needs for LUC processes (Fang et al., 2005; Rutledge et al., 2008; Van Delden et al., 2007).

Currently, there is a choice among a plurality of urban models and approaches. For spatial explicit modeling of LUC covering regional and, especially, local dynamics, the use of CA has become popular (Barredo et al., 2003; White and Engelen, 1993). Since the first uses of CA in an urban context in the mid-1980s, CA models have become more sophisticated and persuasive for simulating spatial patterns of urban LUC. Their strength relies on non-linear, spatially explicit, stochastic processes representing the allocation of LUC. Land-use dynamics basically result from macro-scale and micro-scale dynamics representing different land-use decisions. For cell-based land-use allocation, a range of planning assumptions, transport data and physical suitability in the form of geo-information are considered next to transition rules that imply repulsion and attraction between land-use classes.

The macro-scale dynamics on the global/regional level, in contrast, depend on the input of the local allocation decisions and represent the quantitative LUC (Barredo, et al., 2003; Van Delden, et al., 2007). Model assumptions on the macro-scale (giving back the regional model implications) are often simple linear trends missing feedbacks and restrictions in terms of dynamic behavior (He et al., 2005; Tiyan et al., 2007). Causal interrelations between population, household structure, preferred living styles and residential choice are rarely integrated (Batty, 2007; Petrov, et al., 2009). An imperative for urban LUC models should be the integration of human decisions on the demand side as a crucial driving force for urban LUC (Forman, 2008; Herold, 2003).

This also implies a more detailed specification of the demand side. Human decisions contextualized in urban LUC processes are characterized by individuals and groups of different sectors and interests. Individual residents must be distinguished from investors and planners (Batty, 2003). The former are addressed because they determine the urban housing demand in great measure. However, for our purposes, individual agents as used in agent-based models are not mandatory in the presented approach. Intelligent behavior, including learning and communication between residential agents, is not addressed (Bousquet and Le Page, 2004; Brown et al., 2004; Valbuena et al., 2008). Residential preferences are assumed to be constant for certain demander groups and focus on causal interrelations articulating the demand.

Beyond that, predominant unilateral growth models must be extended by those dealing with stagnation and decline. The simulation of growing and sprawling cities is part of the tradition of urban LUC models justified by the large number of cities in the developing world. However, examining European and U.S. cities that, today, are confronted with population decline and shrinkage (Schwarz et al., 2010), classical growth models have reached their limits. In fact, urban shrinkage and transition are both part of the current urban development (Haase et al., 2007; Kroll and Haase, 2010).

Moreover, specifics regarding various housing segments, which are particularly striking in urban regions, are, thus far, unremarkable as presented in urban LUC models (Lee et al., 2003). In general, housing demand shifts direct shrinkage processes in certain housing segments in contrast to growth phenomena in other housing segments (Haase, et al., 2007). For this reason, the processes and preferences affecting the single-housing segments should be considered in greater detail, as revealed in this paper, for an improved reproduction of LUC. The utilization of residential classes as used by city authorities (in zoning maps) provides modelers with detailed data and city authorities with simulation results that are easy to integrate into the planning processes (Banzhaf and Höfer, 2008).

SD offers a non-linear solution for integrating complex dynamics with the inclusion of causal feedbacks and, subsequently, has been widely used in both the natural and the social sciences

(Dhawan, 2005; Moffat and Hanley, 2001; Seppelt, 2003). Contrary to CA models, SD models are capable of reproducing feedback between socioeconomic and physical factors (Costanza and Voinov, 2004; Tiyan, et al., 2007) by which demand-supply relations in an urban residential context are enabled. Therefore, the missing link between demographic change and land-use change, including effects of growth and shrinkage, can be realized.

We propose an integrated model approach using SD for macro-scale dynamics and CA for spatial dynamics and including causal linkages between preference-driven residential choices of household types, SDT and residential land use (Lauf et al., 2012c). The integration of causal feedback on residential choice due to changing residential use may counteract or reinforce growth and shrinkage. For that reason, we replace the existing macro-model of the applied CA software Metronamica with our proposed model, $H2D_{CA}$ (Household Decision Dynamics for cellular automata). By involving different housing segments (preferred, avoided), we can include residential growth and shrinkage simultaneously. The model is applied to the metropolitan region of Berlin. It is assumed that, by including residential choices based on household dynamics, urban LUC can be simulated more reasonably due to a more comprehensive representation of the social drivers. For the evaluation of the model benefit, we compare simulation results using $H2D_{CA}$ with an NM. It is expected that, in our model, the interrelations between demographic variables and residential land-use classes are more profoundly affected by demographic change and SDT, respectively. Furthermore, more differentiated and, therefore, more realistic results are expected in terms of model accuracy and plausibility for the simulated land-use patterns: the model should show inner-city land-use change processes such as re-urbanization on urban brownfields and demolition due to shrinkage. Kappa means serve as a quality measure of the similarity of simulated and observed land-use patterns for the year 2007.

2 Model background

The presented model simulates the functional relations of urban land-use development and household dynamics and, thus, creates feedback of residential choices. Particular focus is placed on residential land use as vast urban change refers to residential dynamics (Batty, 2007, Stevens et al., 2007).

2.1 Driving Forces

The spatial and functional constraints of the modeled system are as follows. The system constitutes an urban region characterized by interactions with one or more large cities. The urban region includes areas from which individuals commute to cities and includes areas where good accessibility to the functional, economic and cultural resources of one or more cities has an obvious effect on the housing stock.

The drivers of urban LUC are widely discussed (Batty, 2007; Koomen and Stillwell, 2007). This literature places a focus on the internal drivers in the form of shifts in housing demand and supply that are computed by the SD model. The causal relations between demographic and land-use change require the integration of population dynamics into the model. Much of the research indicates that it is not just total population but also household structure that directs urban LUC (Buzar et al., 2005; Haase et al., 2010). SDT describes the change of traditional (larger) family households towards small single, childless couple and single-parent households, which are viewed as non-traditional household types (Buzar et al., 2007; Kaa, 2004). As a consequence, the mean household size decreases, whereas the number of households increases. The effects are an increase of total living space consumption at equal or even smaller population numbers due to higher per-capita space consumption rates (BMVBS and BBR, 2008, Lee, et al., 2003). In several studies, it was demonstrated that despite population shrinkage this trend towards smaller households can stabilize and enlarge housing space consumption. To summarize, there are very good reasons to integrate household dynamics into urban LUC models. Moreover, lifestyle studies in the social sciences identify group specific consumption behavior based on different preferences. Regarding residential demand, households represent different groups of demanders holding varying housing preferences (Beamish et al., 2001; Haase et al., 2005; Harloff, 1993).

In this macro-model, seven household types (cf. App. A) are integrated, including both traditional and non-traditional household types, which hold different housing preferences regarding (1) centrality (distance to the center), (2) distance to entertainment areas, (3) housing costs, (4) housing conditions, (5) safety and security, (6) education facilities, (7) green space provisions, (8) living environment (noise and tidiness) and (9) social neighborhood. Those preferences are linked to a set of (varying) residential uses that exhibit respective characteristics. For the classification of residential land use, we applied seven urban structure types (UST) (Ravetz, 2000 and App.B). They are distinguished by gross floor space density and respective green space availability, mean number of stories, building shape and building structure (cf. app. II-B, Table A-IIb-1). As planners work with these structure types within the established planning categories, the seven types are suitable for use in an LUC model, which should ultimately support planning strategies (Banzhaf and Höfer, 2008). For the integration of urban shrinkage processes compared to growth, we incorporate variables, such as residential vacancy, deconstruction and the active land-use class of (urban) brownfields. Shrinkage is expressed by housing vacancy and land abandonment (Haase et al., 2007). Unused living space is eliminated to stabilize the housing market. Resulting urban brownfields become available for new developments (FOBRP, 2008) but also depict an important potential for new urban green spaces – especially in inner-city areas – if promoted by planning. In turn, increased green space provisions may raise the attractiveness of an area for housing demands. The realization of new residential areas underlies certain restrictions implemented within the spatial rules of the CA. Physical boundary conditions, such as zoning plans, accessibility to main roads and motorways and public transport are considered decisive factors. However, the distance to other land uses – so-called neighborhood effects – are also significant and contribute to spatial dynamics (Verburg et al., 2004). Although inner-city block structures are highly connected to central public and private services, villas, single and detached houses are characterized by forests and proximity to waters. Urban brownfields emerge notably in areas determined to be disadvantaged based on accessibility, neighborhood conditions, green space supply and distance to commercial/business areas or airports.

2.2 Study area

This model is applied to the metropolitan region of Berlin. This exceeds the administrative border of Berlin and involves parts of the federal state of Brandenburg. The inclusion of Berlin's hinterland was chosen to capture urban and peri-urban relationships. As one of the larger and central European agglomerations, Berlin represents a case in point for an ageing population with changing household types as defined by the SDT (SenUD, 1990-2009). Furthermore, Berlin's LUC is characterized by simultaneous growth and shrinkage, which are not just limited to outer (suburban) growth and inner decline but rather emerge next to each other and within the same area. In addition, the city itself, due to its history, is representative of both East and West German urban developments.

Figure II-1 provides an overview of the study region and its land use in the year 2007. Forests represented 32% of the total land use while 25% of the land is arable and another 25% consists of built-up area. Approximately 8% of the developed land is covered by detached or semi-detached family houses, constituting the moderate building density in the region. The region further includes 5.3 thousand km^2 of land and has a population of 4.4 million (Berlin itself has 3.4 million people). The city is characterized as a city in transition due, at least in part, to its tremendous population loss after 1940, when it reached maximum growth with 4.3 million people. Another contributing factor is its population loss after the German reunification, which after 10 years, in turn, changed to smart growth due to positive national and international net-migration (SenETW, 1990-2009; SOBB, 1991-2008). LUC in the last 20 years is mainly characterized by contrasting processes of residential areas due to housing market dynamics. The area inside the city boundary serves for the calibration of the CA.

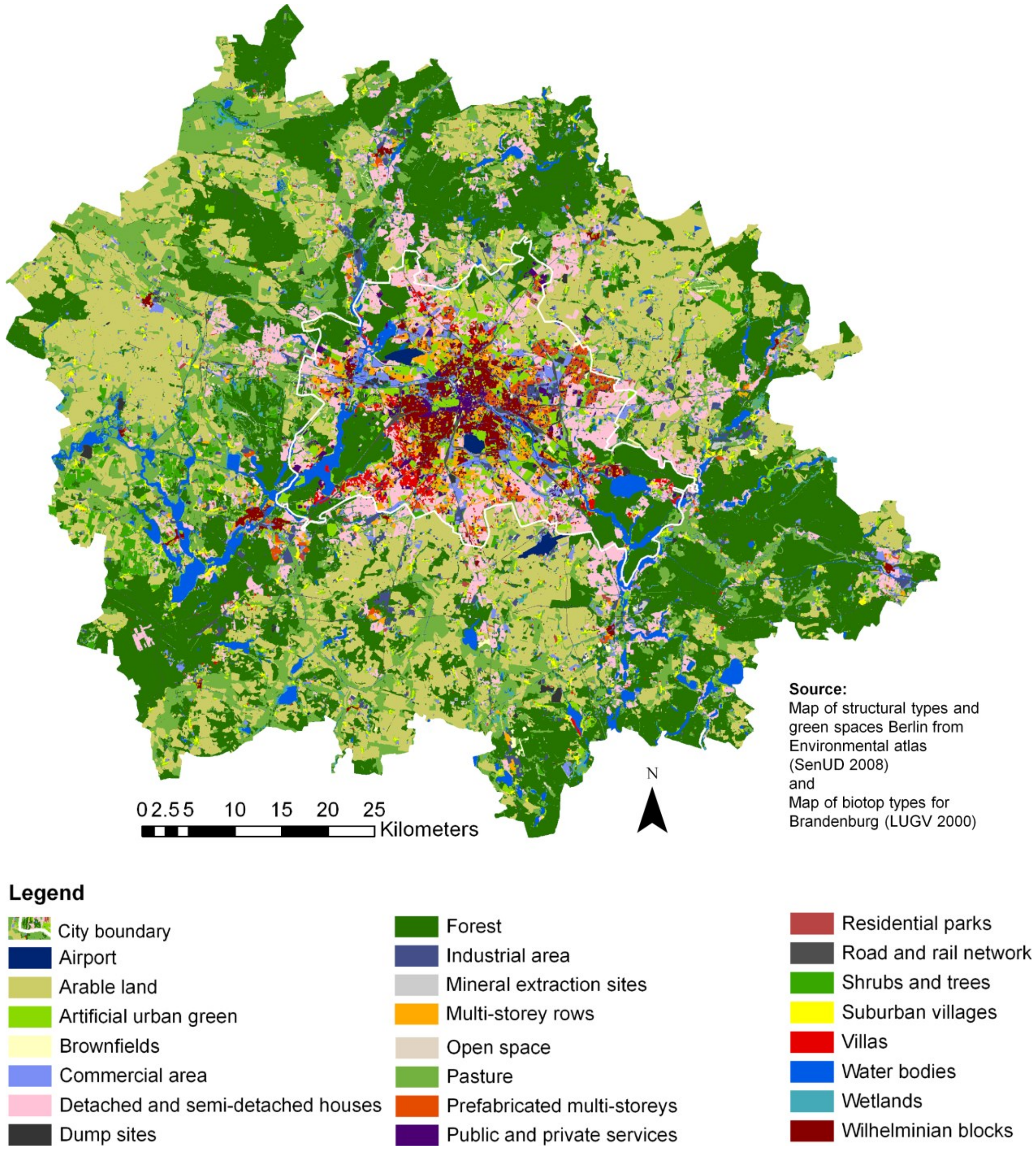

Figure II-1. Land-use map for the metropolitan region of Berlin in 2007

3 Model structure and functionality

An overview of the overall model is given in Figure II-2, describing a three-modular structure. It consists of a population and housing demand-supply model ($H2D_{CA}$), a CA land-use allocation model and an input module. The demand-supply model is realized by SD (Lauf et al., 2012c.). The allocation model is realized using the CA with spatial dynamics as a function of $H2D_{CA}$. The last part, the input module, depicts all variable factors driving and influencing both models.

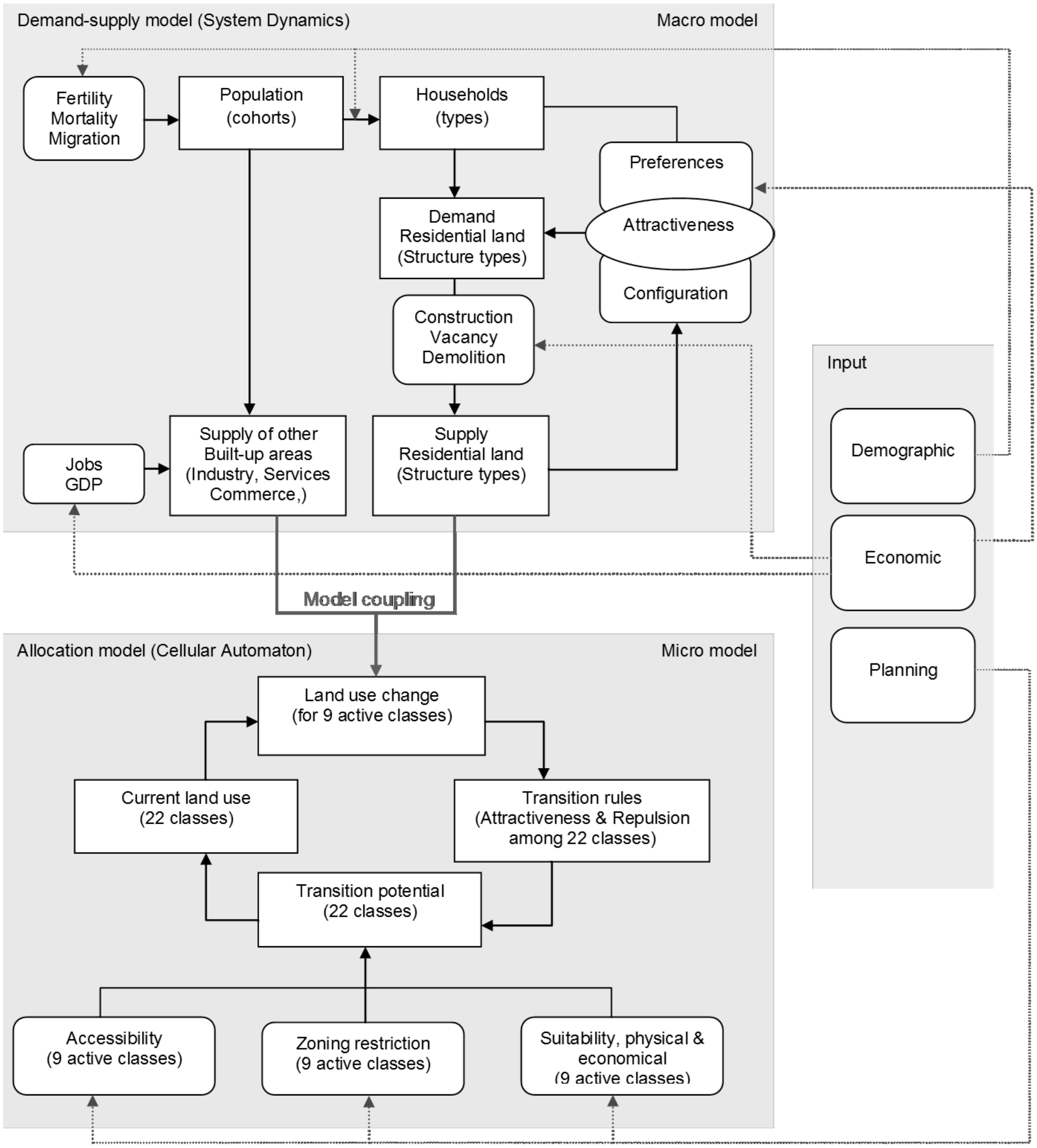

Figure II-2. Model structure overview

The macro-model is implemented in the modeling environment Simile (version 4.7) by Simulistics. Simile provides graphical user interface. Numerous model approaches using system dynamics were performed in Simile due to its easy model linking (Costanza and Voinov, 2004; Lauf, et al., in press, Muetzelfeldt, 2002). For the spatial dynamics, we applied the CA software package Metronamica from RIKS (Research Institute for Knowledge Systems). Metronamica represents a user-friendly, GIS-based CA, which was applied in the European monitoring project MOLAND (Barredo, et al., 2003; Petrov et al., 2006; Van Delden, et al., 2007). Each simulation step represents one year. All equations in the following sections operate as functions of time *t*.

3.1 Macro-model

A detailed technical description of the macro-scale SD model is given for an earlier application in Lauf et al. (in press). This is the reason why, in this paper, we focus on the extensions and improvements. The model was extended by integrating non-residential land uses that actively affect LUC within the micro-model. Improvements were made regarding the residential choice algorithm and the interlinking of residential supply, demand and housing variables.

Population dynamics are computed, including fertility, mortality and net-migration for eight population age classes P_x (cf. App. A), which are interlinked by an ageing process. The youngest class (x=1) integrates the summarized birth rates of all classes. The annual number of people changing from one to the following class depends on the class range. All demographic variables are represented by a start and a trend value. Data were derived from regional census.

The population in each of seven household types, HHT, is calculated by translating the population numbers of all age classes *x* using a transition matrix *M*. The dynamics of household type structures due to SDT, such as increasing single rates is reflected by *p (eq. 1).* Information on household structure and developments arise from census data.

$$HHT_{1...7} = \rho M_{1...7} P_x \quad (1)$$

As previously stated, each HHT *k* holds varying preferences regarding earlier described characterizing variables such as housing cost, *PC*, or distance to amusement areas, *PA.* The same applies for the configuration of residential uses (UST) *j* such as security, represented by crime rate, *CS*, or the availability of educational facilities, *CE.* These neighborhood characteristics are normalized with respect to their rankings to make them comparable by means of a value function.

Consequently, the sum of one characteristic of all residential classes equals 1. The household preferences range between 0 and 1, estimating the importance and weight for each HHT. In this way, the attractiveness can be coded by additive weighting for each household and place as represented in eq. 2:

$$A_{kj} = \sum_{n=1}^{9} I_{kj} \qquad (2)$$

I_n	Description of variables	
$I_1 = PZ_k \cdot CZ_j$	PZ_x	Preferences of households *k* regarding 'centrality'
	CZ_j	Configuration of residential uses *j* regarding 'centrality'
$I_2 = PA_k \cdot CA_j$	PA_k	Preferences of households *k* regarding 'distance to entertainment'
	CA_j	Configuration of residential uses *j* regarding 'distance to entertainment'
$I_3 = PC_k \cdot CC_j$	PC_k	Preferences of households *k* regarding 'housing cost'
	CC_j	Configuration of residential uses *j* regarding 'housing cost'
$I_4 = PB_k \cdot CB_j$	PB_k	Preferences of households *k* regarding 'housing condition'
	CB_j	Configuration of residential uses *j* regarding 'housing condition'
$I_5 = PS_k \cdot CS_j$	PS_k	Preferences of households *k* regarding 'security'
	CS_j	Configuration of residential uses *j* regarding 'security'
$I_6 = PE_k \cdot CE_j$	PE_k	Preferences of households *k* regarding 'education facilities'
	CE_j	Configuration of residential uses *j* regarding 'education facilities'
$I_7 = PG_k \cdot CG_j$	PG_k	Preferences of households *k* regarding 'green provision'
	CG_j	Configuration of residential uses *j* regarding 'green provision'
$I_8 = PL_k \cdot CL_j$	PL_k	Preferences of households *k* regarding 'living environment'
	CL_j	Configuration of residential uses *j* regarding 'living environment'
$I_9 = \sum(PN_k \cdot NM_j \cdot A_{kj})(1-t^{-1})$	PN_k	Preferences of households *k* regarding 'social neighbourhood'
	NM_{kj}	Configuration matrix of 'social neighbourhood' within the households
	A_{kj}	Attractiveness of households *k* above residential uses *j* at time (t-1)

The attractiveness *A* for each household *k* and residential use *j* produces the maximum preference and the initial probability of the household distribution within the seven USTs. Preference values are considered to be constant because of missing empirical knowledge on dynamic adaptive preference shifts. Preference values are derived from empirical studies and surveys on housing satisfaction (Haase et al., 2005; Kabisch, 2005) and adapted to our preference setting. GIS analysis on Berlin and Leipzig provided useful information with regard to household distribution and spatial characteristics to confirm the preference settings. The initial values regarding the configuration parameters for each residential use were determined by merging the spatial allocation of UST with respective additional information provided by administrative geodata infrastructure (SDUDEB, 2012). For example, local average rents were used to determine the average rent per UST, whereas the average distance to the city center of each UST represents the value of centrality. For the determination of distance to amusement or entertainment areas, we mapped the density of restaurants, bars, cinemas and theaters and created normalized values for the comparison of UST (cf. Table II-1). The configuration of residential uses depends on demand–supply relations and is dynamic based on the dimension of decision space changes. Consequently, the attractiveness also changes, and this is equivalent to the housing decision. This defines a decision-making process by city dwellers on the varied residential building stock.

The final demand for the total living space per residential use (*DLS*) results from the population per *HHT,* its specific living space consumption per person (*LSC*) derived from census and its attractiveness *A* (eq. 3)

$$\frac{DLS_j}{dt} = \sum HHT_k \cdot LSC_k \cdot A_{kj} \tag{3}$$

The supply of living space is then calculated by the *DLS*, the built-up area co_j, the flat abandonment and depletion of housing stock dp_j, the demolition dl_j and re-filled vacancies ru_j, which reflect re-urbanization trends (cf. Buzar et al., 2007):

$$\frac{SLS_j}{dt} = co_j \cdot DLS_j - dp_j \cdot DLS_j - dl_j \cdot DLS_j + ru_j \cdot DLS_j \tag{4}$$

The parameters *co, dl, df, ru* are determined by census data on housing market development where similar classes are used together with additional information from real estate agencies. The parameters react dynamically on demand shift as follows: *DLS*↑ → *co*↑, *ru*↑, *dp*↓, *dl*↓ and *DLS*↓ → *co*↓, *ru*↓, *dp*↑, *dl*↑. Thus, a full demand-supply chain is implemented. The parameters *dp* and *ru* are additionally utilized to determine the housing vacancy in each UST. For the conversion of living space into residential land use for each structure type, the specific floor space index *FSD* (ratio of total stacked living space and plot area) is multiplied in combination with another factor representing space loss *SL* due to wall thickness, sidewalks and approaching roads (cf. App. A, App. B). Housing vacancy is included in the supply of residential land uses representing input for the micro-model.

Residential vacancy and demolition shrinkage aspects are already integrated. We use these parameters to determine the change of total abandoned land, denoted as (urban) brownfields *BF* (eq. 5):

$$\frac{BF_j}{dt} = \frac{\alpha \cdot dl_j \cdot DLS_j - \beta \cdot co_j \cdot DLS_j}{FSD_j \cdot SL_j} \tag{5}$$

with α and β being the actual rates of demolished or newly built-up land that become brownfields.

Commercial area *CoA*, industrial area *InA* and areas of public and private services *PPS* are derived from population dynamics and shifts of GDP. We use the annual percentage change of all age classes P_x and the annual percentage shifts of *GDP*. The parameters ε, χ, γ represent simple dynamic trends to feedback changing employment rates of the secondary and tertiary economic sectors.

$$\frac{CoA}{dt} = \varepsilon \cdot \frac{\sum P_x}{dt} \cdot \frac{dGDP}{dt} \cdot CoA(t-1) \tag{6}$$

$$\frac{InA}{dt} = \chi \cdot \frac{\sum P_x}{dt} \cdot \frac{dGDP}{dt} \cdot InA(t-1) \tag{7}$$

$$\frac{PPS}{dt} = \gamma \cdot \frac{\sum P_x}{dt} \cdot \frac{dGDP}{dt} \cdot PPS(t-1) \tag{8}$$

The outputs of the macro-model are not spatially explicit. They represent the constraints for the LU allocation model and determine the number of cells that are transformed (Engelen et al., 1995).

3.2 Micro-model

In this section, a detailed description of the functionality of CA and, more precisely, the Metronamica model in detail (Engelen et al., 1997, Riks, 2007) is not repeated. Rather, the aim is to portray the specifics of the model application. The use of CA implies a cell-space environment. A cell size of 50 x 50 meters was chosen to enable fine-grained dynamics with 2.15 million cells in a uniform grid representing the study area. Each cell represents the dominant land use of the cell space (cf. Figure II-1). Dynamic land uses denoted as active classes have to be distinguished from passive classes, which only change as a consequence of spreading active classes. Land uses that do not change their state at any point during the simulation are considered as static classes. All classes participate in spatial decisions due to underlying neighborhood effects, the key element that constitutes the dynamic behavior of CA. All active classes are formulized in the authors' SD model to generate demand and supply. In addition to the common integration of commercial areas, industrial areas, and public and private services, we focus on the differentiation of residential uses whereby the use of detached and semi-detached houses, pre-war block structures, prefabricated multi-story houses, post-war multi-story row houses, villas and residential parks are defined as active classes (app. II-B, Table A-IIb-1). To integrate a shrinkage feedback component, the land-use (urban) brownfields are also set as a static class. Arable lands, shrubs and trees, forests, pastures, open spaces and artificial urban green areas represent passive classes that, in the first instance, are available for occupation by active classes. All other land uses shown in Figure II-1 are static classes and, by association, constant.

The land use dynamics of the CA highly depend on the quantitative inputs of the SD macro-scale model. The spatial dynamics of the CA are formalized by the change potential P_{fc}. It describes the potential that a land use *f* changes for another land use and is calculated for each cell *c* as presented in eq.6 (Engelen, et al., 1997; Riks, 2007):

$$P_{fc} = R_{fc} \cdot (\omega_s \cdot S_{fc} + \omega_Z \cdot Z_{fc}) \cdot A_{fc} \qquad (9)$$

The neighborhood effect *R* is represented by transition rules in the form of distance-decay functions with cell distance on the x-axis and a comparative measure for attraction or repulsion on the y-axis. The suitability *S,* zoning *Z* and the accessibility *A* are additional decision variables affecting the spatial dynamics. They are integrated as raster-map information using the same grid as the initial land-use map. The factors ω_s and ω_z represent the weighting factors of suitability and zoning assumptions (Riks, 2007) that are equally set to 1. Zoning maps are used to restrict uncontrolled urban development. In this case, a green-belt development around Berlin is allowed. Furthermore, inner-city parks and wetlands are excluded from any transition as they are protected through planning specifications. Table II-1 provides detailed information with respect to the aforementioned. As a result, an updated land-use map for each simulation step is obtained, which can be exported easily for analysis.

3.3 Model coupling

The demand and supply SD macro-model and the cellular allocation micro-model are linked by a loose input-output coupling with no integration of feedbacks. The macro-model is based on differential equations that assign non-linear dynamic results. CA algorithms, on the other hand, give back discrete results for time steps (in our case, one year). In consequence, land uses were initially calculated on a yearly basis for the simulation period within the macro-model. To avoid transferring the results manually for each land use and year, the SD output was incorporated into the macro-model log file of Metronamica. Finally, the land demand of the household types was mapped to the CA land-use classes as follows. The land use for the residential classes represents the total residential supply per UST. Residential supply is a function of living space demand and includes respective housing vacancy. For the macro-model, land uses are simulated in hectare and are then converted into the number of cells (50 x 50 meters). The total non-spatial number of cells for each land use, including the amount of cells for all non-residential classes, represents the drivers for the spatial simulation in the micro-model. The input module, reproducing all changeable model parameters, is directly connected to both the SD and the CA models. Within the SD model, demographic and economic inputs are directly read in as system parameters that are mathematically linked to the system variables. Economic development and planning inputs for the CA model are represented as raster maps. They can easily be uploaded and changed for each simulation. The parameters regarding accessibility are determined by distance and weight functions, which are manually entered, as seen in section 3.2. Zoning maps can be replaced or modified by altering spatial and temporal presettings through an easy "click-and-change" solution.

3.4 Calibration and validation

The parameters of the model for the input module are given in Table II-1. The SD model was calibrated using regional census from 1992 to 2001 (SOBB, 1991-2008). In detail, the following parameters are calibrated: the population drivers fertility, mortality and migration as well as their respective trend variables; the dynamics of household type structure (*p)*; the parameter to determine the residential supply (co_j, dp_j, dl_j, ru_j); the brownfield parameters α and β and the employment rates ε*,* χ*,* γ and GDP. For all parameters, observed data covering nine years are integrated as trend or mean values. A list of all model parameters integrated in the SD macro-model can be found in the app. II-A .

For the spatial calibration of the CA model, two land-use maps (1992, 2007) were prepared for the total study area using satellite imagery and an available biotope-type map for the area of Brandenburg (LUGV, 1996-2009). The calibration of the CA model proved to be more difficult as only two land-use maps of two time steps were available for the total study area while a strict separation of data for calibration and validation is requested. For the calibration of the CA, we divided the study area to analyze LUC patterns for the area within the city borders of Berlin excluding the surroundings due to better data provision, thus covering approximately 30% of the whole study area (Figure II-1). Land-use patterns in Berlin and the metropolitan region are comparable as the city borders already include larger suburban areas. The two calibration maps represent LUC for the time frame 1991 to 2001 The neighborhood effects as distance-decay functions are calibrated by optical interpretation, analysis of cell transitions and recommendations for the calibration of Metronamica (Riks, 2007). Accessibility parameters are calibrated analyzing the distance of land-use patches to the integrated road, and rail networks are derived based on land-use changes between 1991 and 2001. For zoning and suitability, current data were used for the overall study area (Table II-1).

Table II-1. System parameters for demand and allocation module including data sources

Parameters	Demand–Supply model (System dynamics)	Allocation model (Cellular automaton)
Demography (social)	• Population, Fertility, Mortality, Migration per age class (SOBB, 1991-2008) • Number of persons per HHT (SOBB, 1991-2008) • Mean living-space consumption per HHT (SOBB, 1991-2008) • Preferences per HHT regarding decision variables (cf. sect. 2), *emp. studies* (Haase, et al., 2005, Kabisch, 2005) *and GIS analysis for Berlin and Leipzig*	
Economy	• Income HHT (SOBB, 1991-2008) • Built-up are per UST, *land use maps 1992* • Vacancy per UST 1992 (LUV, 2004-2009, SenUD, 1990-2009) • Construction, demolition and vacancy rate per UST (ebd.), quality *test with land use maps 1992, 2007* • Conditions per UST regarding decision variables (cf. sect. 2), *interpretation of geo-information* (PBP, 1990-2005, SenUD, 1990-2009, YP, 2009) • Gross domestic product (SenETW, 1990-2009) • Employees in economic sectors (ebd.)	• Initial situation, *land use map 1992* • Transition rules, *analysis of LUC 1992-2007 just for the city of Berlin* Suitability, *Ground value 1992* (SenUD, 1990-2009)
Planning	• Availability of buildable land (LUGV, 1996-2009) and *land use map 1992* • Mean floor-space density and mean number of stories of UST (SenUD, 1990-2009)	• Zoning, (LUGV, 1996-2009, RPDBB, 1993-2008) • Accessibility, *Autobahn, federal street, regional train, public transportation* (RPDBB, 1993-2008)

The quality assessment of the coupled model is a challenge. In general, evaluation possibilities are very limited for validation results when standing alone. Time series used for validation are generally short, reflecting minimal changes in land use. Consequently, validation measures such as kappa, mean absolute percentage error (MAPE) and mean relative deviation (MRD) demonstrate striking results (Van Vliet, 2009).

The quality of the SD model is tested with MRD and correlations of observed and simulated data in 2007. For good model quality, MRD should not exceed 25% (the maximum deviation of observed in 1992 and observed in 2007 equals 40%). For the overall model quality assessment, we incorporate a comparison of simulation results using $H2D_{CA}$ and a substituting NM whereby all CA parameters are constant. The use of an NM is a common option to test the mode performance (Pontius Jr. and Petrova, 2010). We use the NM to show the improved simulation and segmentation of residential patches in consequence of household-driven housing decisions on different residential uses.

Because a particular focus is placed on residential land uses, only those are revealed in the NM. The quantitative and spatial allocations of LUC are compared by kappa coefficients and MAPE using the Map Comparison Kit software vs.3.2 (Visser and Nijs, 2006). For the NM, it is assumed that the total residential area RA_{NM} is the result of population P and its growth rate φ and the mean living space consumption per capita LSC. FSD represents the floor-space density and SL represents a conversion factor for living space to residential area (c.f. eq. 10):

$$RA_{NM} = \frac{\varphi P \cdot \overline{LSC}}{\overline{FSD} \cdot SL} \tag{10}$$

The simulation run for both macro-model assumptions is 15 years due to data limitations. The results are tested and compared to real data from 2007.

4 Results

4.1 Macro-model quality

To test the model fit, the CA output driven by the $H2D_{CA}$ model is compared with the NM (eq. 10). Before comparing the spatially explicit CA micro-model output, the quality of $H2D_{CA}$ was tested to illustrate both its quality and capacity. Figure II-3 reports the relative deviation of observed and simulated data for all age classes and the coefficient of determination, R^2, for the data points of observed versus simulated data for each age class to show the correlation after a 15-year simulation.

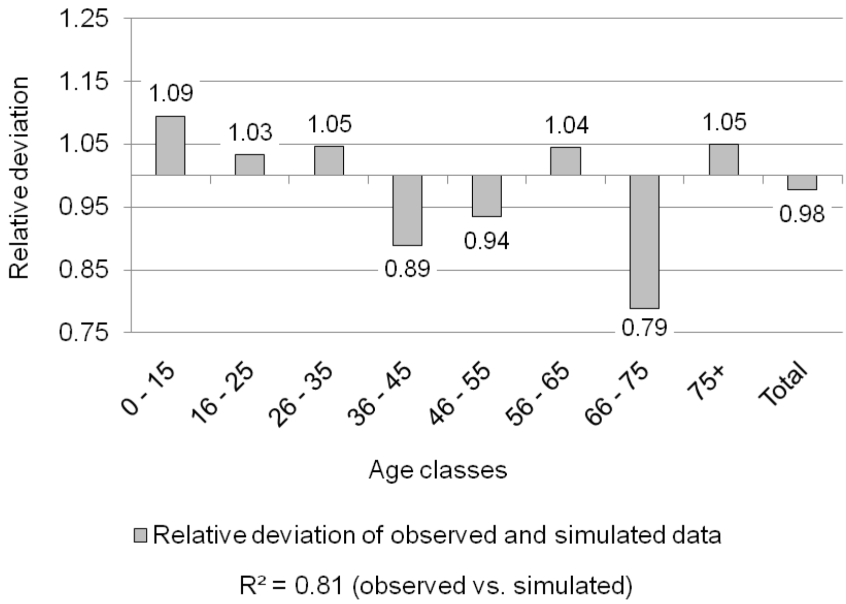

Figure II-3. Model fit of population dynamics for the age classes (simulation run 1990-2007)

A positive deviation suggests a higher simulated value than observed. The deviation of the population for all age classes remains under 10% with the exception of the age class of 65- to 75-year-old individuals, for whom the simulated results are 21% lower than those observed. For the total population, a minimum deviation of 4% is determined. The point data indicate a positive correlation, which is confirmed by an appropriate coefficient of determination. Comparable results are found for the model fit of HHT and residential uses (app. II-B: Figures A-IIb-1 and A-IIb-2).

4.2 Micro-model quality

In the following, the simulation results performed with Metronamica using the outputs of $H2D_{CA}$ compared to the NM for a simulation time of 15 years are presented. The analyses of the quantitative residential LUC of both simulations counting the number of residential land use cells resulted in a total difference of 6944 cells. The relative deviation of cell change between observed and simulated residential use is evidenced in app. II-B (Table A-IIb-2).

The comparison of specific land-use type and urban structure maps is used to illustrate the advantage of the presented macro-model $H2D_{CA}$ by counting the cell matches. Figure II-4 compares the results of simulated and observed residential land-use classes for 2007 (beginning in 1992). The result for the NM is displayed on the left and that for $H2D_{CA}$ on the right. By visual interpretation, more red and blue patches are visible in the map to the left. Furthermore, a higher dispersion and fragmentation of new residential cells is seen on the left whereas on the right, new residential cells originated closer to already existing residential areas. The left map represents a 90.4% cell match, whereas the map on the right indicates a 93.1% cell match. More in-depth insight to the model behavior with respect to varying macro-model assumptions is presented in Table II-2.

Table II-2. Simulated vs. observed comparison results for the metropolitan region of Berlin regarding residential land uses where current land use of 2007 is compared with simulation results for the unconditional NM and the system dynamics H2DCA macro-model

Observed/Simulated	NM				$H2D_{CA}$			
	Kappa	k-Loc	k-Histo	Fuzzy-k	Kappa	k-Loc	k-Histo	Fuzzy-k
Prefabricated multi-story houses	0.91	0.95	0.96		0.95	0.95	0.99	
Multistory rows	0.95	0.97	0.98		0.97	0.98	0.99	
Wilhelminian blocks	0.96	0.98	0.98		0.97	0.98	1.00	
Villas	0.95	0.98	0.97		0.98	0.98	1.00	
Detached and semi-detached houses	0.95	0.98	0.97		0.93	0.93	0.99	
Suburban village	0.61	0.63	0.97		0.96	0.96	1.00	
Total residential area	0.91	0.92	0.98	0.90	0.93	0.93	0.99	0.92

The absolute values for kappa coefficients are of less importance due to the enormous size of the study area and the short simulation period. Consequently, comparatively small changes appear, thus leading to very good kappa results for both macro assumptions.

Comparing kappa values of the respective macro-models reveals the decisive benefit of $H2D_{CA}$. Kappa is composed of k-Loc, representing the spatial model fit, and k-Histo, representing the quantitative model fit. For most of the residential-use classes, as well as the total residential area, better kappa coefficients were performed for the SD macro-model $H2D_{CA}$. In particular, k-Histo contributes to improved kappa coefficients (Table II-2).

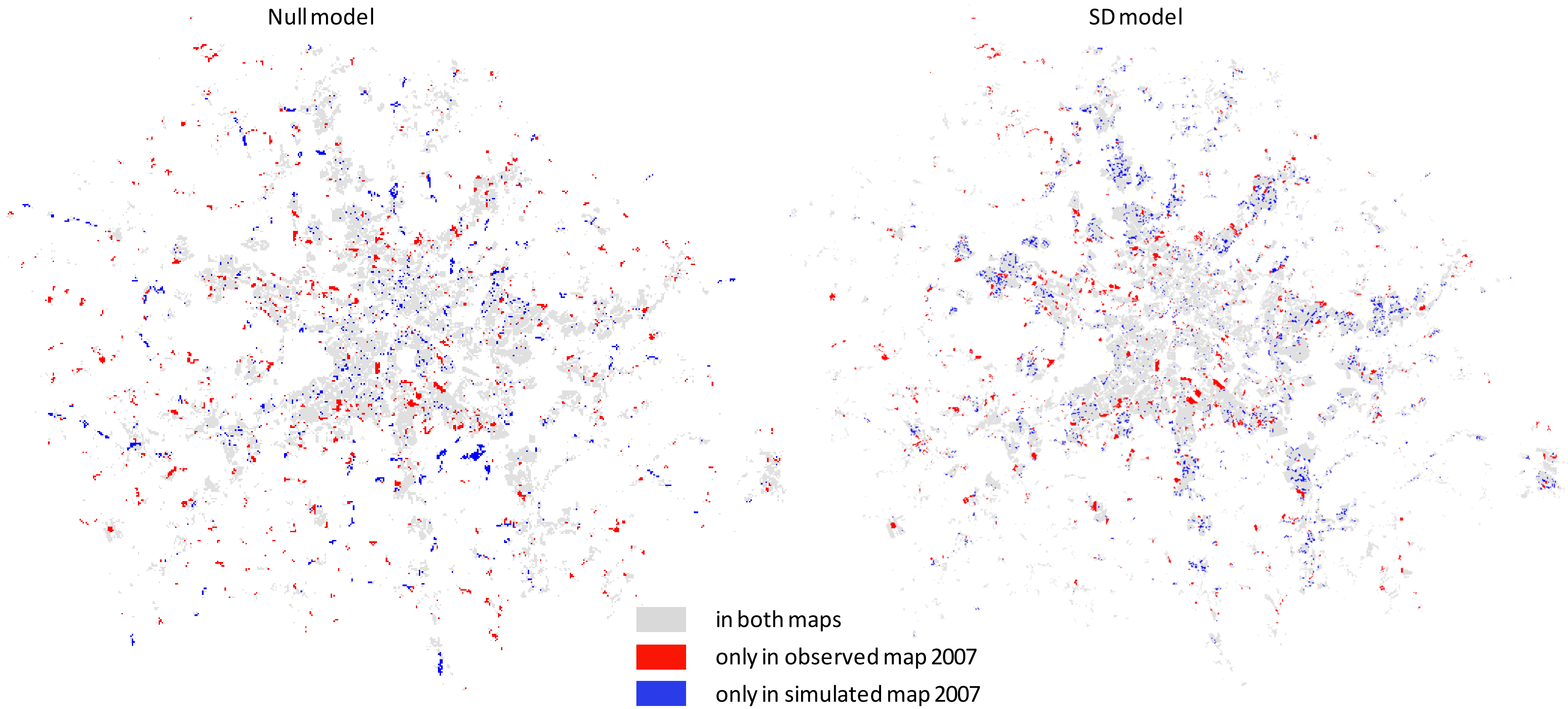

Figure II-4. Map comparison between observed and simulated map of 2007 for the metropolitan region of Berlin (sum of all residential land uses); left: using NM and right: using the H2DCA system dynamics model

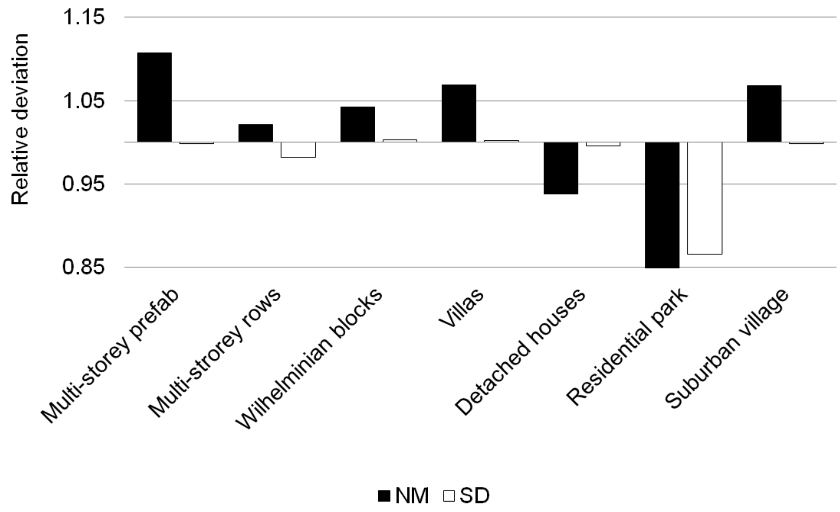

Figure II-5. Relative deviation of measured and simulated areas of residential land use classes for NM and SD macro-model (simulation time = 15 years)

Figure II-5 shows the relative deviation of simulated and observed residential land uses for 2007 after a simulation period of 15 years is shown. The results substantiate a better model fit for the use of the system dynamics macro-model. The land-use class "residential park" exhibits, by far, a less convenient result for the relative deviation due to an enormous relative growth of more than 500% - the result of a very young urban structure built after the reunification in 1990. However, even for this land-use class, better results could be detected using $H2D_{CA}$ with a deviation of 12% versus 28% using the NM.

4.3 Land-use change

Figure II-6 presents relative change values of cell states for all residential land-use classes for the period 1992 to 2007. Simulated residential uses based on $H2D_{CA}$ reproduce observed changes more appropriately than does the NM. In prefabricated multi-story houses and in suburban villages, a decrease in the amount of space occurs in both observed data and simulation results, reflecting changed housing preferences. Using the NM, no residential decline could be found at all. $H2D_{CA}$ reveals that detached (family) houses increased despite decreasing numbers of family households, which is attributable to a "catch-up" suburbanization of East Berlin. Furthermore, an increase in inner-city residential use, such as Wilhelminian blocks and multi-story row houses, was disclosed.

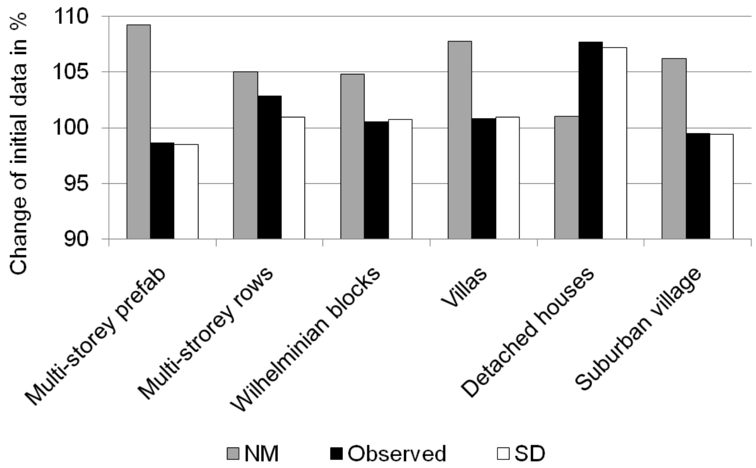

Figure II-6. Comparison of change in residential use classes for a 15-year simulation for NM, observed data and H2DCA macro-model

Figure II-7 represents the share of arable or other open land taken over by residential use. The simulation results, whether using the NM or the SD model, show very similar results. In reality, 52% of all newly constructed residential areas impact arable land and 28% impact pasture for the period 1992 to 2007, which reflects a significant increase in detached and semi-detached houses. This trend was convincingly reproduced by the model. With respect to forests, a noticeably higher cell transition of approximately 16% was achieved for the model simulation. The cell transition is based on the neighborhood functions of the CA, which causes very similar results for both simulations. When examining Figure II-7, an improved model quality (between 0.3% and 3.4%) using $H2D_{CA}$ is conveyed for all land-use classes except open spaces. It is further observed that, between 1992 and 2007, suburban fertile soils were converted to residential land.

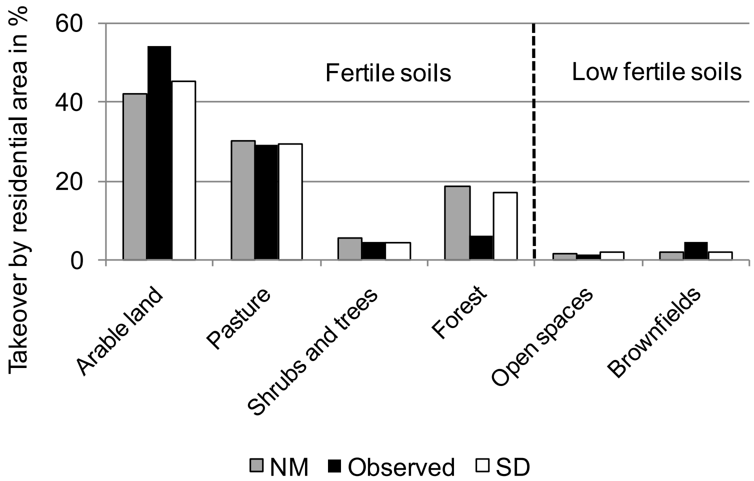

Figure II-7. Relative transition of open land uses to residential land use classes (model run=15 years)

Results of a complete model run including all participating land-use classes are presented in app. II within a cross table representing the cell transitions of all land uses between 1992 and 2007 (Table A-IIb-5).

5 Discussion

The comparison of the 15-year simulation results applied to this case study of the metropolitan region of Berlin was performed using two different macro-model assumptions in combination with a constant CA model. The study demonstrates the relevance of enhanced causal feedbacks with regard to demographic change, household-type specifications and respective residential choice algorithms. The quality assessment and validation of the $H2D_{CA}$ model were found to be more precise than those achieved using an NM representative for conventional macro-models for CA. The simulation results represent the process of demographic changes with respect to an increase of age classes greater than 60 years of age (population ageing), a decrease in family households and an increase in single, childless couple and single-parent households, which is in line with the STD (Börsch-Supan et al., 2001; Kaa, 2004). The effects are an increase in the number of households in line with a decrease in the total household size independent of the total number of residents. This, again, leads to an overall higher housing demand. The relative deviation of quantitative residential LUC between measured and simulated data with 0.89 (using SD) and 0.52 (using NM) reveals a clear advantage of the $H2D_{CA}$ model.

To that end, new land-use patches in CA models are attributable to spatial configurations with respect to zoning, suitability, accessibility and neighborhood effects driven by economic and simple population parameters (Castella and Verburg, 2007; He et al., 2008). In this context, the integration of a more qualified specification of residential land uses attributed to household-type alterations and respective residential choices contributes to a better understanding of the processes determining land-use changes. Moreover, it improves the reproduction accuracy of (existing) land-use patterns, as shown in section 4 (Waddell et al., 2004). Additional benefits of finer residential land-use classes are attributable to a wider perspective on urban density and green space development as well as the high level of importance placed on the issue (often on the basis of vague estimations) by decision makers in urban planning who deal with the development of such classes within their land-use plans (Banzhaf and Höfer, 2008, Ravetz, 2000).

The integration of a residential choice algorithm as a function of changing household types and numbers causes demand shifts in the seven urban structure types and enables the simulation of simultaneous growth and shrinkage processes in different housing segments. Additionally, urban shrinkage is reflected by the integrated land-use class (urban) of brownfields, which enables the consideration of urban fragmentation processes and the development of potential urban greening. A lower fragmentation rate was achieved for the use of our improved macro-model, compared with the NM. This is due to the actual increase caused by converting inner-city brownfields into residential areas in Berlin that is given back by $H2D_{CA}$, whereas residential land use based on simple macro-model assumptions tended to spread and be more dispersive. The urban phenomenon of a growing back-to-city movement, defined as re-urbanization, refers to certain demander groups with specific housing preferences (Buzar, et al., 2007; Kabisch et al., 2010). This is indicated by our model and evident in an increase of inner-city residential land uses of Wilhelminian block structures and multi-story rows. The simulations show that a significant amount of valuable arable land and many pastures on the city's edge are transformed to built-up areas despite a decreasing growth rate of detached and semi-detached houses as a consequence of diminishing family households, which predominantly inhabit such houses. Urban shrinkage was verified for the classes of suburban village and prefabricated multi-story houses. Suburban villages exhibit deficient conditions regarding housing size and shape. Families and households opting for suburbia prefer to have their own house and property adapted to their needs. Prefabricated multi-story houses are less desirable than other types of housing, which is most noticeable in the decline of demand and housing stock (Kabisch, 2005; Nuissl and Rink, 2005).

Spatial allocation and the causes of specific developments, such as reurbanization or shrinkage, can be analyzed precisely as they refer to household-type alterations and respective residential choices. The model demonstrated here presents an adaption of urban LUC models to ongoing socio-demographic processes, which, to date, are rarely considered in-depth (Koomen and Stillwell, 2007). The model integrates new aspects for LUC modeling, such as (1) a detailed representation of the varying housing stock, (2) the incorporation of a dynamic residential choice behavior and (3) an extension towards a growth and shrinkage model.

By combining SD with CA, we benefit from their respective advantages and, at the same time, reduce their disadvantages (Castella and Verburg, 2007, Van Vliet and Van Delden, 2008). System dynamics, the origin of urban modeling, is most suitable for modeling processes implying feedbacks (Forrester, 1971). However, processing spatial information is far more difficult using SD than it is using CA. The plurality of digital spatial information and a better accessibility/availability of GIS promote the use of CA as the dominant modeling tool for LUC. Their weakness is, in contrast, the inability to reproduce cultural, economic and social driving forces that also affect LUC (He, et al., 2005; Tiyan, et al., 2007). The authors' proposed model implements a household preference-driven residential choice algorithm with feedback to household dynamics and migration, both of which are a function of demographic change according to the SDT. The resulting shifts in housing demand affect-participating parameters and define the supply of residential uses. Residential patterns are emerging by altering functions of housing demand and supply formalized as residential choice whereby a complex feedback process with feedback loops is implemented (cf. again Figure II-2). This formulation, in combination with CA, represents an improvement of causal LUC dynamics with the integration of profound household preferences and decision making.

Model uncertainties for both model components are described in the following. For the proposed macro-model, we tested the sensitive behavior determining the effects on residential supply due to shifts in the demographic and housing parameters under constant conditions. $H2D_{CA}$ is, due to its implications, sensitive to demographic parameters, especially with respect to the migration rates, which have a significant impact on residential supply. Residential supply also shows a high sensitivity regarding the initial parameters (construction, demolition and vacancy). This may be the result of a delayed response to a demand shift, suggesting short-term simulation results could be misleading. Model uncertainties also accrue from untested parameters. The effects of the described residential parameters (e.g., housing costs, green space provisions, and security) are, thus far, not fully revealed. Dynamic housing preferences are not integrated as an option to adapt to the housing market. The sensitive behavior of CA models and of Metronamica, in particular, are recorded variously (Pontius Jr. and Petrova, 2010). Metronamica is highly sensitive to changing transition rules, indicating the neighborhood's effects between land-use classes; thus, a sound calibration is difficult. In general, model results are representative based on the short time interval between calibration and validation.

With minimal effort, the model is transferable to other cities on a national level. Only a minor calibration regarding the specific demographic variables is required. For other urban areas to apply this model, a good data infrastructure is required. Furthermore, the residential types may have to be adapted, which implies intensive data analysis.

6 Conclusions

The proposed model represents an approach that addresses one of the current gaps in LUC modeling. The combination of $H2D_{CA}$ and the Metronamica CA provides an enhancement of dynamic model behavior due to improved causal interrelations of system elements and drivers of LUC. Through the integration of more profound population and household dynamics, demographic impacts on urban land use are implemented, which are particularly relevant for residential land-use development. The model enables the simulations of growth and shrinkage processes to occur concurrently. Residential choice based on demography and lifestyles refers to the subdivision of residential land use into prevailing urban structural types that serve as housing. Consequently, more detailed information is provided for the analysis of land-use patterns due to demographic change. In the results section, it was shown that the simulated land use patterns are far more realistic and detailed than CA outputs based on a prevailing simple macro-model. Finally, this contributes to urban system understanding due to the following functional chain: population → households → residential choice → LUC and the feedback +mechanism: LUC → residential choice.

The comparison of simulation results using two different macro-models ($H2D_{CA}$ and NM) substantiates the added value of $H2D_{CA}$. Although the model functionality test and quality control were satisfying, further testing of parameter sensitivity and model behavior is required. For robust forecasts, the model should be additionally tested for extreme (growth or shrinkage) scenarios.

The model has been applied to the metropolitan region of Berlin. The size of the study region represents a challenge because it is a large and complex urban region that is dynamically displayed at a 50x50 meter cell raster. Good data availability is a prerequisite to making the model applicable to other urban regions or cities. It must be considered that, for accurate model reproduction of a specific case study, a wide range of various data are needed, and this requires a good data infrastructure. The practical use of this model for end-users in the field of policy making is the profound analysis of a subdivided housing market under different future scenarios of demographic and economic development. The provided detailedness of LUC enables the evaluation of ecosystem services, such as green space provision or climatic regulation due to the use of urban structure types.

Further work will focus on different populations and planning scenarios for the Berlin metropolitan region. Scenarios will incorporate varying population trends, alterations of household patterns and stability, economic and employment assumptions as well as different forms of planning policies. Another idea is to integrate further components, such as an ecological impact model. This component will be interlinked with the consisting model through feedback loops to analyze the consequent LUC as a result of the ecological impacts due to LUC. This is crucial when considering the protection and the improvement of urban quality of life for city dwellers.

Acknowledgments

This research is part the Graduate Research Program 780/3 "Perspectives on Urban Ecology III – Optimizing urban nature development – Dynamic change of nature functions and the urban environment of city dwellers" and is funded by the German research foundation. Special thanks are directed to the Research Institute of Knowledge Systems (RIKS) and Director Hedwig van Delden for cooperating and for the research license of the Metronamica software. Furthermore, we want to thank all listed Berlin and Brandenburg institutions for data provision.

The supplementary material offers further information and results.

Chapter III:

Interactions of demography, preference shift and the urban development

Lauf, S., Haase, D., Kleinschmit, B. (to be submitted): Contrasting interactions between urban development and demographic and residential preference shifts in the Berlin metropolitan region – a spatial scenario analysis. *Applied Geography*.

Abstract

At present, we are observing diverging urban development trends in many European cities showing population aging, growth, shrinkage, and reurbanization, without clearly understanding their implications for land-use and patterns change, especially when occurring simultaneously and in a short period of time. We use contrasting scenario assumptions integrating exceeding variants of these urban development trends to uncover possible interactions, focusing on demographic and residential preference shifts which were analyzed and modelled in a previous paper (Lauf et al., 2012). With urban form indicators and landscape metrics we determine urban to peri-urban effects. Out of many highly interesting results, we discovered, for instance, that population aging expedited by population shrinkage affects land consumption to a large extent, especially in the outer city due to the residential preferences of elderly people, and by that reduces urban shrinkage. Against this, a preference shift proceeding towards reurbanization reduces land consumption significantly. Population aging produces synergies in terms of urban growth and landscape fragmentation and trade-offs in terms of urban shrinkage and compactness, and vice versa for increasing reurbanization.

1 Introduction

At present, we are observing diverging urban development trends in many European cities (Brade et al., 2009; Kasanko et al., 2006; Turok and Mykhnenko, 2007), including cities in Germany (Haase et al., 2005; Müller and Siedentop, 2004; Nuissl and Rink, 2005). These trends include urban and peri-urban growth (Catalán et al., 2008; Tavares et al., 2012), depopulation and shrinkage (Couch et al., 2005; Haase et al., 2012), reurbanization (Buzar et al., 2007; Rae, 2013) and, along with all the aforementioned development types, aging of the urban population (Davoudi et al., 2010; Rechel et al., 2013). Next to their societal, socio-economic and fiscal impacts, all these urban development trends have specific spatial infrastructure and land-use implications affecting the urban form (Forman, 2008; Lauf et al., 2012a; Tinker, 2002), which merge into various future challenges to urban planners and policy makers, e.g. safeguarding of interests of elderly people, limited housing space in inner cities or land degradation due to urban sprawl (Alberti, 2008; Temelová and Dvořáková, 2012).

Urban development is the results of several processes that can emerge simultaneously and can interact, expressing various effects. These might directly affect urban dwellers or their societal conditions, e.g. population aging or household compositions and decisions; others might affect the urban form (e.g. growth or shrinkage). According to major trends in European cities, the following processes can be distinguished and are explained, hereinafter:

1. Population aging;
2. Household and preference shifts (i.e. reurbanization);
3. Growth and shrinkage.

In almost all European cities, population aging can be observed *per se* as an aspatial process, but with characteristic implication on the urban space (Nefs et al., 2013), in that ageing might lead to an increased segregation of the population in cities (Rosenberg and Everitt, 2001) or to an increase of the local vulnerability in urban districts (Kim and Joh, 2006; Namdeo et al., 2011). Thus, it seeks for a re-thinking of the urban health, transport, and shopping infrastructure (Douglas, 2012; Forman, 2008; Rosenberg and Everitt, 2001) as well as the provision of recreation and green spaces (Barbosa et al., 2007; Tzoulas et al., 2007). Knowledge about the ageing of the urban population is empirically based on the overall census and respective demographic prognoses – aspatially – but it might also be produced as an outcome of a scenario analysis based on a computational model showing different alternatives of an ageing urban society and additionally, allocating ageing in the city space using residential preference functions (Lauf et al., 2012b).

Growth, shrinkage and reurbanization are predominantly socio-spatial processes that might simultaneously occur in cities (Couch et al., 2005; Haase et al., 2012; Lauf et al., 2012a). Urban shrinkage in early industrialized cities often appears in form of the decline of traditional industries, a decline that induces general economic crises, unemployment, low fertility, and outmigration to other prospering regions (Couch et al., 2005; Haase et al., 2012); whereas urban growth is the result of opposite trends. Reurbanization, at the city scale, is a process of absolute or relative population gains in the city in comparison with its suburban regions. At the district level, reurbanization captures both the populating and diversifying of the inner city with a variety of residential groups of different ages and socioeconomic backgrounds (Buzar et al., 2007; Haase et al., 2005). In this sense, reurbanization is closely related to changing patterns of living arrangements and residential preferences (Haase et al., 2005).

Current research results by urban scholars (Kabisch and Grossmann, 2013; Lauf et al., 2012a; Rink and Kabisch, 2009) suggest that these urban development trends will occur simultaneously; however, it is difficult to foresee which one will dominate the very next future of different European cities. In addition, not much knowledge is available about the future of current peri-urban settlements in the urban surroundings, defined as ”discontinuous built development, [...] of less than 20,000, with an average density of at least 40 persons per km^2 […].” (Ravetz et al., 2013), regarding the outcomes of urban sprawl.

The German Federal Office for Building and Regional Planning (2008) assumes that European cities are ageing and will do so for the next decades. Along with this statement and the assumption that young sub-urbanites as well as remaining elderly parents will move back towards the inner city, future reurbanization will be coupled with ageing. In addition, demographic research suggest that the trend towards small single- and two-person households will continue (Alders and Manting, 2001; van de Kaa, 2001). Thus, more living space and more housing units (increasing per-capita living space) are needed despite an ageing and declining population. But what does this mean for urban and peri-urban land-use patterns?

In this paper, we simulate the simultaneous effects of different assumptions on population aging, growth and shrinkage and reurbanization using the study site of the metropolitan region of Berlin, which represents a suitable case study as all above-mentioned processes can be detected (cf.

sect. 2.1). We link our assumptions to an already implemented and well-validated land use change (LUC) model covering the above processes (Lauf et al., 2012a) and create different combinations of them. Running the calibrated model for a time horizon of 2030 (cf. Lauf et al., 2012b), we should be able to detect the effects of each of the processes and their combinations for the urban development and land-use patterns in the Berlin Metropolitan region on the one hand. On the other, the interpretation will allow a better understanding of what the consequences are of simultaneously running – and possibly exceeding – urban concentration, individualization and ageing processes in a spatial sense.

The objectives of this paper are:

- to implement recent and future urban development trends of (1) population aging, (2) household and preference shifts (i.e. reurbanization), and (3) growth and shrinkage, into a spatially-explicit urban land-use model,
- to analyze and evaluate contrasting trends of population and household development (growth versus shrinkage),
- to assess the effects on residential choice, related land consumption and loss of open land and vice versa in combination with exceeding trends of population aging and reurbanization, and finally
- to determine the spatial effects of different development scenarios and the effectivity due to shifts in households and household decisions along the urban to peri-urban gradient.

2 Methods

2.1 Study area

The study focuses on the metropolitan region of Berlin, which has a spatial extent of more than 5.3 thousand square kilometers and a population size of 4.5 million (SOBB, 2008). The region is characterized by specific patterns and typical land uses along the urban to peri-urban gradient. Figure III-1 shows that the inner city consists of almost 50% central located dense residential uses, 30% other built-up structures, and 20% green spaces (mainly artificially arranged parks). The outer city is characterized by 20% decentralized low-density residential uses, 20% intermediate and central located dense residential uses, and over 30% green spaces and a small amount of agricultural land (less than 10%). The periphery consists of a small amount of about 10% built-up structures (mainly decentralized low-density residential use), 40% agricultural land and about 40% green spaces (mainly forests).

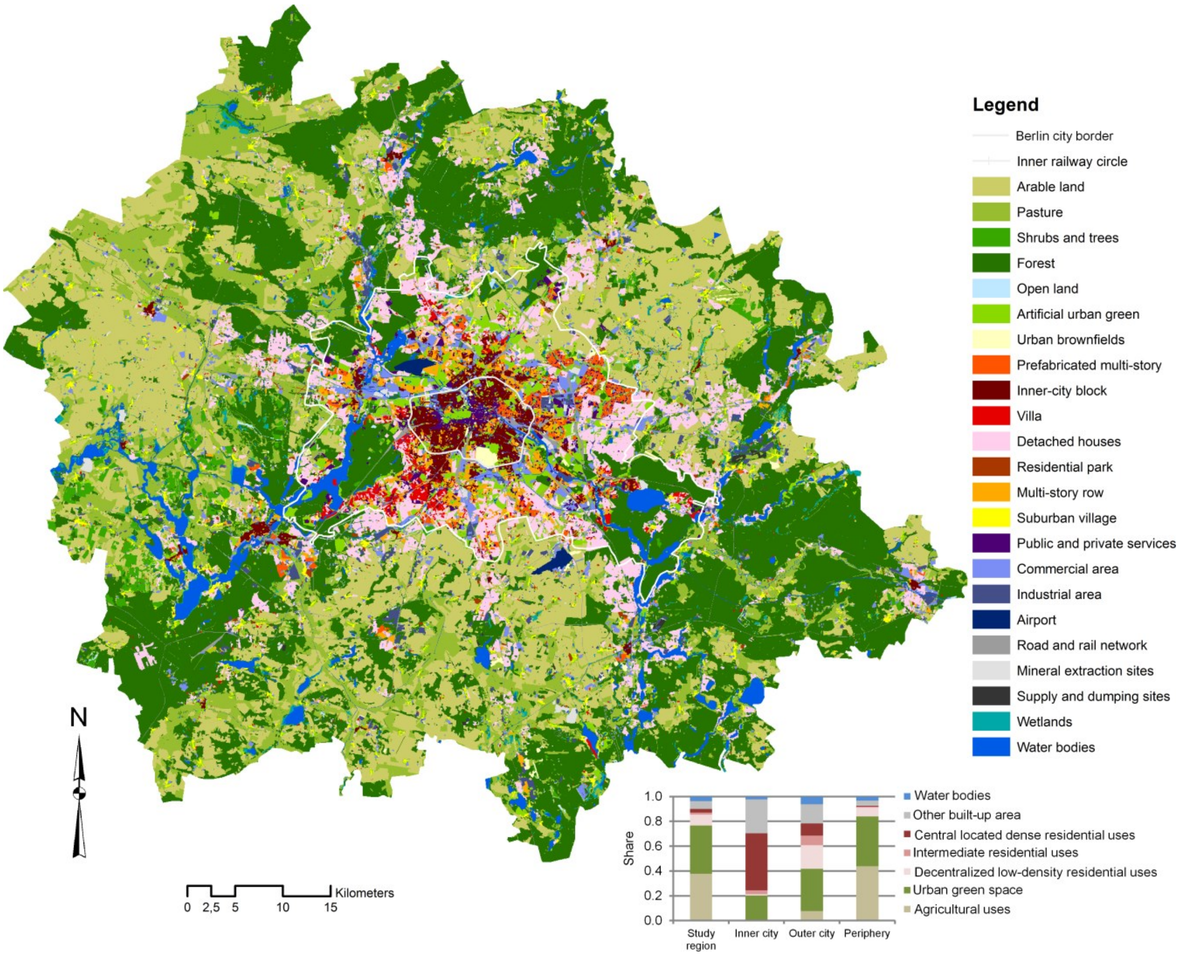

Figure III-1. The metropolitan region of Berlin with its land uses; listed land-uses provide the basis for the applied LUC model; the distribution of land uses presents aggregated classes and specific spatial units as used in this study; the inner city describes the area inside the inner railway circle, the outer city is defined by the area bounded by the Berlin city border and the inner railway circle, the periphery is defined by the area extending outside the city border

Berlin's urban development after the reunification in 1990 and until the millennium was characterized by high rates of suburbanization and the abandonment of Eastern-Berlin industrial locations, accompanied by population loss at the end of the 1990s (FOBRP, 2008; Haeussermann and Kapphan, 2004; SOBB, 2008). Since the year 2000, many building projects for public and private services (such as the government quarter) occurred. In addition, moderate population growth fostered a new trend of central urban living (referred to as reurbanization) leading to increasing urban concentration (Brake and Herfert, 2012). The demography is influenced by population aging and the increase of smaller households (of ≤ 2 persons; SOBB, 2008; van de Kaa, 2001).

2.2 LUC model and scenario development

To meet the objectives we applied a self-developed land-use change model consisting of a combination of system dynamics (SD) and cellular automaton (CA; Lauf et al., 2012a; Lauf et al., 2012b). Figure III-2 shows the components and the functionality of the model. Population dynamics for eight age classes are transferred into seven household types (HHT; cf. Figure III-3), representing single and couple households differentiated according to their age, family and single parent households and flat sharers. Each HHT has specific preferences that are considered in the decision process of selecting a specific residential structure. These preferences are weighted according to their importance.

To determine the location attractiveness (the HHT distribution across seven residential structures), selectable residential structures are characterized by their settings. Residential demand for each residential structure results from assigning the location attractiveness to the household sizes. Demand shifts control relevant housing parameters, such as the construction and abandonment rates, which then regulate the supply side within a closed feedback loop (Lauf et al., 2012b). Besides the integration of household decisions at the demand side to determine LUC, neighborhood transition rules, accessibility and planning are crucial for the spatial allocation of land-use changes.

This fact is integrated in the CA; applied zoning maps decide whether a cell is transformed from one use to another using a spatial resolution of 50x50 meters per cell. The model enables the simulation of simultaneous growth and shrinkage processes as demonstrated in (Lauf et al., 2012a; Lauf et al., 2012b).

Figure III-2 presents the input data used for model calibration and introduces the six scenarios that have been set up. For all scenarios the model run was 22 years (from 2008 and 2030), which defines a reasonable prediction period in terms of reliability of socio-demographic variables. The basic growth and shrinkage scenarios (BG and BS) represent contrasting trend-based economic (i.e. gross domestic product) and population projections derived from census data of the analytical period 1991-2008 (SenETW, 1990-2009; SOBB, 2008), under constant residential preferences.

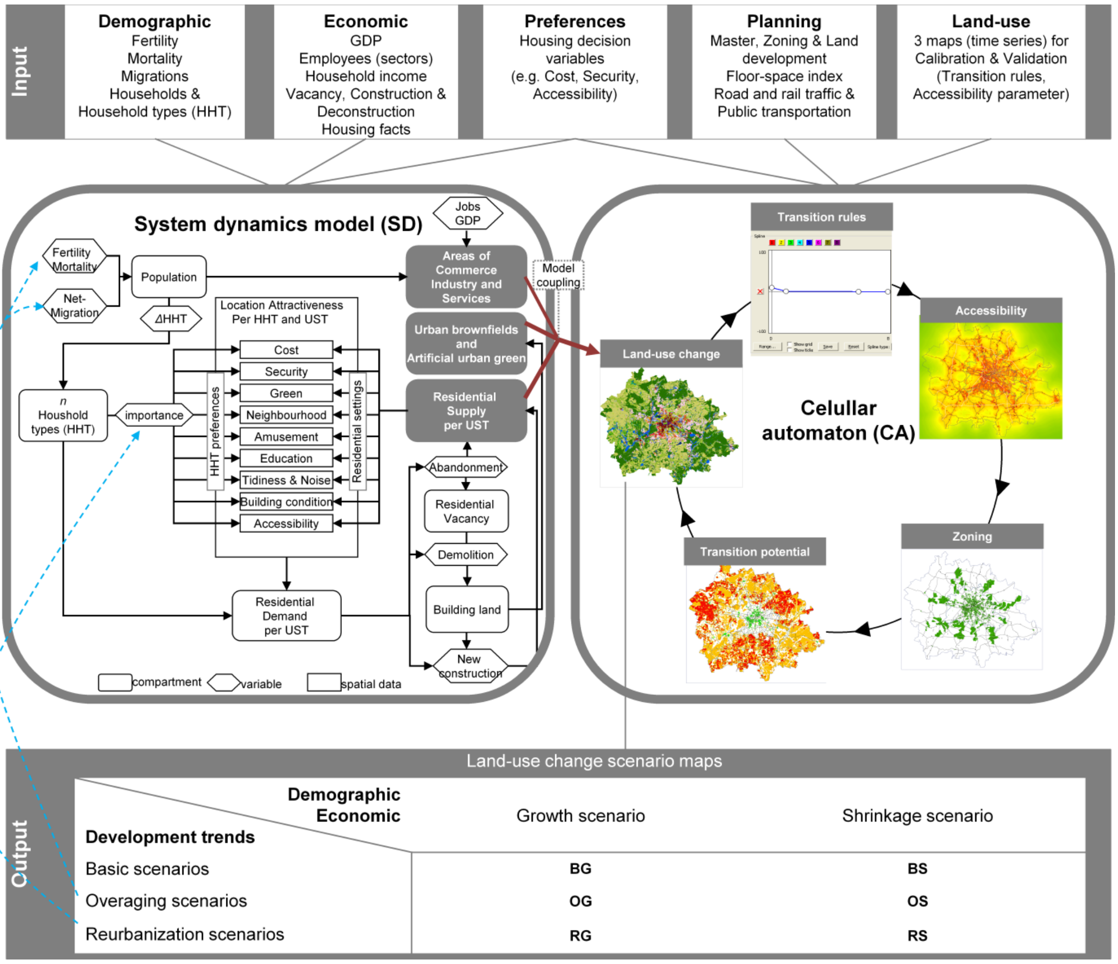

Figure III-2. Model overview and considered scenarios; the blue broken line shows where inputs were varied for respective scenarios (HHT=household types; UST=urban structure type)

The overaging scenarios (OG and OS) are defined by exceeding population aging (with regard to expected trends) as a result of reduced fertility rates and increased immigration of elderly people, matching the total population numbers of the basic scenarios. The reurbanization scenarios (RG and RS) represent an exceeding inward residential movement (with regard to expected trends) with household preferences are shifted towards a higher attractiveness of central located residential uses. The respective scenario storylines and parameter shifts are presented in Table III-1.

The analysis of the presented scenarios' implications consists of two parts: Firstly, the presentation of likely urban developments, contrasting the urban effects caused by population growth versus population shrinkage (BG and BS) and secondly, the analysis of urban effects due to exceeding developments of population aging and reurbanization (OG, RG, OS and RS).

Table III-1. Storylines and scenario configuration of contrasting and exceeding urban developments; the scenario implications for overaging and reurbanization scenarios represent fictional exceeding trends, whereas the growth and shrinkage scenarios are based on the expected maximum population and economic development range (cf. SDUDEB and SOBB, 2009)

Scenario	Storylines
Growth	Against the forward projection of the gross domestic product, annual changes are increased at the rate of 1.096; against the forward projection of the total population, annual changes of demographic variables were modified, for birth rates at factors of 1.002, for immigration rates at factors of 1.003, for emigration rates at a factor of 0.997
Shrinkage	Against the forward projection of the gross domestic product, annual changes are decreased at the rate of 0.904; against the forward projection of the total population, annual changes of demographic variables were modified, for birth rates at factors of 0.997, for immigration rates at factors of 0.996, for emigration rates at a factor of 1.004
Overaging	Birth rates are restricted to one child per couple, births under the maternal age of 15 are restricted and fertility rates are constant over time. The annual immigration change rates within the age groups under 45 years are reduced to 0.85 whereas the difference to the annual population derived in the basic scenario is attributed to the four age groups greater than 45 years in equal parts
Reurbanization	The importance of single preference parameters (derived from the summarized ratio of respective values ranging from 0 to 10) for the housing decisions [Accessibility, Amusement, Cost, Building condition, Security, Education, Green, Tidiness and Noise, Social neighborhood] are shifted from [2,3,8,2,4,2,3,3,2] to [10,8,0,0,0,1,0,0,1] for all household types

2.3 Analysis of contrasting and exceeding urban development

We analyze likely shifts and differences in age groups, household types, residential demand and supply, including residential vacancy and in the development of particular land uses. According to the spatial structure (defined by their density and distance to the city center) all seven residential land uses are assigned to one of the following classes for generalized statements (cf. Figure III-1):

1. Central located dense residential (inner-city block, multi-story row);
2. Intermediate residential (villa, residential park, multi-story prefab); and
3. Decentralized low-density residential uses (detached houses, suburban village).

To uncover the spatial differences in the allocation of land-use change, we used the raster based software Map Comparison Kit (Visser and Nijs, 2006) and analyzed the changes of aggregated built-up and non-built-up areas between the years of 2008 and 2030 contrasting BG and BS.

Exceeding scenarios are analyzed according to their deviation from basic developments. For this purpose, simple differences and relative changes are used with regard to demographics, residential demand and supply, residential vacancies, and LUC. The spatial variation of these scenarios was detected using the spatial distribution of agreement of built-up area (Visser and Nijs, 2006). Beyond that, we contrast kappa values with a variation index which is defined by the summed area of varying patches to the area of identical patches multiplied by 100.

2.4 Urban form indicator

To understand how and to which extent contrasting implications of the population aging and reurbanization trends affect the spatial configuration of the urban to peri-urban region, we applied different urban form indicators. Table III-2 presents and explains the indicators used to make conclusions on specific urban and peri-urban patterns. We used four simple but well-proven residential form indicators to define sprawling, dispersion and concentration; and seven commonly used landscape metrics (cf. Baur et al., 2014; Herold et al., 2005; Zhou et al., 2011) to describe the spatial characteristics of built-up areas, i.e. compactness and fragmentation. Landscape metrics were calculated using the software FRAGSTATS, v.4 (McGarigal et al., 2012). All form indicators were applied to four different spatial dimensions:

1. The entire metropolitan region,
2. The inner city,
3. The outer city, and
4. The periphery (respective boundaries are explained in Figure III-1).

With this subdivision effects become measurable along the urban to peri-urban gradient.

To evaluate the sensitivity of the spatial configuration *S* towards exceeding developments *E* (overageing or reurbanization), we consider the respective model parameters causing human/household decision change *b* and relate it to each urban form indicator *a* in comparison to the basic scenario *B* during the simulation period *t* (2008-2030):

$$S_{a,b} = \frac{a_E^t - a^1}{a_B^t - a^1} \cdot \left(\frac{b_E^t - b^1}{b_B^t - b^1}\right)^{-1} \quad (1)$$

The sensitivity was calculated for the scenarios of urban growth and urban shrinkage.

Table III-2. List of indicators to describe the urban form

Indicator	Description	Calculation	
		Residential form indicators	
Share residential land (SRL)	SRL gives the amount of residential land use for a given spatial unit; SRL > 0.5 indicates a high degree of urbanization	$SRL = \frac{\sum_{r=1}^{7} A_r}{A}$ $0 \leq PRL \leq 1$	
Sprawling index (SI)	SI gives the relation of built-up residential land and non-built-up land for a given spatial unit, SI > 2 indicates a high a large urban sprawl	$SI = \frac{\sum_{r=1}^{7} A_r}{\sum_{g=1}^{5} A_g}$ $DI \geq 0$	A = Total area, A_r = Area of residential land uses r,
Dispersion index (DI)	DI relates the amount of decentralized low-dense residential uses to the total residential area; DI > 0.5 indicates a high rate of dispersion	$DI = \frac{A_4 + A_7}{\sum_{r=1}^{7} A_i}$ $0 \leq SI \leq 1$	A_g= Area of urban green areas g (excluding arable land and pasture), A_4 = Detached family houses,
Concentration index (CI)	CI describes the relation of central dense residential to decentralized low-dense residential area; CI > 0.5 indicates a high residential concentration	$CI = \frac{A_2 + A_6}{A_4 + A_7}$ $CI \geq 0$	A_7 = Suburban villages, A_2 = Innercity block, A_6 = Multi-story row
		Landscape metrics	
Area metrics to indicate growth or shrinkage			
Percentage of Landscape area (PLAND)	PLAND quantifies the percentage amount of a class in the landscape; PLAND close to 100 indicates a dominance of a class, close to 0 a low occurence	$PLAND = \frac{\sum_{j=1}^{n} a_{ij}}{A}(100)$ $0 \leq PLAND \leq 100$	A = Total area, a_{ij} = Area of patch j of class i,
Shape and edge metrics to indicate compactness			
Edge density (ED)	ED determines the total patch length of a class in proportion to the total landscape area; high ED values indicate a high dominance of a class in the landscape	$ED = \frac{\sum_{k=1}^{n} e_{ik}}{A}(10{,}000)$ $ED \geq 0$	
Fractal Dimension Index (FRAC)	FRAC reflects the mean shape complexity of patches from a given class; FRAC apporaching 1 explains simple structures (perimeters) such as squares (indicating a high compactness within a class) wheras FRAC approaching 2 explains more complex shapes (indicating a low compatness)	$FRAC = \frac{2\ln(0.25 p_{ij})}{\ln a_{ij}}$ $1 \leq FRAC \leq 2$	e_{ik} = total length of edge in landscape involving in class i, A = Total area, p_{ij} = Perimeter of patch j of class i,
Contiguity Index (CONTIG)	CONTIG assesses the spatial connectedness (contiguity) of cells within a patch using a moving window to provide an index on patch boundary configuration and thus patche shapes; CONTIG close to 1 indicates a high patch connectedness	$CONTIG = \frac{\left(\frac{\sum_{r=1}^{z} c_{ijr}}{a_{ij}}\right) - 1}{v - 1}$ $0 \leq CONTIG \leq 1$	a_{ij} = Area of patch j of class i, c_{ijr} = Contiguity value for cell r in patch j of class i , v = Sum of the values in a 3-by-3 cell template
Aggregation and subdivision metrics to indicate fragmentation			
Patch density (PD)	PD provides a simple measure of the extent of subdivision or fragmentation within one class; PD approaching 0 idicates a low fragmentation	$PD = \frac{n_i}{A}(10{,}000)(100)$ $PD > 0$	A = Total area, n_i =Number of patches in the landscape of class i,
Mean patch size (MPS)	MPS describes the mean area size of all patches within a class; a high MPS indicates a low rate of fragmentation	$MPS = \frac{\sum_{j=1}^{n} a_{ij}}{n_i}$ $MPS > 0$	a_{ij} = Area of patch j of class, g_{ij} = Number of like adjacencies between cells of patches j of class i (double-count method),
Percentage of like adjacencies (PLADJ)	PLADJ measures the percentage amount of cell adjacencies for patches within one class types; high PLADJ signifies a high aggregation of patches within one class	$PLADJ = \left(\frac{g_{ii}}{\sum_{k=1}^{n} g_{ik}}\right)(100)$ $0 \leq PLADJ \leq 100$	g_{ik} =Number of adjacencies between cells of patches j of class i and k (double-count method)

3 Results

3.1 Contrasting urban development (growth versus shrinkage)

In the following section we present the scenario results of the contrasting developments of basic growth (BG) and shrinkage (BS).

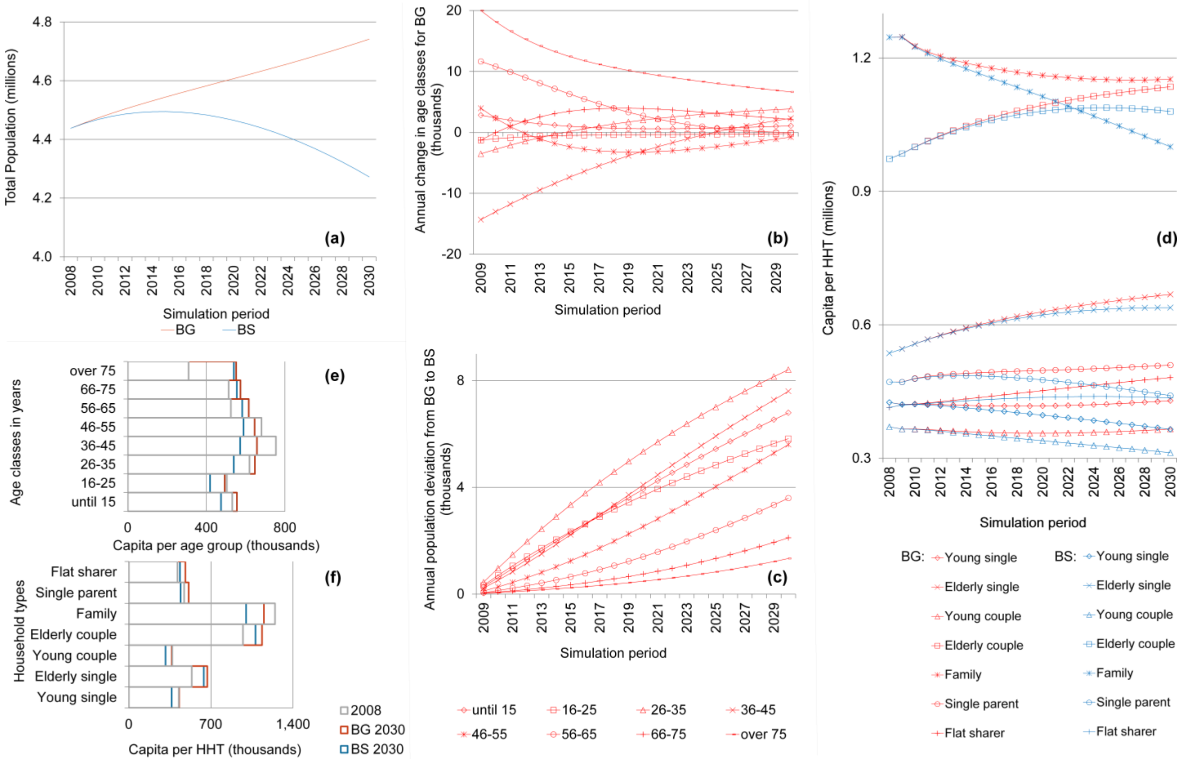

Figure III-3. Population developments between 2008 and 2030 for BG and BS; (a) total population, (b) population in age classes for BG, (c) population deviation between BG and BS, (d) population development in household types, (e) population distribution change within age classes and (f) change in capita per HHT between 2008 and 2030

Figure III-3 shows a linear growth of over 300,000 people between 2008 and 2030 for BG and a decline of 160,000 for BS, after an initial phase of growth. Figure III-3b reveals for BG that elderly people increase and younger people decrease, both with decreasing tendencies, which looks similar for BS, but with a weaker dynamic and resulting in an increasing population deviation especially in younger age classes (compared to BG) of up to 8,000 people in 2030 (Figure III-3c). Figure III-3e shows for both scenarios a decline in the middle age classes and an increase in the population over the age of 55, but contrary developments under the age of 35. The share of the population aged 65 and over changed from 18.5 % to 23.7% (BG) and 25.6% (BS) with an increase of the oldest (older than 75) at a factor of 1.8 (for BG and 1.7 for BS). This trend of population aging was also evident in the development of HHTs.

The share of elderly single and couple households increased by 4.0% (BG) and 6.2% (BS) whereas the share of younger people in small households (≤ 2 persons) decreased by 1.1% (BG) and 2.1% (BS). Moreover, we observed a distinctive decline in the amount of people in family households, from 28.1% to 24.3% (BG) and 23.4% (BS), (cf. Figure III-3d,f).

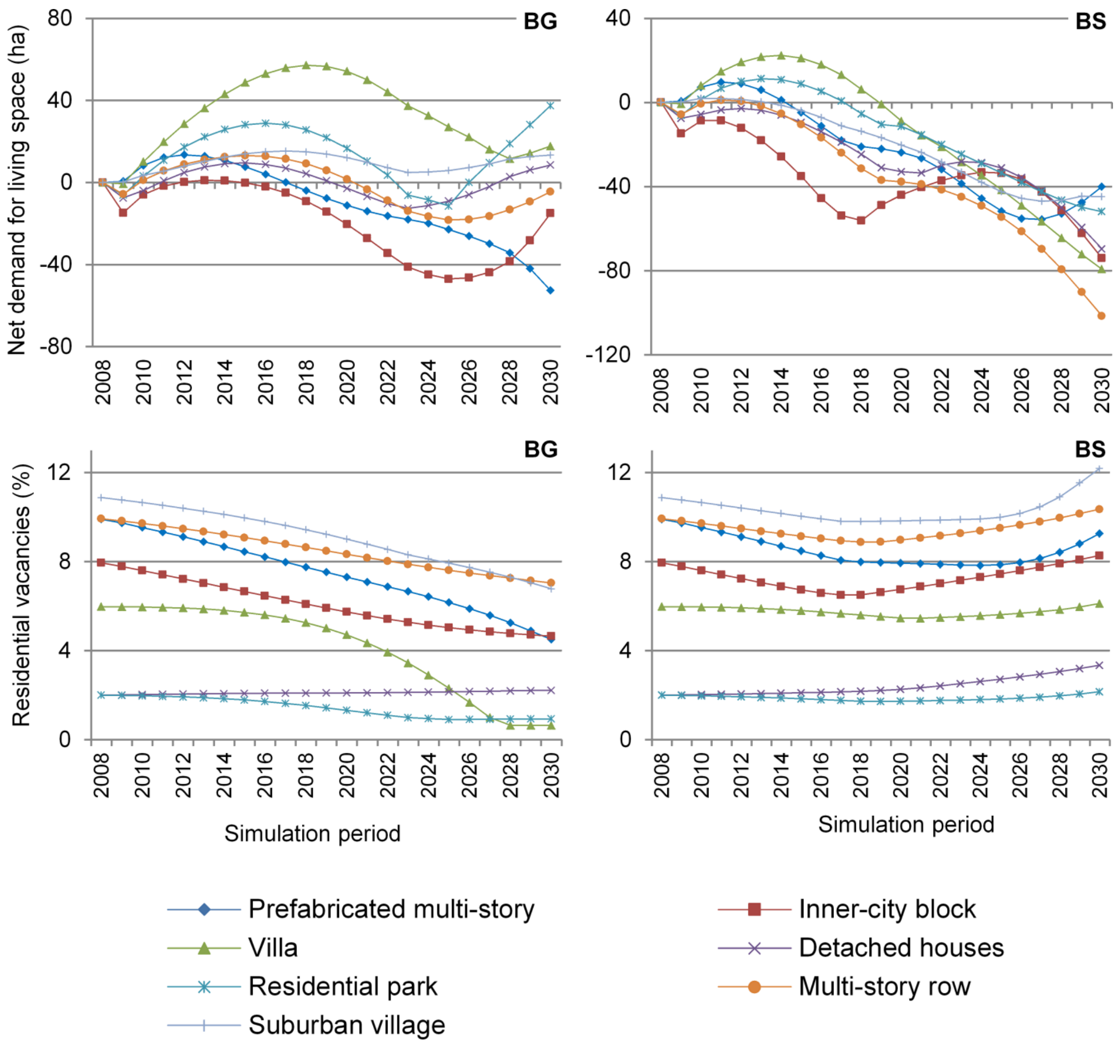

Figure III-4. Development of net demand for living space (above), showing the demand and supply relations with values >0 indicating undersupply (demand surplus) and values <0 indicating oversupply; and the resulting residential vacancy (below) between 2008 and 2030 comparing BG and BS

The relative demand distributions revealed that for all HHT, except for young singles, prefabricated multi-story housing is the least preferred residential structure with less than 10% (location attractiveness). Singles, couples and flat sharers prefer inner-city blocks with up to over 30%. Families and to a lower extent single parents express high residential preferences for detached housing, residential parks and villas, followed by couple households and elderly singles.

During the simulation period these preference distributions are almost homogenous except for two minor dynamics, identically occurring for all HHTs: the demand decline in prefabricated multi-story houses and the increase in the demand for residential parks (app. III-A, Figure A-IIIa-1). Preference distributions for BG and BS were almost equal with only a slightly higher preference for residential parks and a lower one for detached houses in all HHT for BG.

The final living space demands per hectare resulted from preference and HHT demander shifts. Figure III-4 presents the net demand shifts comparing BG and BS, indicating similar initial trends for different residential structures with, e.g. unsatisfied demand for villas and residential parks. For BG an oscillating demand-supply relation is given whereas for BS an oversupply originates from all residential types after a small period of demand surplus, which results in increasing residential vacancies (cf. Figure III-4).

Figure III-5 shows that the increase in living space of detached houses is accompanied with enormous land consumption, whereas the highest living space increase in inner-city blocks (under growth conditions) is causing marginal land consumption due to respective floor-space densities. Detached housing was the fastest growing land use for BG and the second fastest for BS which predominantly developed on arable land resulting in the highest land loss in this class (cf. app. III, Figure A-IIIa-2). Residential land uses evolved similarly, being more distinctive for BG in the case of increase and more distinctive for BS in the case of decline. Other built-up uses, except for the airport use, show contrasting developments. Non-built-up uses altered similarly, with lower land loss in BS, and a higher increase in the only positive shifting land use, artificial urban green spaces.

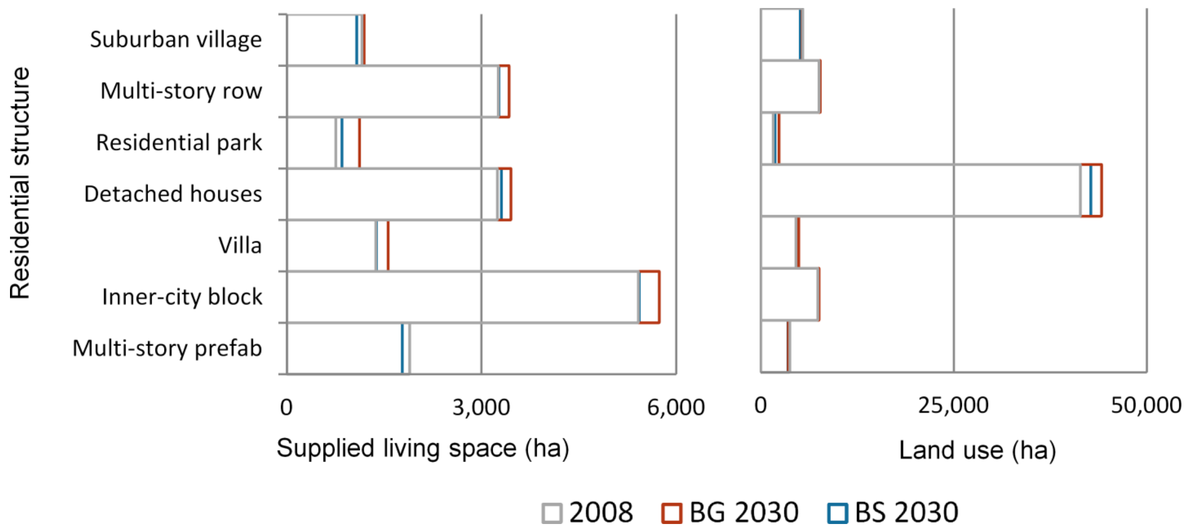

Figure III-5. Comparison of living space supply with resulting land use extent between 2008 and 2030

LUC effects of both scenarios regarding the spatial configuration are contrasted in Figure III-6. Identical developments for BG and BS were obtained, such as for the new Berlin Brandenburg International Airport (BBI) in the southeast (1), new central located built-up areas including sites of the former airport Tempelhof (2), new non-built-up areas (i.e. urban green spaces) at the airport Tegel (3) (closing with the opening of BBI) as well as the increase of decentralized low-density built-up areas along existing urban structures. While BS showed a reversal in built-up area development after a period of increase, built-up areas are continually increased for BG with increasing intensity from the inner city to the periphery. In contrast, for BS non-built-up areas emerged to a larger extent in the outer city and the periphery.

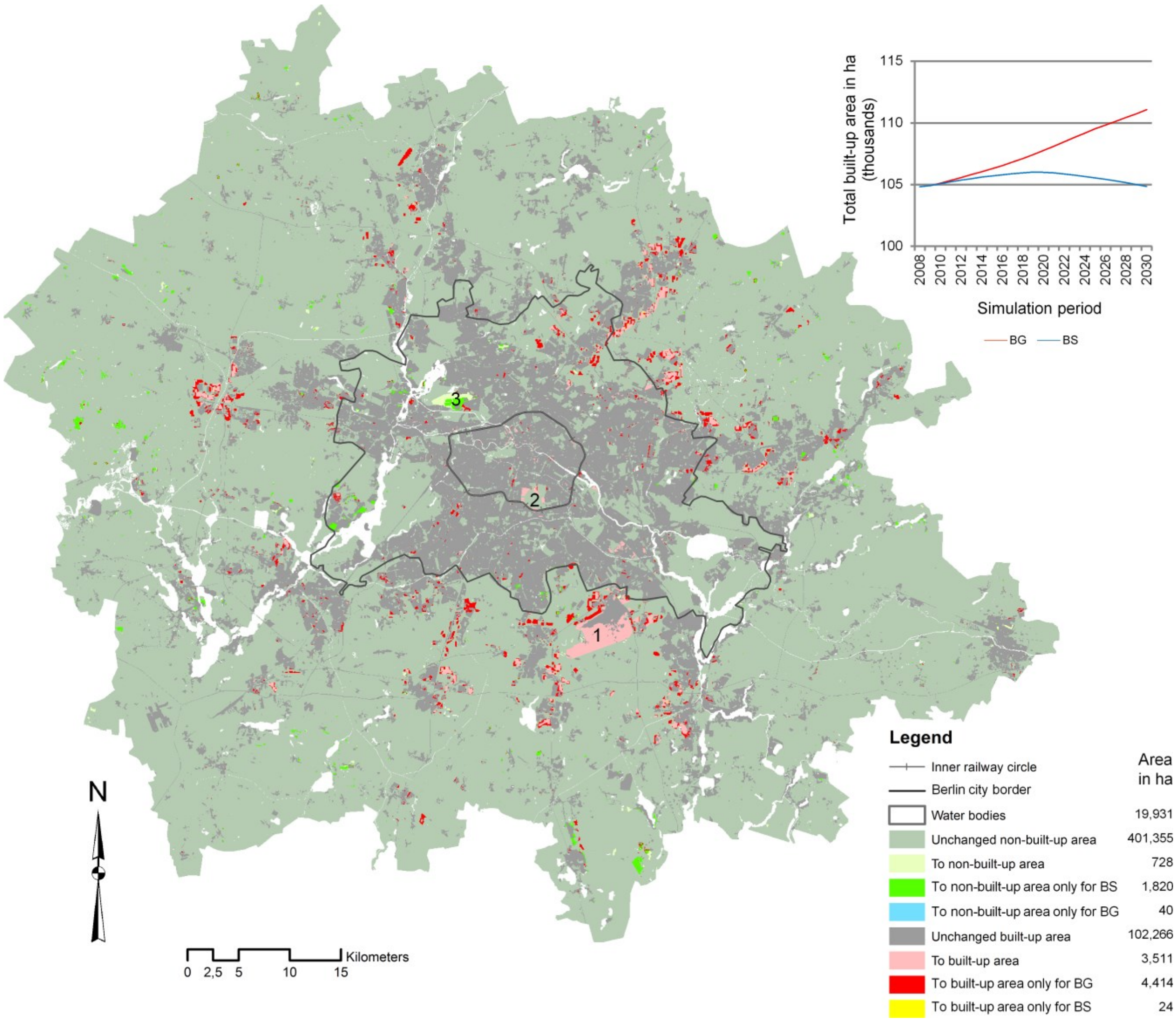

Figure III-6. Map of changes regarding built-up area and non-built-up area between 2008 and 2030, comparing BG and BS and its underlying dynamics (upper right); (1) Airport Berlin Brandenburg International (BBI), (2) Former airport Tempelhof, (3) Airport Tegel

3.2 Exceeding urban developments (overaging and reurbanization)

The overaging scenarios are characterized by a clear demander shift towards elderly people living in smaller households (at a rate of about 1.8) related to a loss of small households of young people and family households (at rates of about 0.3 for BG and 0.5 for BS), (cf. Figure III-7a). The reurbanization scenarios are characterized by a distinctive demand increase for inner-city blocks (at a mean rate of about 2.0) and a demand decrease of decentralized low-density residential land uses (at a mean rate of about 0.5), (cf. Figure III-7b).

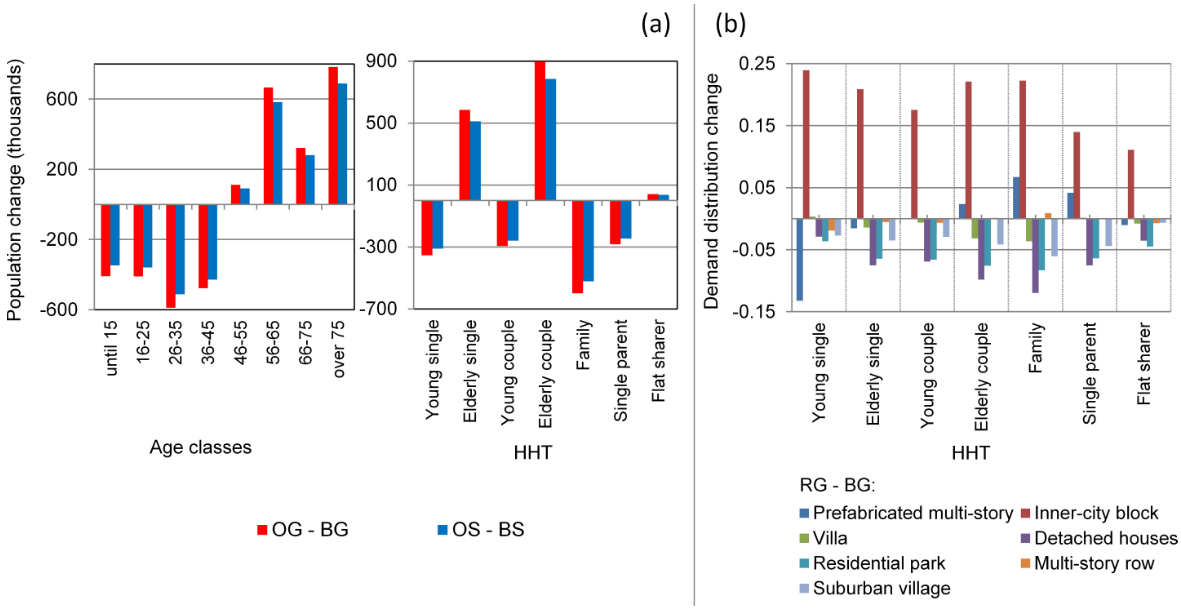

Figure III-7. Driver changes for exceeding scenarios (overaging and reurbanization); (a) change in demography between basic and overaging scenarios in 2030, (b) change in the HHT demand distributions across different residential land uses between basic and reurbanization scenarios in 2030 (almost equal for growth and shrinkage scenarios)

The resulting effects on demand-supply relations are shown in Figure III-8 and reveal very dynamic change patterns of undersupply from central located dense residential uses, to intermediate residential uses in the case of overaging (more evident for growth). Reurbanization scenarios revealed more steady changes with a long lasting undersupply in inner-city blocks and prefabricated multi-story housing, and simultaneous oversupply in detached houses and residential parks for growth; except for increasing oversupply in inner-city blocks starting in 2019 and reaching 2.1% in 2030, the curves look similar.

Vacancy rates showed inverse trends with increasing rates in case of oversupply (and decreasing rates in case of demand surplus). Accordingly, declining vacancy rates of inner-city blocks were more obvious for RG than for OG. Also noticeable were the higher vacancy increase in residential parks and the slight increase in detached houses for reurbanization scenarios. In total, residential vacancy decline was more pronounced in overaging scenarios (cf. app. III-B, Figure A-IIIb-1).

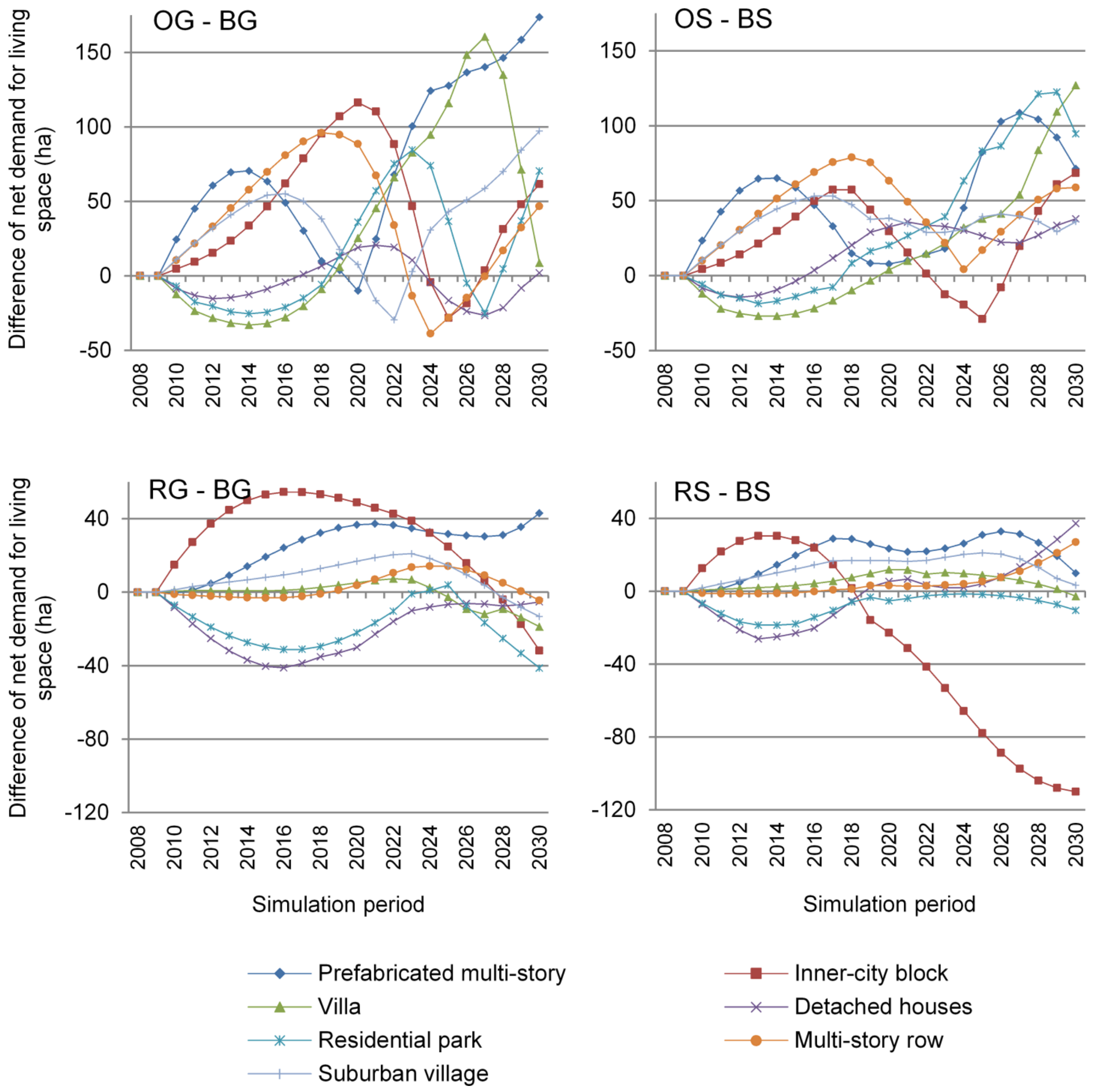

Figure III-8. Net demand shifts for living space comparing contrasting and exceeding development trends between 2008 and 2030 (above: overaging scenarios, below: reurbanization scenarios; values > 0 express higher demand surplus, values < 0 express higher oversupply

Table III-3 shows to which extent LUC was affected by the exceeding scenario implications. Clear and consistent differences regarding the transformation of non-built-up area occurred. Increasing residential land uses expressed higher change rates (except for detached houses in OG) and all declining ones expressed lower rates for overaging scenarios. Under reurbanization only three of five residential uses (mainly those being centrally located and of dense structure) showed higher rates of increase whereas the two decreasing residential uses provided lower rates. Change rates are mostly more distinctive for overaging compared to reurbanization.

Table III-3. Rates of varying land-use change of exceeding and basic scenarios; rates are based on the differences of land use extent between 2008 and 2030 (missing classes indicate no change)

Land uses	Basic trend	Growth scenarios		Shrinkage scenarios	
		OG vs. BG	RG vs. BG	OS vs. BS	RS vs. BS
Arable land	↘	1.19	0.63	1.23	0.70
Pasture	↘	1.25	1.19	0.42	0.80
Shrubs and trees	↘	1.07	1.13	0.74	1.19
Forest	↘	0.81	1.50	0.50	1.17
Open space	↘	1.09	1.02	0.56	0.95
Artificial urban green	↗	0.96	1.08	0.51	0.88
Urban brownfields	↘	1.63	0.52	10.84	-0.13
Prefabricated multi-story	↘	0.28	0.57	0.34	0.70
Inner-city block	↗	1.30	1.75	2.84	1.36
Villa	↗	4.40	1.07	1.08	1.25
Detached houses	↗	0.94	0.39	1.69	0.51
Residential park	↗	1.57	0.38	3.39	0.36
Multi-story row	↗	1.52	1.02	3.32	1.07
Suburban village	↘	0.12	0.44	0.06	0.64

Residential land use compositions showed that the percentage amount of central located dense residential uses decreased in the basic and even more in the overaging scenarios and increased in the reurbanization scenarios (with higher intensity for RG), (cf. app. III-B, Figure A-IIIb-2). The percentage amount of intermediate residential uses increased in all scenarios of urban growth and overaging with the highest rate in OG. Decentralized low-density residential uses achieved a relative increase under urban shrinkage with a drop in OS towards the end of the simulation. A rapid decline for OG was determined according to the model assumptions.

Figure III-9 presents the spatial and quantitative variations of exceeding compared to basic developments after the simulation run of 22 years, indicating a higher deviation of reurbanization under growth and a higher deviation of overaging under shrinkage (cf. app. III-B, Figure A-IIIb-3).

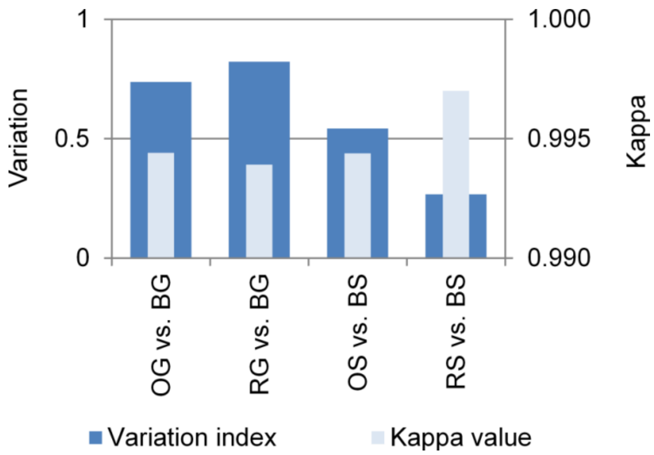

Figure III-9. Spatial variations of built-up area in 2030 for different scenario combinations using Cohen's kappa (high values indicate a high consistence) and the variation index (low values indicate a high consistence)

3.3 Changes in the urban form

The scenario-based effects on residential form parameters and landscape metrics are contrasted in Figure III-10. The simulated spatial differences are presented in app. III-B (Figure A-IIIb-3) to assist the interpretation of the results. In some cases indicators did not (or did only slightly) respond to varying scenario implications and/or spatial subdivisions; i.e. all residential form indicators and PD for the inner city and FRAC for the outer city. In some cases indicators did not respond to the exceeding scenarios but to growth versus shrinkage scenarios, i.e. PLAND, ED, FRAC, PLADJ for the inner city, or PD and PLADJ for the outer city, or PLADJ for the study area. Contrary to the inner city, indicator trends varied markedly for the periphery with a strong influence on indicator trends for the entire urban to peri-urban region.

The inner-city was characterized by a consistent growth of built-up area (more evident for growth) with progressing concentration and compactness and lowering dispersion (for shrinkage) with declining fragmentation. The outer city indicated an increase of built-up area for growth and a decline for shrinkage despite the consistent growth of residential land, which was expressed more strongly for overaging scenarios, resulting in higher residential concentration and lower dispersion. Built-up structures proved to be more fragmented under growth and less fragmented under shrinkage and more compact in both. The periphery was characterized by an increase of built-up area especially for growth and overaging with an increase in residential uses. Residential dispersion declined for growth and reurbanization scenarios and especially for OG. Residential concentration only increased for RG. Compactness in built-up structures increased in all scenarios, except for OG, and was more distinctive under shrinkage, while fragmentation declined (cf. Figure III-10).

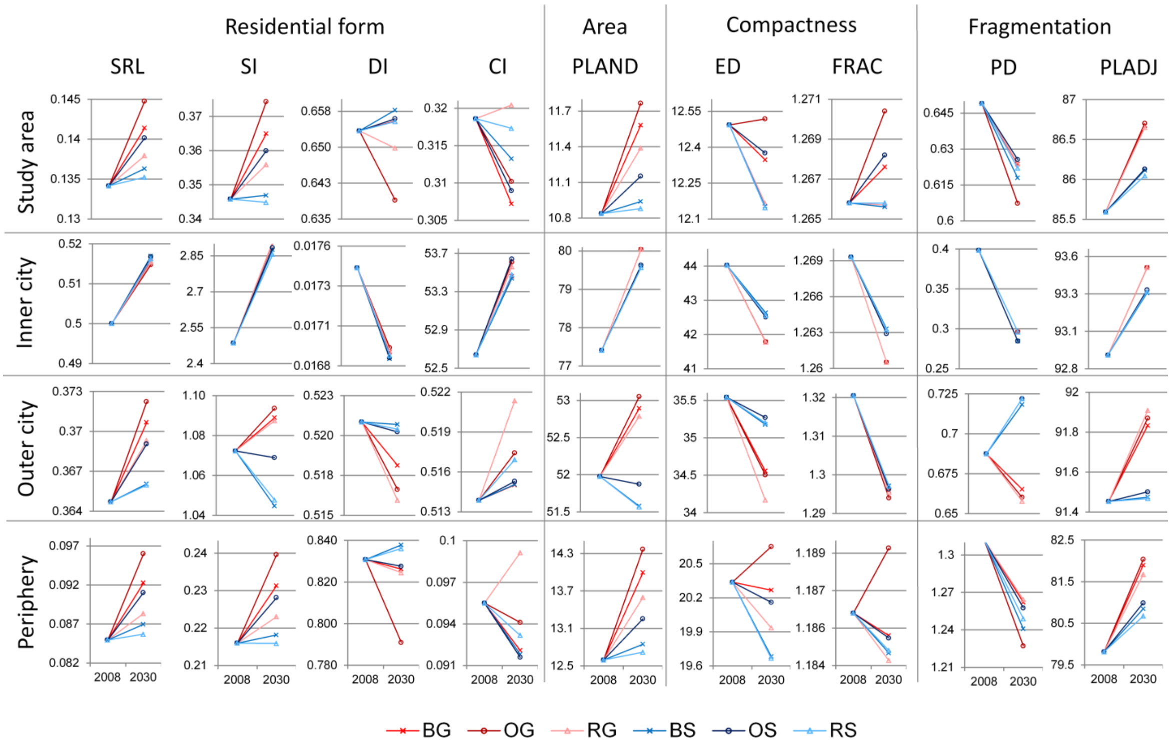

Figure III-10. The change of urban form parameters and landscape metrics between 2008 and 2030 comparing different scenarios for the region and along the urban to peri-urban gradient; SRL (share residential land), SI (sprawling index), DI (dispersion index), CI (concentration index), PLAND (percentage of landscape area), ED (edge density), FRAC (fractal dimension index), PD (patch density), PLADJ (percentage of like adjacencies)

The effectiveness of relevant scenario drivers (within exceeding scenarios) towards change in land-use patterns is shown in Figure III-11. Half of the indicators were particularly sensitive towards overaging drivers under conditions of urban shrinkage, i.e SI, SRL and PLAND. We detected that the increase of elderly and especially single households effectively increases the amount of residential land (SRL) and the rate of built-up area (PLAND). Values of 0.5 indicate a halved proportional increase.

For OG, the fragmentation (PD) within built-up structures was reversely sensitive towards the increase of elderly and single households, accompanied with a significant reduction effectiveness of residential dispersion (DI). For OS, the increase of elderly and single households was significantly and effectively increasing residential sprawling (SI). The increase of family households provided reverse effects; under shrinkage the increase of only 1% in family households decreases the sprawling rate by almost 3.4%.

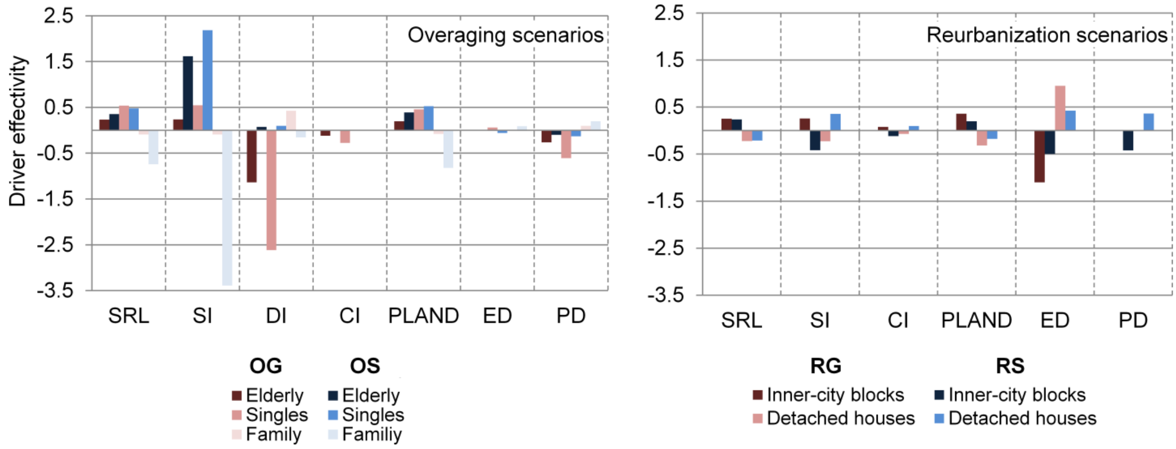

Figure III-11. Sensitivity of urban form indicators towards changing decision drivers, i.e. household shifts for overaging and preference shifts for reurbanization (missing indicators indicate a negligible deviation to the basic scenarios of less than 0.1%); bars indicate the multiplier of relative change and the direction of change; cf. app. III-C (Table A-IIIc-1)

For the reurbanization scenarios, two contrarily effective drivers revealing the specific residential preference shift were tested. For three indicators the effects followed the expectation and were similar with slightly higher impact in case of growth (SRL, PLAND, ED). Exceeded reurbanization showed to be highly effective towards increasing the compactness within built-up structures, especially under growth (ED). Results revealed that the sprawling intensity (SI) of built-up areas is reduced through reurbanization only under shrinkage despite relatively low effects on residential concentration (CI). Effects on fragmentation (PD) were only substantial for urban shrinkage. Table A-IIIc-1 in app. III presents the sensitivities of urban form indicators along the urban to peri-urban gradient.

4 Discussion

The obtained results are discussed along the study objectives.

1. Implementing recent and future urban development trends such as shrinkage, growth, population aging and reurbanization into spatially explicit urban modeling

This attempt was achieved by applying a spatially explicit land-use model which combines system dynamics and cellular automaton through the inclusion of population dynamics, household residential choice behavior and spatial constraints (Lauf et al., 2012a; Lauf et al., 2012b; cf. sect. 2.2). The model enabled the integration of contrasting trends of population growth versus shrinkage (basic scenarios) providing non-linear projections. Beyond that, we also showed that exceeding trends (either aspatial or socio-spatial) of population aging or reurbanization can be implemented, processed and evaluated. In total, six scenarios were tested comparatively.

Compared to other model approaches, only focusing on spatial analytic GIS methods, such as the SLEUTH model, which uses spatial statistical growth coefficients derived from historical LUC (cf. Heinsch et al., 2012), the advantages of the applied model are: (1) the high demographic dynamics and the use of characteristic household types (e.g. defined by age and size) to simulate population aging and HHT shifts; (2) the integration of residential choice and demand-supply algorithms to simulate growth and shrinkage processes in different residential land uses simultaneously, which allows for explanatory processes such as reurbanization and suburbanization; and (3) the spatial allocation of typical local residential land-use types characterized by their form, structure and density to evaluate changes in the urban pattern.

These components may help to support decision making for urban planners as they reveal causally explicable LUC and consequent spatial configurations along an urban to peri-urban gradient (Rutledge et al., 2008; Tavares et al., 2012; Van Delden and Hagen-Zanker, 2009), which is discussed in the following paragraphs. To derive additional information on exact household distribution patterns within varying neighborhoods, which was not addressed in this paper, ABM approaches seem promising (Batty, 2007). They would allow for testing segregation processes of elderly people connected to disadvantaged accessibilities to environmental or economic goods and services, in order to promote fair-minded urban development planning (Feitosa et al., 2011; Gaube and Remesch, 2013). A disadvantage of ABM approaches is, however, the strong dependency on valuable behavioral data (Filatova et al., 2013).

The model showed to be very sensitive towards demographic assumptions (e.g. fertility and immigration rates) and initial housing variables (e.g. demolition or new construction rates). The complexity of the residential decision algorithm revealed some uncertainties in terms of feedback control and thus need further testing. The large number of different data (cf. Figure III-2) required for the model calibration could be seen as a disadvantage in terms of transferability.

2. Analyzing and evaluating contrasting population and household development and shifts

The two scenarios, growth and shrinkage, provided contrasting population developments with an increase of 6.7% (growth) and a decline of 3.6% (shrinkage) until 2030, following the expected maximum range of the local authorities (SDUDEB and SOBB, 2009). The biggest disparities occurred in the younger age groups (≤ 45 years) with partly contrary developments. In the case of shrinkage the decrease in net migration and fertility rates accelerated population decline, confirmed by the nonlinear course (Figure III-3a). The amount of elderly people notably increased in only 22 years, being more pronounced under population decline. The share of people over the retirement age (> 65 years) increased by 5.2 to 7.1% (growth/shrinkage). In contrast, the loss of people in the employable age (26-65 years) declined equally by about 4%. The development of household types revealed a continuous decline in traditional family households against the increase of small (and elderly) households (> 45 years) proceeding more rapidly under population shrinkage.

These developments observed across the whole of Europe imply considerable consequences in the social and economic systems especially when occurring along with population decline (Davoudi et al., 2010; Haase et al., 2013). Increasing pensions with decreasing (wage) tax income create a financial burden that might affect welfare (Rechel et al., 2013; Tinker, 2002). Besides age-related diseases, the increasing vulnerability towards urban environmental stressors such as pollution or heat, which are showing additionally tendencies towards increasing due to climate change, will multiply future demand in and costs for medical care (Basu and Malig, 2011; Namdeo et al., 2011). Finally, elderly people gain power in societal and economic decision-making which might raise conflicts in the case of social segregation. Among others, these forthcoming challenges require changes in thinking, e.g. in terms of immigration policies, health prevention and efficiency in health systems, retirements and the integration of the elderly in labor markets and not least in terms of general social participation of the elderly (Długosz, 2011; Heijdra and Romp, 2009).

3. Assessing the effects on residential choice, related land consumption and loss of open land and vice versa in combination with exceeding trends of population aging and reurbanization

Land consumption and LUC in urban regions are predominantly related to residential land use (in our study 54-61%) caused by household or preference shifts. Relatively constant residential preferences under growth and shrinkage conditions (app. III-A, Figure A-IIIa-1), confirmed known and well-established trends, such as: singles, couples and flat sharers preferring central living and families preferring intermediate to decentralized living (Brade et al., 2009; Buzar et al., 2007). The increasing rejection of multi-story prefab is consistent with social studies in which they are perceived negatively (Brade et al., 2009; Kabisch, 2005). In contrast, residential parks (a modern urban structure) became increasingly important.

The increase of small (mostly elderly) households with higher rates of per capita living space with a simultaneous decline of family households resulted in increased living space demand which is consistent with other case studies (e.g. Haase et al., 2013). This led to an initial phase of undersupply even under population shrinkage. The subsequent oversupply resulted in rising residential vacancies; in central located residential uses especially due to the decline of younger households, in villas, suburban villages and in detached houses especially due to the decline of family households (cf. Figure III-3; app. III-A, Figure A-IIIa-1). Residential vacancies deteriorate the perception and accelerate the emptying process which reduces prices and eventually promotes social disintegration and segregation leading to deprived neighborhoods, and thus, can be considered as the beginning of a downward spiral which requires the immediate actions of urban planners (Couch et al., 2005; Haase et al., 2013; Kabisch, 2005).

Under growth conditions, altered living space supply demonstrated a parallel process of suburbanization and reurbanization with higher annual increase in central living space (although with decreasing tendency), which is currently observed in other urban regions, especially in Eastern Europe (Brade et al., 2009; Brake and Herfert, 2012). Reurbanization processes in Berlin are due to its international popularity, currently fostered by its cultural rather than economical functions in combination with low living cost (Brake and Herfert, 2012). But the associated increasing housing costs (especially in the inner city) might lead to equilibrium and slowing of this process in the future. The highest living space increase, however, took place in intermediate residential uses.

Differences in structure and density of residential uses result in varied land consumption (Figure III-5), which for detached housing showed to be 9.4 times higher than for inner-city blocks; affecting LUC to a great measure. The total built-up area increased linearly by almost 7%, following the linear increase of the total population, transforming 2.3% non-built-up areas with over 67% of arable land (mainly due to new detached housing), followed by pasture, forests, shrubs and trees and urban brownfields. Under shrinkage similar trends were observed for the first 10 years, before depopulation and decline took over with the lowest effects in intermediate residential uses. Interestingly, built-up areas did not decline under the initial state (+0.9%), unlike the population development (-3.7%) due to the cushioning effect of observed household shifts. The lower transformation of non-built-up (1.1%) and the stronger increase of artificial urban green areas indicate an improvement in terms of ecosystem services and thus might reduce the expected vulnerability increase of urban dwellers due to the increase of elderly people (Harlan et al., 2006; Lauf et al., 2014).

Under exceeding population aging, mainly moderate residential preference shifts of under 2% towards central/intermediate living were achieved, confirming studies of age related residential preferences (Rosenberg and Everitt, 2001; Temelová and Dvořáková, 2012); beyond that striking shifts towards multi-story prefab housing could be revealed. Kabisch and Grossmann (2013) showed that residential satisfaction in formerly rejected multi-story prefab housing increased with the proportional increase of elderly people, not least because of the comparatively low renting costs (cf. Figure III-2). All residential uses increased in extent (except for detached houses under growth conditions) with a considerable gain in intermediate residential uses that predominantly occurred in the outer city.

Exceeding reurbanization resulted in an assumed preference increase for central located residential uses (with up to 24%). The initially growing undersupply of inner-city blocks was satisfied, and declined until oversupply was reached, which in case of shrinkage proceeded rapidly. Also multi-story prefab housing gained in importance. The demand decline in residential parks and especially detached family houses resulted in a reduction of built-up areas -1.7% (growth) and -0.6% (shrinkage) resulting in lower land consumption, especially of arable land and respective shortening of walking/travel distances. Unfortunately, we observed a higher loss of forest, which provides several ecosystem services supporting human wellbeing at local scale, and becomes crucial in view of population aging (Lauf et al., 2014).

4. Determining the spatial effects of different development scenarios and the effectivity due to shifts in households and household decisions along the urban to peri-urban gradient

The spatial distribution of LUC was integrated as a function of neighborhood-related transition rules, accessibility and prescriptive urban planning. Accordingly, similar transformation patterns occurred for all scenarios, such as the airport developments and the city sprawling along existing urban structures. We ascertained that new built-up area occurs with increasing intensity towards the periphery. Also the opposite development from built-up to non-built-up areas, especially under conditions of shrinkage, showed higher rates with increasing distance to the city center, following a shrinking pattern towards the periphery (cf. Figure III-6). The comparative scenario analysis revealed that shifts in elderly people are having a stronger spatial effect under conditions of shrinkage (higher sprawling rate), whereas preference shifts towards reurbanization are having stronger spatial effects under conditions of growth, as is explained hereinafter.

The use of exceeding scenarios of population aging (associated with the increase of small households) revealed a higher increase of residential built-up areas in the region, especially under shrinkage conditions, resulting in less compact urban structure. Under growth conditions a less fragmented urban structure was observed with a slight shift towards residential concentration (in the outer city and the periphery) due to the substitution of low-density by intermediate residential uses. Exceeding population aging under shrinkage conditions resulted in a less concentrated and more fragmented urban structure (especially in the periphery) which is problematic in terms of infrastructural cost balancing (population and income decline at increasing infrastructural costs) and has to be considered critically (Deal and Schunk, 2004; Travisi et al., 2010).

Exceeding reurbanization resulted in sprawling reduction of residential built-up areas in the outer city and the periphery with a significant concentration increase in dense residential uses, associated with a clear reduction of residential dispersion. As a consequence, urban compactness increased significantly which resulted in a more fragmented structure in the periphery, but a lower one in the outer city, especially under population growth.

We showed that the urban form and structure showed to be sensitive towards demographic transitions and preference shifts in different ways and intensities, additionally depending on the population development (either growing or shrinking) with varying characteristics along the urban to peri-urban (Figure III-11; app. III-C, Table A-IIIc-1). The extenuating effect of decreasing family households under population decline effectively reduces urban shrinkage, or inversely, the increase of family households can effectively reduce land consumption (under current housing prefernces, due to the reduced per capita space consumption). Under growth conditions, residential dispersion (by detached housing) can be reduced by the increase of elderly people. Compactness was almost insensitive towards demographic transitions. Increasing single households under population growth are slightly senstive towards fragmentation reduction. Residential preference shifts (towards reurbanization) turned out to be less effective in influencing the urban form, which was proven by sensitivity values mainly under 0.5. Only compactness revealed a noticable sensitivity, confirming that reurbanization is asociated with increasing compactness (e.g. Rae, 2013). Our results provide a contextualized an sytemic understanding on the reltion of current urban processes drivers and the effectivity to influence the spatial configuration and the direction where to influence it. This might indicate at which point an unintended development should be more strongly influenced by planning, e.g. the higher relative rate of land consumption and sprawling despite population decline, related to more infrastructural costs, together with the increase of elderly people, might raise financial conflicts and should be realized and counteracted in due time.

Among all scenarios, the highest diversity comparing the urban form indicator changes (between 2008 and 2030) was obtained for the outer city (Figure III-10), although only the fragmentation indicator PD is significantly sensitive (in varying degrees) towards scenario driver changes. The outer city can be considered to be the connector of the urban to peri-urban region buffering contrary urban development directions, which in the case of growth and reurbanization is the location of densification, and in the case of shrinkage and suburbanization is the location of dispersion (Ravetz et al., 2013; Wiechmann and Pallagst, 2012). The outer city was revealed to of high residential attractiveness for the elderly and is characterized, firstly, by a full provision of relevant urban functions within a polycentric structure (Gornig and Häussermann, 2002); secondly, by a higher rate of green space provision; and thirdly, a lower environmental burden compared to the inner-city (Lauf et al., 2014), meeting the needs of elderly people (Rosenberg and Everitt, 2001). However, the consequent increment of built-up area (for overaging compared to the basic development) of 1.6% (growth) and 1.9% (shrinkage), causing higher loss of non-built-up land has to be seen critically, even though less ecological valuable forests were transformed. The general observed higher urban transformation and urban form sensitivities in the periphery is due to the high LUC intensity of detached houses (Figure III-5) and the realization of intermediate residential uses (app. III-B, Figure A-IIIb-2) as urbanization of the inner and outer city is broadly completed, which offers lower development potential.

In this context, the European and German directives of favoring the compact compared to the dispersed urban development should be revisited, not only considering the direct economic benefits of the compact city (i.e. due to infrastructural costs), but also keeping in mind ecosystem service provision, ecological function and environmental load which are strongly influenced by the urban form in combination with city dwellers' residential decisions and their vulnerbility towards probable future risks (e.g. heat stress risk), especially with regard to population aging, which eventually results in additional (health related) costs (Martins, 2012; Symes, 1997).

5 Conclusion

The study uncovered the relationship of human decision, residential choice, land use change and urban patterns in the light of current aspatial and sociospatial urban processes driven by demographic and preference shifts, i.e. population aging, urban growth and shrinkage, and reurbanization (vs. suburbanization). For this purpose, we tested six plausible scenarios under contrasting (growth and shrinkage) scenarios combined with exceeding (population aging and reurbanization) development assumptions using a model combination of system dynamics and cellular automaton. The model simulation results revealed strong and dynamic cause and effect relationships that are suitable to uncover the decision-making of urban dwellers under various conditions and to determine consequent effects on LUC and urban patterns which in turn imply specific requirements for infrastructure provisioning and energy consumption costs, as well as for ecological functioning and urban ecosystem services.

One of the major challenges of future urban development was confirmed to be population aging, which under conditions of population decline accelerates. The ensuing risks of increasing city dwellers' vulnerability, societal costs, changing residential needs and social and spatial segregation have to be addressed and highlight the need for international immigration and the encouragement of younger households to stay through family-friendly policies linked to an economical perspective in the region. The support of integrated housing projects seems promising to strengthen societal cohesion, providing additional synergies for elderly and family households (e.g. childcare engagement). We showed that population aging implies a higher rate of additional land consumption under conditions of shrinkage, whereas preference shifts towards reurbanization revealed higher potentials for saving land under conditions of growth. We proved that urban sprawling and dispersion are especially sensitive towards demographic shifts of population aging, whereas urban compactness is especially sensitive towards preference shifts of central living. The outer city with its predominate intermediate residential uses showed to be very important for urban development as a buffer zone, playing a notable role for the increasing elderly population in satisfying their residential preferences.

The complex interactions of scenario inputs and outputs revealed that despite population aging associated with development trends towards the city, suburbanization proceeds, implying the highest land consumption; whereas reurbanization supported by an increase in the elderly leads to significantly reduced land consumption, increasing compactness, but also a higher loss of forest which could be evaluated negatively in view of increasing vulnerability of urban dwellers towards environmental risks. In contrast, land consumption in the periphery from arable land to detached housing might only affect ecosystem services moderately and provide better living conditions in terms of future urban health related risks (Lauf et al., 2014). This aspect needs to be further researched. The consequence of reurbanization when broadly occurring leads to increasing housing prices and is frequently associated with gentrification and the displacement of poorer elderly people towards the periphery resulting in spatial and social exclusion. Thus, the directions and directives of urban development have to be considered carefully in terms of the European ideal of the compact city and reconsidered in terms of population aging.

We discovered that under conditions of shrinkage, an increase of green spaces that provide varying supporting functions for human wellbeing might be a potential improvement in terms of elderly people and vulnerability increase. Thus, a changed concept of shrinkage should consider and relate ecologic and economic trade-offs.

Acknowledgements

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The supplementary material offers further information and results.

Chapter IV:

Ecosystem service assessment under conditions of growth and shrinkage

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Abstract

Urban regions face transitions in land use that affect ecosystem services (ES) and thus human wellbeing. Especially in urban regions with high population densities and high demand for ES, the future availability of such services must be considered to promote effective and sustainable decision-making and prevent further ecosystem degradation. With a combined model approach focusing on household decisions regarding the choice of residence, future urban land-use development was simulated for metropolitan Berlin, Germany for growth and shrinkage scenarios. We simulate the change in six provisioning, regulating, and cultural ES indicators for both scenarios from 2008 to 2030. We compare regional alterations in ES, ES synergies and trade-offs by merging them into an assessment matrix for each land-use transition. Our results indicate that the land-use transitions that most significantly affect ES degradation or improvement are those from arable land to mainly non-residential uses—especially public and private services. The results show that most changes in land use are related to land consumption and soil sealing; however, as urban brownfields provide excellent opportunities for the development of new urban green spaces with superior ES qualities, the shrinkage scenario ended up being very positive in terms of ES improvement.

1 Introduction

The broadly accepted anthropocentric concept of ecosystem services (ES), defined as benefits to human wellbeing from ecosystems, has become popular as a tool to raise awareness of both globally given natural capital, as the basis of the human existence; and continuously progressing ecosystem degradation (MA, 2005; Seppelt et al., 2012; TEEB, 2011). Major effects derive not only from human activities such as land-use transitions and soil sealing, but also from energy and material flows. Moreover, natural disasters and global change, especially climate change, contribute to ecosystem degradation. Both human activities and global climate change might accelerate the process of degradation via underlying interactions (MA, 2005).

In the future, an increasing number of people will face ES loss as the urban population and associated human activities increase exponentially (Bolund and Hunhammar, 1999; Douglas, 2012). As a consequence, regional and local ES decrease while the demand for ES increases (CBO, 2013). Thus, urban living conditions might continuously worsen if no mitigation strategies are implemented; therefore urban and demand-driven ES approaches are needed (Burkhard et al., 2012; Douglas, 2012). Research conducted in the last decade confirms that ES approaches are increasingly important for communication and decision-making (Bolund and Hunhammar, 1999; Daily et al., 2009) and have started to be successfully applied in economic incentive systems of payments for ecosystem services (PES) to stem further ES degradation (Huberman, 2009; Rawlins and Westby, 2013). However, there are still many challenges to successful and uniform implementation, such as the focus on the needs of planners and decision-makers on the one hand and urban dwellers on the other, the combining of ES approaches with sophisticated scenario-based land-use models, the involvement of cross-scale effects, the integration of multiple ES and linkages and the availability of highly diverse approaches for ES assessment (ESA; Daily et al., 2009; Elmqvist et al., 2013; Seppelt et al., 2012) as the new City Biodiversity Outlook (2013) requires.

The first step in the effective implementation of ESA-based decision-support and participatory tools is to satisfy the requirements and interests of both decision-makers and residents, starting with the selection of suitable ES indicators and ending with the appropriate communication of findings on relevant subjects, such as human health or economic benefit (CBO, 2013; Raudsepp-Hearne et al., 2010; TEEB, 2011). A fundamental condition for drawing the correct conclusions is the use of solid quantification models (Elmqvist et al., 2013; McIntosh et al., 2011). Furthermore, ESA should promote convenient decision-making by integrating multiple ES linkages, such as trade-offs or synergies, of which little is known (Haase et al., 2012b). Finally, the ESA must be provided systematically, such that it is replicable and applicable (Seppelt et al., 2012). With the Millennium Ecosystem Assessment (MA) and The Economics of Ecosystem and Biodiversity (TEEB), guidelines to categorize ES were introduced as first attempts to promote standardization (MA, 2005; TEEB, 2011). Progress in ES research has created a desire for ESA standards (Boyd and Banzhaf, 2007; Seppelt et al., 2012).

Because land use is one driver of ES change, credible scenario-based land-use simulation models are needed for sophisticated ESA. To this end, detailed socio-demographic data, economic and political factors, functional interrelations with human decisions, land-use change, ecosystem services, and human wellbeing must all be considered in these models (Batty, 2007; Bennett et al., 2009; Seppelt et al., 2012).

Consequently, urban dynamics recently observed in many European and North-American cities, such as reurbanization or urban shrinkage, must be formalized along with assumptions of permanent growth (Buzar et al., 2007; Haase et al., 2007). The combination of close-to-reality land-use scenarios with ESA has a potential to promote policy-making because risks or benefits of land-use-based ES flows can be revealed and monitored with regard to conservation, especially when urban development is under consideration (Alcamo and Henrichs, 2008; Butler et al., 2013). At the same time, close-to-reality scenarios help to get urban residents “on board” as the imaginability of such scenarios is high (Alcamo and Henrichs, 2008). The translation of urban variety into urban structure types derived from housing markets and zoning maps seems promising for that purpose (Bennett et al., 2009; Heiden et al., 2012). Another critical point for ESA standardization is the inconsistency of utilized ES indicators. Highly diverse environmental relations are described in ES approaches on different scales, with varying effectiveness. Poor-quality data arise when ES flows are observed on the local and regional scales without distinguishing between the two (Chan et al., 2006). To improve urban quality of life and health, local services (on the neighborhood and building scales) must apply ES-based modeling, as these scales are sensitive to minor changes in the urban setting (Elmqvist et al., 2013; Huberman, 2009). These local findings should be considered in the context of regional ES flows.

The objective of this paper is to address the above-mentioned challenges using a combination of Land-Use Change (LUC) and ESA models. In so doing, we focus on the impact of human decisions on LUC and the consequences for ES. In this context, we test a growth and a shrinkage scenario with regard to the prevailing position that urban shrinkage is generally positively related to ES. Multiple ES indicators will be used to quantify and compare ES linkages. We propose an ESA framework addressing the following issues on the local and regional scale:

1. Scenario comparison
2. Integration of ES linkages (synergies, trade-offs)
3. Multi-criteria ESA on the basis of land-use transitions
4. Contribution to support decision-making and system understanding via items 1 – 4

2 Methods and materials

We combine land-use-scenario modeling and environmental-impact modeling, using the concept of ecosystem services to develop an integrative ESA. Figure IV-1 presents the conceptual background and structural organization of this paper. The basic idea for improving the understanding of ES dynamics and linkages is to focus on the link between land-use change and interdependent effects on multiple ES. For this purpose, we systematically explore the complexity of the urban environment and its drivers. Land-use transitions given regional and local dynamics are reproduced via a newly developed land-use-simulation model focusing on human decisions, especially in terms of choice of residence (sect. 2.2). The variability in the urban environment is represented by a compatible and detailed land-use classification. Urban dynamics embedded in the model reflect current urban processes; they are not limited to urban growth and sprawl, but include trends of reurbanization and urban shrinkage, which are expected to influence ES dynamics. ES dynamics driven by human decisions are analyzed for two urban scenarios under different population and economic dynamics (sect. 2.2).

Six ES indicators were selected with regard to the identification instructions suggested by TEEB (2011). We included two competitive provisioning services (energy supply and food supply), three regulating services (net carbon storage, thermal emission and bioclimatic comfort), and one cultural service (provision of recreational green area). These services affect human wellbeing and are crucial to living spaces. Accordingly, their importance increases in urban regions with high population densities, where human activities affect ecosystem services precisely where they are most needed. The selection integrates services that are effective locally (e.g., bioclimate), regionally (e.g., thermal emissions) and globally (e.g., carbon storage); cross-scale effects are thus integrated and identifiable (Boyd and Banzhaf, 2007; Fisher et al., 2009). We address climate-relevant ES, as climate change is of major importance for cities and urban regions, especially in terms of hazard, vulnerability, costs and cost avoidance (Haase et al., 2012b; Scherer et al., 2014). Finally, similar ES selections were found to be important in other studies on urban ES (cf. eds. and sect. 2.3). We provide new and adapted quantification models, enabling local and regional analysis (sect. 2.3). The proposed ESA framework, as applied to the Berlin metropolitan region (sect. 2.1), is described in sect. 2.4.

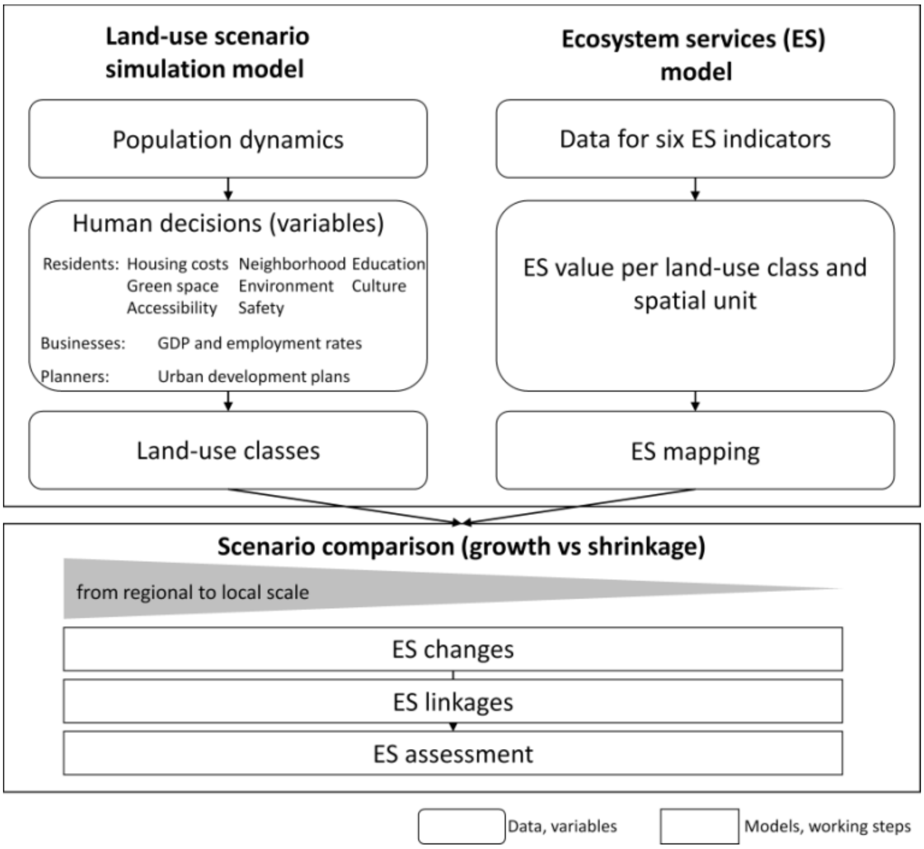

Figure IV-1. Methodological overview of the presented study

2.1 The study region

The Berlin metropolitan region, one of the larger European urban regions, was chosen because it represents a large variety of processes affecting the urban ecosystem. In contrast to other urban regions, Berlin is fragmented and polycentric, connected by large infrastructural corridors and green areas, especially urban forests (cf. Figure IV-2). The Berlin metropolitan region extends over 5.3 thousand km² and has a population of 4.4 million.

Berlin itself has a population of 3.4 million (SOBB, 2012). The Berlin hinterlands, situated in the federal state of Brandenburg, were included to capture urban-to-periurban relationships, which are characterized by strong functional linkages (Haase et al., 2012b; Kroll et al., 2012). In particular, the fall of the Berlin Wall in 1990, associated with the reconnection of infrastructure, opened the way to new investments and triggered a construction boom in the inner city; however, population decline due to a weak economy and increasing suburbanization resulted in the highest vacancy rates in central residential uses in the inner city (in 2001), 10 years after reunification. Suburbanization, which was previously limited, transformed large areas in Berlin's periphery; however, reurbanization has been observed since the beginning of the new millennium (Buzar et al., 2007) in conjunction with population growth, inner-city densification, high-quality renovation and cultural development, though also with increasing land-use conflicts and gentrification (Overmeyer, 2007). These developments, together with the abandonment of two central airports, the construction of a new airport in the southern periphery, and simultaneous growth and shrinkage within the diverse housing market, reveal the highly urban dynamic, which has consequences for the ecosystem. Still, Berlin is one of the most livable places in Europe today, not least because of its green infrastructure and cultural and leisure resources (Lachmund, 2007; MMF, 2011; Oswalt, 2000).

Despite the availability of a high-quality geodata infrastructure and the forward-facing integrated urban-development planning, interdisciplinary examinations of ES effects of LUC are still missing (SDUDEB, 2012).

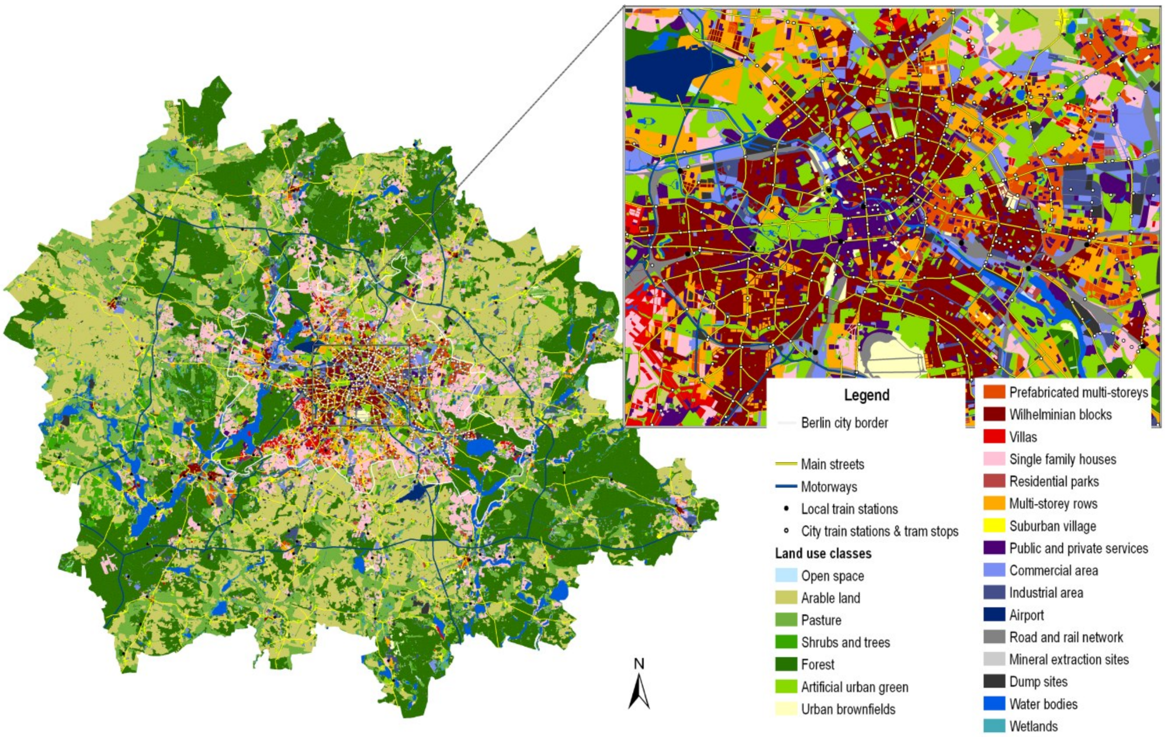

Figure IV-2. Land-use map of the metropolitan region of Berlin in 2008; both maps present all applied land-use classes and transportation data covered in the model; the left map gives an *impression of Berlin's urban pattern and its extension into the hinterland; on the right map, the dense inner-city area with it green spaces and urban brownfield is enlarged*

2.2 Land-use simulation model

Model overview

In this section, only a short overview of the applied land-use model is given. A detailed model description is presented elsewhere (Lauf et al., 2012a; Lauf et al., 2012c). To integrate all indirect drivers affecting ES, such as population, economy, and sociopolitical and cultural aspects of land-use change (MA, 2005) we combine a system-dynamics (SD) and a cellular-automaton (CA) model. With SD, we integrate residential choice dynamics within a decision process based on household socioeconomic factors which are influenced by demographic and economic change, integrating the decisive factors in Figure IV-1. The CA translates the SD output (including demands for business developments) into spatially explicit results for the allocation of land-use changes under consideration of urban planning (land development plan), neighborhood functions and transportation accessibility. The combined model produces results on an annual basis in a 50x50-meter cell resolution, representing a compromise between a high local resolution and the large study region. The residential types were classified with regard to differing ES potentials and match those used by urban authorities in land development plans, which facilitates interoperability (Heiden et al., 2012). Moreover, these classes present a more detailed residential differentiation than would the Corine Land Cover data collected by the European Environmental Agency (Heiden et al., 2012; Schwarz et al., 2011). Land-use pattern reproduction improved considerably due to the verified models and applied residential classes (Lauf et al., 2012a); enabling e.g. realistic processes such as inner-city (re-)densification and urban green development to proceed alongside the abandonment of formerly built-up areas.

Land-use scenarios

In two scenarios, growth and shrinkage, we present the range of plausible urban development through the year 2030 by integrating expected population and economic dynamics (Lauf et al., 2012b; SDUDEB and SOBB, 2009). Respective input parameter shift are presented in app. IV (Table A-IV-1).

Below, we contrast the main results of the simulations. The total population in 2030 ranged from 4.27 million (-3.7% compared with 2008) for shrinkage to 4.74 million (+6.8% compared with

2008) for growth. On average, the number of persons older than 65 years increased from 19 to 25%, and the number of persons younger than 25 years decreased from 23 to 21%. The number of persons living in traditional family households decreased from 28 to 23%; the number of persons living in small households (2 persons maximum) or in shared flats increased from 61 to 66%. In consequence, the mean household size declined and the mean per-capita living space increased, resulting in an increase in total residential area in both scenarios of 1.6 (shrinkage) – 5.4%(growth),despite population decline.

Examining the development of different housing segments and other land uses, we obtained a differentiated picture for each scenario (cf. app. IV, Table A1a). For all residential uses, the shrinkage scenario revealed higher vacancy rates, showing the delay effect of population decline on residential supply. Less attractive residential uses such as prefabricated multi-story houses or suburban villages declined (particularly in the shrinkage scenario), while others increased (particularly in the growth scenario). For the shrinkage scenario, we observed the decline of industrial and commercial areas, which prospered in the growth scenario. Reurbanization was confirmed by the increase in central residential uses between 0.6% (shrinkage) and 1.96% (growth). In contrast, the spread of detached (family) houses associated with suburbanization continued despite family decline, and was twice as high in the growth scenario (with 6.7%). The ratio of green and open land to total residential land is unchanged for shrinkage and decreased from 2.81 to 2.67% under the growth scenario,(cf. app. IV, Figure A-IV-1).

2.3 ES quantification and mapping

Table IV-1 shows the quantification models for selected ES indicators. We chose a non-monetary approach due to the associated uncertainties (Carreño et al., 2012; Spangenberg and Settele, 2010). Instead, we applied common units with regard to particular target values and computation methods (Burkhard et al., 2012; Schwarz et al., 2011). Units refer to one hectare land use or mean index values that can be spatially assigned to each land-use class and land-use map. Accordingly, we related ES values to the initial land-use map of 2008 and the two simulated maps of 2030 (shrinkage and growth) and retained the map resolution. For a sound assessment of multiple ES, chosen ES are not reduced to only the dominant land-use providing a service, but include all verifiable land-uses. Table IV-1 contains information on the ES calculation and the applied data.

Table IV-1. Overview and quantification models of six selected ES indicators

	ES indicators	Quantification models			Variable description
Provisioning services	Energy provision *(photovoltaic, solar heat, wind energy, energy from biomass)*	$E^i = \alpha^i(E^i_{sol} + E^i_{wind} + E^i_{bio})$	(1)	E^i	Energy potential per land use *i* and year in GJ per ha
				E^i_{sol}	Energy potential of photovoltaics and solartermics per land use *i* and year in GJ
				E^i_{wind}	Energy potential of wind power per land use *i* and year in GJ
		$E^i_{sol} = \frac{3.6 \cdot (S^i_s \cdot P^i_s + S^i_p \cdot P^i_p)}{A^i}$	(2)	E^i_{bio}	Energy potential of biomass per land use *i* and year in GJ
				α^i	Land ratio per land use *i* available for energy production
		$E^i_{wind} = \frac{WPP^i \cdot MP \cdot 3.6 \cdot H}{A^i}$	(3)	$S^i_{s,p,b}$	Available surface solar thermal power *s*, photovoltaic *p* and biomass *b* of total land use *i* for energy production
		$E^i_{bio} = \frac{Y^i_b \cdot S^i_b}{A^i}$	(4)	$P^i_{s,p}$	Useable solar power in MWh per m² and year for solar thermal power *s* and photovoltaic *p*
				WPP^i	Number of available and planned wind power plants per land use *i*
				MP	Mean power of WPP in MWh per year
				H	Full-load hours of WPP
				${Y_b}^i$	Yield of biomass *b* of land use *i* in GJ per ha
				A^i	Total area of land use *i* in ha
	Food provision *(crop, livestock, fish)*	$F^i = (1-\alpha^i) \cdot (E^i_{crop} + E^i_{livestock}) + E^i_{fish}$	(5)	F^i	Food production per land use *i* and year in GJ per ha
				F^i_{crop}	Energy potential of 36 crop types *c* per land use *i* and year in PJ
				$F^i_{livestock}$	Energy potential of 6 livestock types *l* per land use *i* and year in PJ
				F^i_{fish}	Energy potential of 7 fish types *f* per year for land use *i=water bodies* in PJ
		$F^i_{crop} = \sum_{c=1}^{36} \frac{A^i_c \cdot Y_c \cdot CV_c}{A^i}$	(6)	$1-\alpha^i$	Land ratio per land use *i* available for food production
				A_c	Crop area per crop *c* in ha
		$F^i_{livestock} = \sum_{l=1}^{6} \frac{L_c \cdot AP_l \cdot D_l \cdot CV_l}{A^i}$	(7)	Y_c	Crop yield per crop *c* in kg per year
				$CV_{c,l,f}$	Caloric value in GJ/kg per crop type *c*, livestock *l* and fish species *f*
				L_c	Number of livestock per livestock species *l*
		$F^i_{fish} = \sum_{f=1}^{7} \frac{AF \cdot FC_f \cdot CV_f}{A^i}$	(8)	AP_l	Animal production per livestock (including eggs and milk) in kg per year
				D_l	Digestible amount of an animal for food production per livestock species *l*
				AF	Fishing areas which are identical with land use *i=water bodies*
				FC_f	Fish catch of fish species *f* in kg per year
				A^i	Total area of land use *i* in ha
Regulating services	Climate regulation *(emissivity index)*	$TEI_i = \frac{TE_i}{TE_{[urban\ green]}} \cdot 100 - 100$	(9)	TEI_i	Thermal emission index
				TE_i	Emission mean derived from lookup table for neighboring urban region (Schwarz et al. 2012)
	Biophysical regulation *(PMV index)*	$BI_i = \frac{BE_i}{BE_{[urban\ green]}} \cdot 100 - 100$	(10)	BI_i	Bioclimate index using PMV values (calculated analogous to TEI_i)
				BE_i	PMV values derived at 22.00 using data from Berlin climate model (SDUDE 2012)
	Net carbon storage	$C^i = C^i_{heat} + C^i_{power} + C^i_{traffic} - C^i_{sequest}$	(11)	C^i	Net carbon sequestration (emission-sequestration) per land use *i* and year in tons per ha
		$C^i_{heat} = \frac{\sum_{HHT=1}^{7}(HC_{HHT} \cdot POP^i_{HHT}) \cdot M_h}{A^i}$	(12)	C^i_{heat}	Carbon emission by heat generation per land use *i* and year in tons per ha derived from 7 household types *HHT*
				C^i_{power}	Carbon production by power generation per land use *i* and year in tons per ha derived from 7 household types *HHT*
		$C^i_{power} = \frac{\sum_{HHT=1}^{7}(PC_{HHT} \cdot POP^i_{HHT}) \cdot M_p}{A^i}$	(13)	$C^i_{traffic}$	Carbon production by traffic volume per land use *i* and year in tons per ha
				$C^i_{sequest}$	Carbon sequestration by urban green per land use *i* and year in tons per ha
		$C^{road,rail}_{traffic} = \frac{B \cdot RE_t \cdot F_t}{A^i}$	(14)	HC_{HHT}	Heat consumption per person and household type *HHT* in MWh per year
				$M_{h,p}$	Carbon emission based on current energetic mix in tons per MWh by heat production *h* and power production *p*
		$C^{airport}_{traffic} = \frac{AP}{A^{airport}}$	(15)	POP^i_{HHT}	Population density in persons per household type *HHT* and ha
		$C^i_{sequest} = \frac{\beta^i_t \cdot SC_t + \beta^i_g \cdot SC_g}{A^i}$	(16)	PC_{HHT}	Power consumption per person and household type *HHT* in MWh per year
				B	Buffer area around traffic lines defining transportation area in km
				RE_t	Carbon emission per route and means of transport *t* in tons per km
				F_t	Frequency per means of transport *t* in km per year
				AP	Total Annual emission of carbon due to air traffic
				$A^{airport}$	Total area of land use *i= airport* in ha
				$A^{road,rail}$	Total area of land use *i= road and rail network* in ha
				$\beta^i_{t,g}$	Amount of tree cover t or grass cover *g* per land use *i*
				$SC_{t,g}$	Mean annual sequestration rate of tree cover *t* and grass cover *g*
				A^i	Total area of land use *i* in ha
Cultural services	Recreation *(urban green and forest)*	if $A_g \geq 2$ and $distance(A^i_g, A_g) \leq 300\ m$ then:		R^r	Recreation potential of residential units *r* on close-to-home urban green spaces *g* in ha green space per person
		$R^r = A_g \cdot \sum_{i=1}^{n} \left(\frac{POP^i_g}{A^i_g}\right)^{-1}$	(17)	A_g	Urban green areas including land uses forest and artificial urban green in ha
				POP^i_g	Population density of each residential land use *i* within neighboring green space radius *g*
				A^i_g	Residential area of land use *i* within the accessible radius of A_g
		if $g > 1$, $A_g \geq 2$ and $distance(A^i_g, A_g) \leq 300\ m$ then:		g	Number of close-to-home green spaces available for residential unit *r*
		$R^r = \sum_{g=1}^{n}\left[A_g \cdot \sum_{i=1}^{n}\left(\frac{POP^i_g}{A^i_g} \cdot g^{-1}\right)^{-1}\right]$	(18)		

Energy supply as provisioning service

Renewable and decentralized energy provision becomes more and more important for urban regions due to the rising awareness of environmental degradation from fossil energies. Only renewable energy sources (solar and wind power) are counted as contributing to the regional energy provision (Table IV-1, eq. 1). Waterpower plays an insignificant role and thus was not included. Information and data on photovoltaic and solar thermal energy are derived from Berlin's digital environmental atlas (SDUDEB, 2012). Wind energy is calculated from the number of wind turbines per land use, the mean power per wind turbine and the mean full-load hours per year. Applied data are obtained from the Brandenburg environmental information system (MUGV, 2012; MWE, 2012). Biomass is composed of forestry biomass (wood, waste wood), agricultural biomass (energy plants, horticultural and agricultural waste, animal residues), landscape-maintenance matter (wood, greenery) and industrial, commercial and housing biomass (biogenic wastes and residues; FNR, 2008; Hirschl et al., 2011). The sums of energy per land use summarizing all energy sources are presented in GJ per ha and year. Intermediate calculation steps can be found in app. IV (Table A-IV-2).

Food supply as provisioning service

The provision of food was implemented via energetic values currently generated by cultivated crop types (including berries), livestock and fish products available in the region (Table IV-1, eq. 5). The calculations were based on regional statistics on agribusiness defining yield and crop area, livestock (including egg and milk production) and fishery products for the year 2010 (Hirschl et al., 2011; MIL, 2010; SOBB, 2012). Energetic values were derived using current nutrition tables (FAO, 2012). For the translation of the total consumable caloric energy output from food production per land-use class, conflicting uses of agricultural land had to be considered, such as crop products for grazing animals or fodder production and biomass for energy production. To this end, we used mean production shares of agricultural land from the federal state of Brandenburg (covering over 80% of our study region, cf. Figure IV-2) and adapted them to our land-use classes. Intensively used arable land provided the highest amount of total caloric energy. On pasture, which is the main supplier for fodder production, the energy loss due to the transition from fodder to livestock production was remarkable with 56.4 PJ per hectare. The detailed calculation of energetic values is given in app. IV (Tables A-IV-3).

Thermal surface emission as climate regulating service

Climatic effects due to urban patterns or land-use change can be measured on the regional (e.g., temperature shift along the urban-to-rural gradient) to local scale (heat/cooling island effects). Land-surface emissivity, a convenient and commonly used proxy variable, is the total thermal energy emitted by a surface (Schwarz et al., 2011; Xu et al., 2008). We decided to use emissivity values from the look-up table proposed by Schwarz et al. (2011) because of the similarities in land-use classes and equal structural and climatic conditions arising from the proximity of their study region to ours. The given emissivity values are averaged over the land-use classification used. The mean thermal emissions (Landsat 6, band 6.1) across different land uses were very similar (regional mean 137.7 with STD 3.7). To highlight the differences we used index values by dividing all emissivity values of each land-use class by the emissivity value of the reference class "artificial urban green space" following Schwarz et al. (2012). As a consequence, negative values showed higher and positive ones lower potential for climate regulation compared to urban green space.

Bioclimate as biophysical regulating service

Bioclimate describes human thermal comfort, acknowledging that climatic conditions may have effects on human physiology, as in heat stress (Yao et al., 2009). On this basis, we introduce human thermal comfort as a health-regulating service. With regard to the available data from regional planning, we chose the predicted mean vote (PMV) as a bioclimatic indicator (SDUDEB, 2012). PMV values were derived from mean summer air temperatures at 4 p.m. and transferred via GIS to mean bioclimatic values per land-use type. PMV values revealed the adverse effects of dense urban structures like inner-city blocks; however, relatively low maximum values of 1.5 suggest a moderate thermal discomfort in the whole study region (Yao et al., 2009). We produced a PMV index analogous to the emissivity index, with "artificial urban green space" as a reference class.

Net Carbon storage as a regulating service

The carbon storage capacity of ecosystems or single trees is addressed in current interdisciplinary research (Churkina, 2008; Schaldach and Alcamo, 2006). We include carbon emissions and carbon storage in tons per ha and year for each land-use type. Carbon emissions from housing in mean carbon production per kilowatt hour are integrated by combining the population density per residential land use and household type and the mean heat and electricity consumption with the energy source for electricity and heat production (BEA, 2012; SDUDEB, 2012). We further integrate carbon emissions from all non-residential built-up areas, using the mean energy consumption according to economic sectors involving the energy mix linked to specific carbon-production rates (ISI, 2009). Traffic-related carbon emissions comprise all public and private transportation, including air traffic. Emissions from public transportation are calculated in tons per km and year, taking into account the number of passengers, the electricity mix, transportation volumes and the importance of each transportation type in km per year (SDUDEB, 2012). For street-traffic emissions, data on congestion for different transportation types (car, truck, bus, motorbike), specific fuel consumption and consequent emission values were used (LfUB, 2011; SDUDEB, 2012). Buffers around traffic lines define adjacent emission zones. Emissions from airport areas comprise emissions from airspace and those from ground traffic (including all vehicles; SB, 2012; TCM, 2007). Finally, we consider above-ground carbon storage within different vegetation types. The storage capacity of different vegetation types (shrubs, trees and grassland) was derived from existing studies of similar plant species (Davies et al., 2011). Existing data on the cover density of plant species for Berlin provided mean values of carbon storage in tons per ha for applied land uses (SDUDEB, 2012). The appendix offers further information on the calculation (app. IV, Tables A-IV-4).

Provision of public green space as recreational service

Based on existing studies on urban green-space accessibility (Coombes et al., 2008; Van Herzele and Wiedemann, 2003), we consider the provision of nearby public green space as an important cultural service; it is expressed as available green space in ha per person and residential land-use type. The maximum distance to public (close-to-home) green spaces was set at 300 meters; the minimum size of green spaces providing a recreational function was set at 2 ha, following existing standards (Handley et al., 2003). Accordingly, starting from green spaces, the catchment areas were created using buffer analysis in GIS. Then, the total number of residents from all residential uses within a catchment area was assigned to green spaces using the population density and segment size of included residential land uses.

2.4 Scenario-based ESA on the local to regional scale

The scenario-based ESA uses a cell-based approach. It integrates multiple ES to test linkages. To determine only the effects of LUC on ES flows with no additional interference factors, we assume that all ES assigned to land-use type are constant over time. To incorporate all six ES in the assessment, we normalized obtained ES to values ranging consistently between 0 and10 where 10 describes the most beneficial value reached across all land uses. For the comparative analysis, we use the ArcGIS software. Land-use-caused ES flows are contrasted for the growth and the shrinkage scenarios over the simulation period (2008 to 2030). We then focus on comparing ES flows, ES linkages and ESA values.

2.4.1 ES flows and sensitivities

ES values are assigned to corresponding land-use classes in a spatially explicit manner. Local changes within the ES distribution are detected using simple cell-based differentiation methods, thus enabling the comparison of different time steps and scenarios. On the regional scale, the total ES change becomes measurable, as we predominantly use spatial units to calculate integrated ES indicators (here, ha) that can be combined with the quantitative LUC. The drivers of ES change are considered with regard to their sensitivity to ES, with S^{ES} defining the sensitivity of an ecosystem service (ES), using the ratio of the product in both scenarios for the year 2030 to the product of the tested drivers (D) in both scenarios:

$$S^{ES} = \frac{(ES_{2030}^{Growth} \cdot (ES_{2030}^{Shrinkage})^{-1} - 1) \cdot 100}{(D_{2030}^{Growth} \cdot (D_{2030}^{Shrinkage})^{-1} - 1) \cdot 100} \qquad (19)$$

Values approximating 1 or (-1) indicate a high driver sensitivity to ES change, whereas values approximating 0 or being distinctively higher than 1 or lower than (-1) indicate a low sensitivity. Depending on the direction of the sensitive behavior, values can be positive or negative.

2.4.2 ES linkages

To provide detailed information on ES linkages, the ESA is computed on the local scale and aggregated to the regional scale. ES linkages are defined after various authors, as follows (Bennett et al., 2009; Haase et al., 2012b):

- Synergy: a minimum of two ES are improving, none are worsening.
- Trade-off: a minimum of one ES is improving, and a minimum of one ES is worsening.
- Loss: A minimum of two ES are worsening, none are improving.
- No linkage: all ES remain constant.

We begin the analysis of ES linkages by incorporating all six ES indicators. In that regard, we examine whether the sum of general ES changes are either improving (+1) or worsening (-1). This first attempt to characterize and compare ES linkages is conducted for each cell on the local scale and then summarized to relative frequencies of defined linkages on the regional scale. For a more detailed insight into ES linkages, we consider changes within ES combinations for all land-use transitions. For this purpose, normalized ES values are assigned to each cell according to present land uses in 2008 and 2030. By using simple difference equations, we obtain all cells subject to ES change for both scenarios. ES changes occur due to land-use transitions and changes in green-space provision. In a database, we summarize all cells underlying equal land-use transitions and

ES changes. The normalized changes in ES pairs are contrasted within a quadrant diagram projecting one ES on the x-axis and the other on the y-axis such that each quadrant represents a specific type of linkage, as described before. On this basis, a qualitative and quantitative evaluation of ES linkages is provided. Additionally, correlation coefficients are calculated for each ES combination to characterize its linkage. To interpret ES combinations, we provide percentage distributions across the linkage categories and mean linkage values. This process helps to reveal and understand regional differences when comparing the scenarios.

2.4.3 Multi-criteria ESA matrix

Finally, a multi-criteria ESA matrix is generated for all land-use transitions to provide a detailed and comprehensive evaluation of ES relationships. The first criterion depicts the sum of general ES changes (from -6, all ES deteriorate, to +6, all ES improve); the second criterion lists which services developed positively or negatively; the third criterion represents the ESA value, summing the normalized changes of ES values; and the final criterion reveals the proportion of transition from total LUC, addressing the effectivity of ES change. These results are compared between scenarios to support system understanding on land-use driven ES effects. Within decision maps, we provide the initial scenario and the local changes in ESA values through 2030 to identify the spatial characteristics of multiple ES qualities.

3 Results

3.1 ES quantification and mapping

Table IV-2 shows the calculated ES values per land-use class and provides an initial impression of ES distribution within the region and across land uses. The ranges of these values differ notably due to the initial data applied and their specific reference systems and units, and are thus not comparable among each other. To make them comparable we used a normalization of ES values. The last column summarizes the normalized ES values (ESA value). Arable land has the highest and inner-city blocks the lowest ESA value. Interestingly, low-density residential uses reach high values mainly from the positive energy potential, but also from the relatively large amount of green space with positive effects on regulating services. Another factor influencing land-use related ESA values is the fact that recreation is only related to green-space provision within residential land use, so not all land uses are considered for recreational service. This effect can be ignored, hereinafter, as we focus on comparing ES changes across two scenarios.

Table IV-2. ES quantification results per land-use class, including statistical values of ES distribution (in grey for normalized values); land uses are arranged according to the total ES quality (ESA value)

Land use	Energy provision [GJ(ha*a)$^{-1}$]	Food provision [GJ(ha*a)$^{-1}$]	Climate regulation [Emissivity index]	Biopysical regulation [PMV index]	Net carbon sequestr. [t(ha*a)$^{-1}$]	Recreation [sqm per capita]	nomalized ESA value [0 - 60]
Arable land	44,6	108,4	-0,12	24,4	16,0	0	36,0
Detached houses	1407,8	0	0,10	8,8	29,0	18,6	32,3
Villas	885,2	0	-0,22	8,1	35,8	17,4	29,0
Forest	199,7	0	-0,54	15,5	13,4	0	28,4
Wetlands	0	0	-0,72	16,7	14,5	0	27,5
Multi-story rows	1601,4	0	0,75	-12,1	73,2	15,7	21,9
Shrubs and trees	38,8	8,6	-0,09	7,1	23,2	0	20,0
Water bodies	0	0,03	-0,51	0,1	21,9	0	19,6
Pasture	20,5	8,9	-0,31	6,8	33,1	0	19,0
Suburban villages	1,0	0	0,16	1,8	82,9	19,3	18,8
Mineral extraction	28,1	0	0	13,0	49,4	0	17,0
Open spaces	9,4	0	0,01	3,7	26,9	0	17,0
Residential park	276,9	0	0,79	-5,3	45,8	17,7	16,8
Urban green space	45,7	0	0,00	0,0	25,4	0	16,7
Airport	0	0	0,58	22,5	50,0	0	16,3
Commercial area	369,6	0	0,40	-10,5	25,3	0	14,5
Brownfields	0	0	0,14	-6,2	45,6	0	12,0
Infrastructure	0	0	0,13	-5,4	55,7	0	11,6
Industrial area	401,0	0	0,24	-15,6	65,5	0	10,9
Multi-story prefab	26,4	0	0,92	-13,4	96,7	13,7	9,9
Services	125,8	0	0,47	-11,3	59,3	0	9,4
Supply and disposal	4,9	0	0,22	-10,9	136,4	0	8,6
Inner-city blocks	295,6	0	1,48	-18,9	119,5	13,6	7,5
Range	1601.4 (10)	108.4 (10)	2.2 (10)	43.3 (10)	122.9 (10)	30 (10)	33,1
Mean	239.4 (1.5)	27.6 (2.5)	-0.2 (7.6)	11.7 (7.1)	25.3 (7.1)	18.6 (6.2)	26,7
STD	399.4 (2.5)	45.8 (4.2)	0.37 (1.7)	10.9 (2.5)	19.9 (2.8)	13.4 (4.5)	8,1

Figure IV-3 shows ES values mapped for all six ES indicators based on the initial land-use situation in 2008. The maps show how selected ES are distributed across the study region. These distributions indicate a relationship between ES quality and urban-to-periurban allocation. High local diversity is also present; the distribution does not only follow a distance function from the center to the periphery. ES allocations reflect the presence of parks, forests or dense built-up areas.

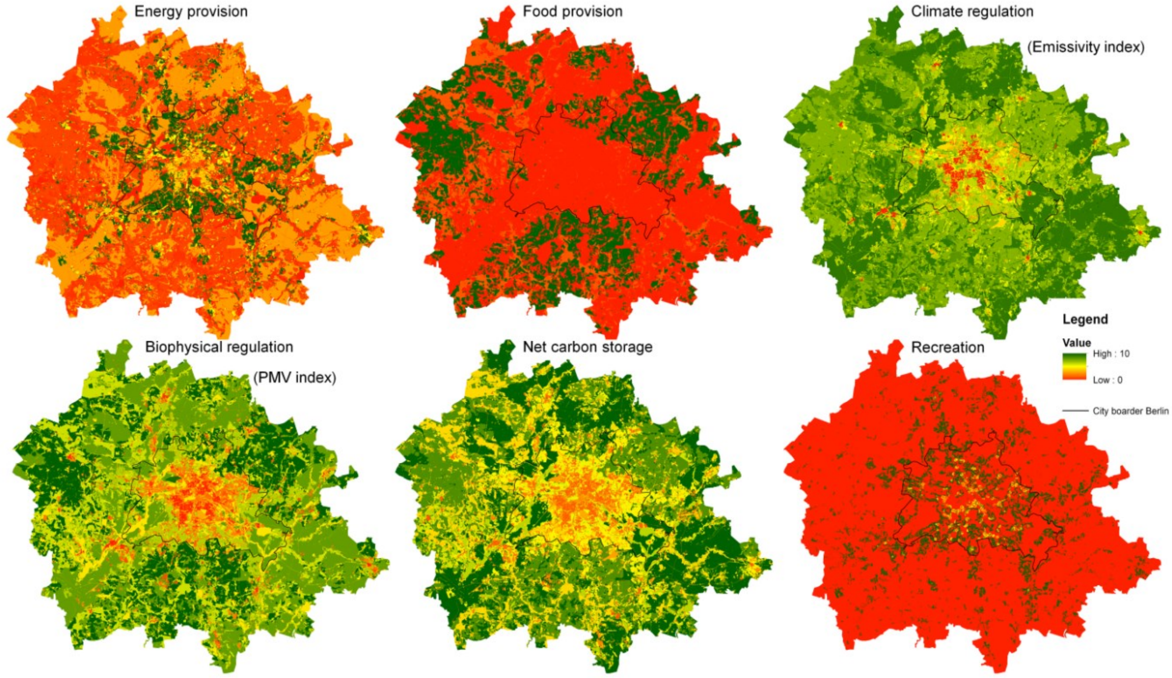

Figure IV-3. ES maps for the Berlin metropolitan region in 2008 for all selected six ES indicators using normalized values ranging from 0 (low) to 10 (high)

3.2 Scenario based ESA

3.2.1 ES flows and sensitivities

Table IV-3 contrasts the regional differences in individual ES for both scenarios. Except for net carbon storage and recreation, ES indicators behave similarly, whereas these changes are more distinctive in the growth scenario for both improving and worsening ES. The increase in recreational space is more obvious in urban shrinkage. Carbon storage exhibits opposite trends: whereas it decreases slightly in the shrinkage scenario, it increases under growth conditions. Within the shrinkage scenario, all values obtained were better, except for energy provision. The mean relative ES change rate, taking all services into account, ranges between +2.3% for shrinkage and -2.4% for growth, indicating the benefits of shrinking cities. The greatest differences in relative ES change between both scenarios were found for energy provision (2.7%) and emissivity (2.5%); the lowest was found for carbon (0.9%). Simple driver sensitivities are included in Table IV-3 to provide information on functional system interrelations. Population dynamics have a relatively moderate impact on single ES. The directions of ES change due to population change are as expected. Unsurprisingly, ES values are more sensitive to consequent land-use changes, as can be clearly seen for green and agricultural area. The change in built-up uses affects ES, especially for residential areas.

Table IV-3. Absolute and relative changes in ES and its drivers, including land use, for the growth and shrinkage scenarios covering 2008-2030, aggregated across the entire metropolitan region (green represents improving and red worsening ES changes); additionally, ES sensitivities to drivers are represented within a contingency table derived from scenario differences, revealing the efficiency of a specific driver for ES provisioning

		2008	**2030**		**Change** between 2008 and 2030 [%]		**Sensitivities**					
			Shrinkage	Growth	Shrinkage	Growth	Popu lation	Buitl-up area	Resi dential use	Eco nomic use	Green area	Agri cultural area
Drivers	Population [10^6]	4.56	4.27	4.74	-6.4	3.9	1.0					
	Buit-up area [10^3ha]	104.4	105.4	111.6	0.9	6.9	0.5	1.0				
	Residential use [10^3ha]	71.6	72.8	75.5	1.6	5.4	0.3		1.0			
	Economic use [10^3ha]	24.5	23.4	26.8	-4.5	9.7	1.4			1.0		
	Green area [10^3ha]	206.0	208.7	205.9	1.3	-0.1	-0.1				1.0	
	Agricultural area [10^3ha]	202.1	198.5	195.2	-1.8	-3.4	-0.2					1.0
Ecosystem services	Energy provision [PJa^{-1}]	127.8	129.4	132.8	1.2	3.9	0.2	0.4	0.7	0.2	-1.9	-1.6
	Food provision [PJa^{-1}]	14.7	14.4	14.1	-2.1	-4.2	-0.2	-0.4	-0.6	-0.1	1.6	1.3
	Climate regulation [Emissivity index]	-0.2	-0.2	-0.2	-1.1	-3.6	-0.2	-0.4	-0.7	-0.2	1.9	1.5
	Biophysical regulation [PMV index]	11.7	11.6	11.4	-0.5	-2.2	-0.2	-0.3	-0.5	-0.1	1.3	1.0
	Net carbon storage [Mta^{-1}]	49.5	49.5	49.9	-0.1	0.9	0.1	0.2	0.3	0.1	-0.7	-0.6
	Recreation [sqm per capita]	17.0	17.9	17.5	4.8	2.9	-0.2	-0.3	-0.5	-0.1	1.4	1.1

A spatially explicit summary of changes in individual ES values comparing the scenarios is shown in in app. IV (Figure A-IV-2). We summed the normalized ES-change values between 2008 and 2030. Resulting maps for each indicator show the scenario-based range of possible ES changes and their effects on ES distribution according to the growth or shrinkage scenario.

3.2.2 ES linkages

The first attempt to define linkages and compare them between scenarios explores the dynamics between 2008 and 2030, incorporating all indicators. Figure IV-4 contrasts the relative distribution within linkage categories. Multiple changes in ES (+1 or -1) per cell were summarized accordingly. ES linkages in the growth scenarios shift toward service loss, whereas the shrinkage scenario shows a higher rate of synergies. A detailed view showed the higher rate of maximum ES loss (-5) for the shrinkage scenario and almost equal maximum synergy rates (+5) in both scenarios; however, these rates neither provide information on the linkage quality, nor the intensity of ES loss.

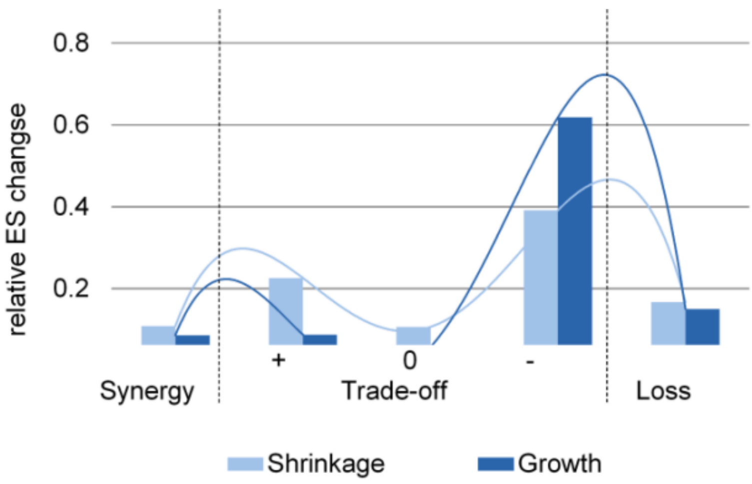

Figure IV-4. Overall ES linkages of 6 service indicators between 2008 and 2030 for the growth and the shrinkage scenario

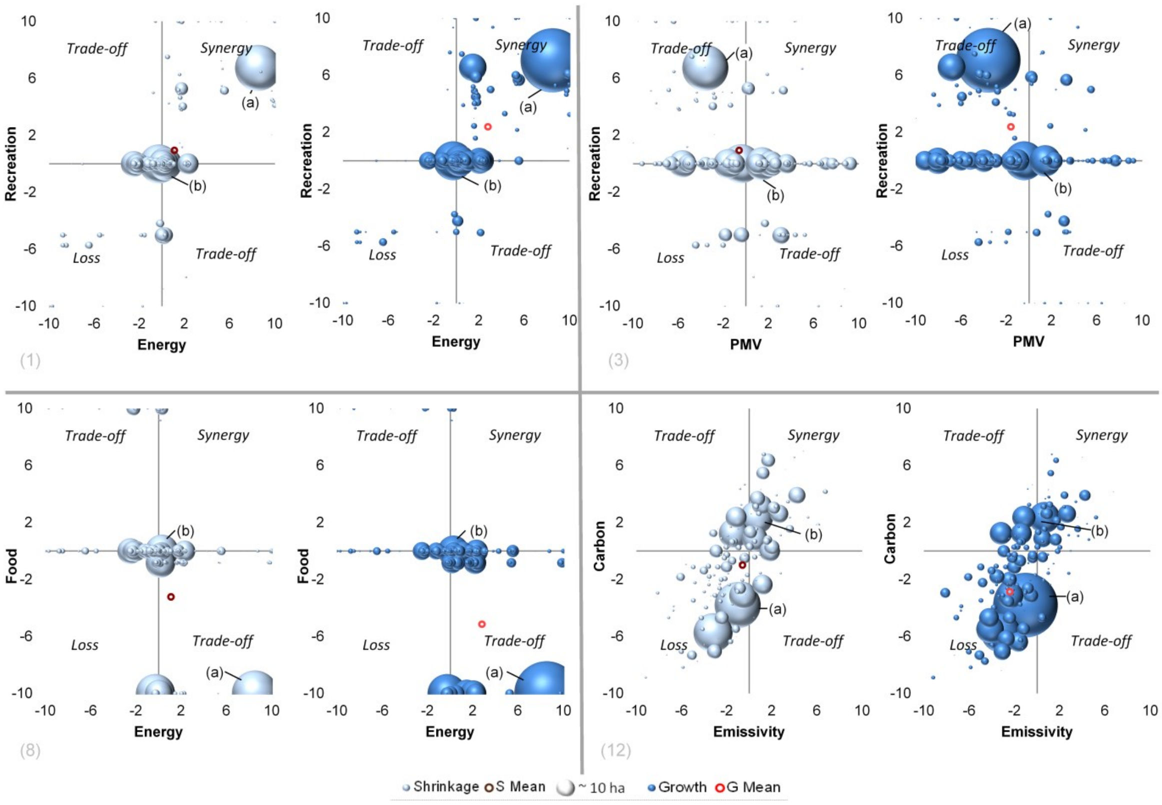

Figure IV-5. ES linkages due to obtained land-use transitions and normalized ES changes between 2008-2030 for 4 of 15 ES combinations; each of the quadrants represents one of the defined ES linkages, pairs of variates on one of the axes indicate no linkages; ES combination (1) presents on average a positive ES synergy, combination (3) presents on average ES loss, and combinations (8) and (12) present on average ES trade-off; the bubble size represents the summed area of a specific land-use transition and thereby the regional magnitude of a specific linkage; two dominant ES linkages are indicated: ES linkage (a), resulting from the transition of arable land to detached family houses, and ES linkage (b), resulting from the transition of urban brownfields to artificial urban green space

To achieve detailed information on the qualitative extent of ES linkages, we analyzed pairwise and comparative ES dynamics for both scenarios. Therefore, the changes in normalized ES values are displayed within a quadrant diagram (Figure IV-5). Each pair of variates represents the mean change values for one specific land-use transition and the ES-linkage intensity. Figure IV-5 presents these linkages for four relevant ES combinations. All missing combinations are given in app. IV (Figure A-IV-3).

The distribution of pairs of variates differs noticeably between ES combinations, but only marginally between the scenarios, because ES values are assigned to each land use in the same manner, so differences occur only due to differences in land-use transitions. By contrast, bubble sizes reflecting the magnitudes of transition differ across scenarios but stay constant across different combinations, as shown for two transition examples (Figure IV-5). The presented relative means indicate the overall linkage trends. For all ES combinations, these mean values exhibit higher linkage intensities for growth assumptions, as expressed by greater ES-change values. The highest rates of LUC are attributed to the transition from arable land to detached family houses, with distinctive ES-linkage intensities, followed by the transition from arable land to commercial use and the positive, related, transition from urban brownfields to artificial urban green space. Obtained ES linkages are summarized in Figure IV-6.

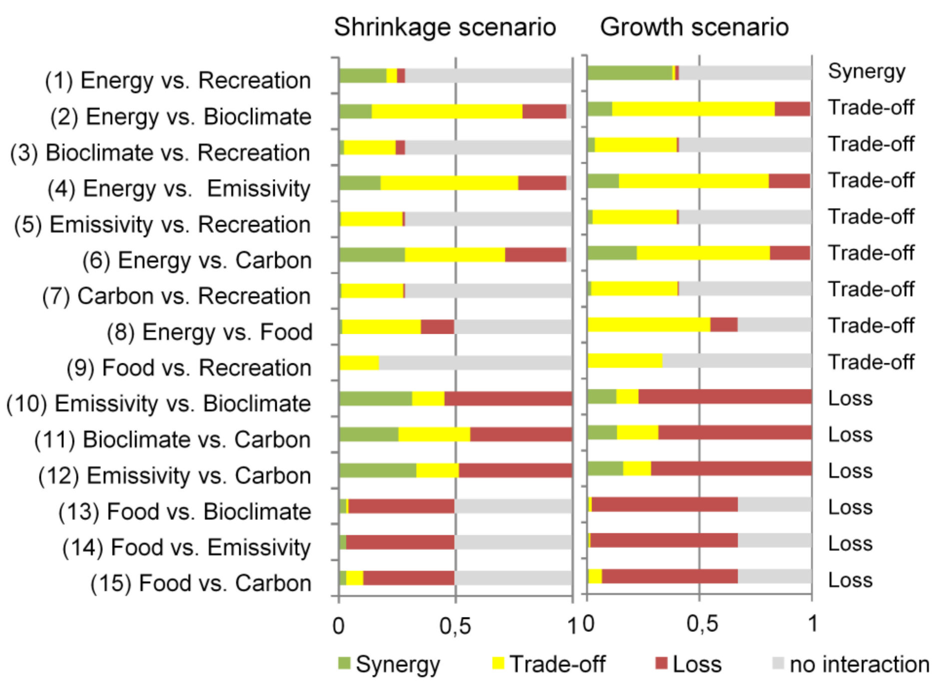

Figure IV-6. Summarized amounts within ES linkages categories for all ES combinations derived from LUC (2008-2030) and sorted by its beneficial quality; the mean linkages trend is listed on the right

These linkage distributions reveal a similar picture for both scenarios. Surprisingly, less than half of the considered combinations (10-15) reveal higher rates of service loss and lower synergy rates for the growth scenario. For combinations 1, 3, 5 and 7, linkages were found to be more positive for the growth scenario, with higher synergy effects and less service loss. The remaining 5 combinations exhibit equal distributions of linkage, with slightly improved values for the shrinkage scenario. Linkages between the strongly focused and competitive services of energy and food provision (8) are mainly attributed to the transition from arable land to detached family houses, forming a trade-off (Figure IV-5). The decline in food provision is not totally substituted by the increase of energy provision. Considering all land-use transitions, food and energy provision show trade-offs at rates from 34% (shrinkage) to 54% (growth), similar rates of no linkage, minor rates of ES loss and negligible synergies.

Table IV-4 compares the correlation values for both scenarios and for all ES combinations. All cells are subject to at least two ES changes between 2008 and 2030. Differences between scenarios occur due to varying LUC rates. As energy and food linkages contribute substantially to the transition of arable land, a higher negative correlation was observed for the growth scenario due to the higher transformation of arable land. The strong correlation of carbon balancing with food provision and climate regulation is evident. These combinations mainly describe a negative synergy with loss of ES (Figure IV-6, (13, 14, 15)).

Table IV-4. Pearson correlation coefficients for pairwise ES changes (2008-2030)

	Food	Energy	Emissivity	Carbon	Bioclimate
Energy	-0.57 *** -0.63 ***				
Emissivity	0.48 *** 0.42 ***	-0.21 *** -0.13 ***			
Carbon	0.78 *** 0.78 ***	-0.35 *** -0.38 ***	0.71 *** 0.70 ***		
Bioclimate	0.58 *** 0.59 ***	-0.46 *** -0.40 ***	0.33 . 0.51 .	0.51 *** 0.59 ***	
Recreation	-0.07 *** -0.23 ***	0.26 *** 0.38 ***	-0.14 *** -0.16 ***	-0.15 *** -0.21 ***	-0.09 *** -0.15 ***

Stat. significance: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 (Student's t- test)

3.2.3 Multi-criteria ESA matrix

The detected land-use transitions that are most sensitive to the ESA criterion are summarized in Table IV-5 and are listed in ascending order of inherent ESA values. Obviously, the sum of ES changes is not automatically associated with the ESA value. The transition from arable land to public and private services was determined to have the strongest effect on ecosystem degradation and ES loss, whereas the transition from industrial area to arable land proved to have the strongest effect on ecosystem improvement and ES synergies. For both of these transitions, one ES stayed constant and another changed sign. In terms of area, they are of minor significance.

The transition from arable land to detached family houses is the greatest for both scenarios. With the improvement of four and the worsening of two services, the ESA value describes minor ecosystem degradation (-3.2). The transition from urban brownfields to artificial urban green space yields the greatest improvement in ecosystem services by size. The development from one residential urban structure to another can improve ES, as, for instance, seen for the transition from multi-story prefab to residential park. Generally, the negative effects of changes from arable land to dense built-up structures (and positive effects of the reverse) are remarkable.

In both suburbanization (e.g., arable land → detached houses) and reurbanization (e.g., brownfields → inner-city blocks), ESA values are moderately negative. Considering the new airport construction in the south of Berlin, the model revealed a tremendous worsening in ES over a large area (about 10% of the total LUC until 2030 refer to the airport transition). The new airport extends over 56% former arable land, 24% former airport land and 20% mixed-use land. The suggested ESA value has worsened at four times with a decline in five services; only the marginal transition of built-up areas improves the ESA value (slightly and locally). Figure A-IV-4 in app. IV shows this loss of multiple ES in the south of the Berlin.

The detailed ESA for all observed transitions from 2008-2030 for both scenarios is shown in app. IV (Table A-IV-5). Additionally, the spatially explicit overview of ESA-value changes for both scenarios can be found here (Figure A-IV-4).

Table IV-5. ESA matrix for most relevant land-use transitions between 2008- 2030 with the following criteria: the summed direction of ES changes ranging from +6 to -6, the list of improving and worsening services (reflecting the ES linkages), the changes in ESA values (theoretically ranging from +60 to -60) and the shares of total LUC for both scenarios (reflecting the regional effectiveness of ES change and linkage). ESA values in bold indicate highly significant values in terms of LUC and thus ES change

Land-use transition		Σ ES changes	ES linkages (+) & (-)	ESA value change	% LUC	
					Shrinkage	Growth
Arable land	Services	-3	E F CR B C	-26.6	0.01	1.76
Arable land	Industrial area	-3	E F CR B C	-24.3	0.19	2.35
Arable land	Urban brownfields	**-5**	E F CR B C	-24	0.54	0.99
Arable land	Commercial area	-3	E F CR B C	-21.5	0.16	**4.19**
Arable land	Residential park	-2	E F CR B C R	-19.9	0.14	**4.67**
Detached houses	Urban brownfields	**-5**	E CR B C R	-19.8	0.15	0.09
Arable land	Airport	**-5**	E F CR B C	-19.7	**11.67**	**9.37**
Arable land	Urban green space	-3	E F CR B C	-19.3	**5.66**	1.31
Forest	Services	-4	E CR B C	-19	0.01	0.35
Forest	Urban brownfields	-4	E CR B C	-16.4	1.63	1.75
Forest	Urban green space	-4	E CR B C	-11.7	1.43	1.02
Shrubs & trees	Urban brownfields	**-5**	E F CR B C	-8	0.18	0.12
Pasture	Urban brownfields	**-5**	E F CR B C	-7.1	0.99	1.23
Pasture	Commercial area	-1	E F CR B C	-4.6	0.46	**3.06**
Arable land	Detached houses	-2	E F CR B C R	-3.2	**16.24**	**25.68**
Pasture	Urban green space	-1	E F CR B C	-2.4	**6.63**	2.65
Industrial area	Urban brownfields	2	E CR B C	1	**4.98**	1.98
Urban brownfields	Commercial area	0	E CR B C	2.5	**3.37**	**3.26**
Urban brownfields	Urban green space	4	E CR B C	4.7	**8.31**	**5.94**
Suburban village	Villas	4	E CR B C	10.8	x	0.47
Multi-story prefab	Residential park	**5**	E CR B C	11.9	0.08	0.21
Urban brownfields	Villas	**5**	E CR B C R	16.4	0.58	0.92
Industrial area	Villas	**5**	E CR B C R	17.3	x	0.36
Suburban villages	Arable land	4	E F CR B C	18.6	0.12	0.02
Urban green space	Arable land	3	E F CR B C	19.3	0.31	0.22
Commercial area	Arable land	3	E F CR B C	21.5	0.16	0.08
Urban brownfields	Arable land	**5**	E F CR B C	24	1.26	0.26
Industrial area	Arable land	3	E F CR B C	24.3	1.43	0.2

E=Energy provision, F=Food provision, CR=Climate regulation (emissivity), B=Biophysical regulation (PMV), C=Net carbon storage, R=Recreation

4 Discussion

4.1 ES quantification and mapping

To calculate and map ES, quantification models were introduced on the basis of 23 land-use classes that proved solid and easy adaptable. Land-use related ES values showed comparable results to other ES approaches (Burkhard et al., 2012; Haase et al., 2012b; Kroll et al., 2012;

Schwarz et al., 2011). However, differences occurred due to regional specifics of land-use composition, methodological and scale-related inequalities and the availability of input data, which are key challenges for comparing ESA from different regions (Seppelt et al., 2012). We evaluated six ES indicators on the regional scale and in the form of ES supply maps on the local scale. The observed spatial patterns followed the expectation of urban-to-periurban ES distribution (cf. Kroll et al., 2012). The applied normalization enabled us to interrelate all six land-use-based ES and to obtain aggregated ESA values. These results are, under specific conditions, transferable to other study regions (cf. 4.3). On the regional scale, provisioning services showed a high spatial dispersion whereas regulating services showed a considerably lower regional dispersion with higher regional mean values, indicating respective regional ES potentials (Table IV-2). We detected that low-density residential land uses, i.e. detached family houses and villas, were exceptionally positive in terms of ES benefits. It would, however, be wrong to conclude that dispersed and fragmented cities are desirable in terms of ES benefits; the regional perspective has to be considered, which would reveal a higher total ES loss due to the high consumption of beneficial arable land (cf. Tables IV-2 and IV-5). In addition, the costs of providing infrastructure and energy consumption and emission rates would increase due to more commuter traffic (Bart, 2010; Yang et al., 2011). This example emphasizes the need of integrated cross-scale ES assessments (Chan et al., 2006; Elmqvist et al., 2013).

A challenge in the ES concept for environmentally sensitive planning is the broad use of different ES indicators, e.g. in terms of the spatial scale and the functional meaning that affect the quality and the results of ESA. The selection of ES generally depends on available data and the regional peculiarities of the observed ecosystem which often results in a subjective choice and impedes interoperability (Elmqvist et al., 2013; Seppelt et al., 2012). We chose six ES indicators of special interest for the urban context, focusing on regulating services that are crucial for the long-term persistence of other ES (Bennett et al., 2009). The substitution of the climate-regulating indicator thermal emission by e.g. the normalized differenced vegetation index, might change the distribution of ES values across land uses, to give one example of the future challenges regarding interoperability and comparability. The presented approach focusses on shifts of final ES indicators based on LUC and not on intermediate ES (or supporting ES) relating to the underlying ecological processes (Fisher et al., 2009). Accordingly, we do not base ES shift on the causal ecological functions, but on statically derived (constant) mean values of land-use related spatial data to describe multiple ES indicators whereby ES dynamics due ecological processes changes are neglected.

Additional drivers within basic ES-quantification models would improve the dynamic behavior and spatial specifics of the ES values per land-use type considered so far. For instance, energy provision might be influenced by new stimuli or subsidies (or payments), which might affect the use of alternative energy sources and thereby reduce carbon emissions. Global climate changes might affect climate relevant ES (Bennett et al., 2009). General uncertainties also accrue from the use of land-use related ES regarding spatial concordance and harmonization, which are unable to describe small-scale ecological functionality (Bennett et al., 2009).

4.2 Scenario based ESA (ES flows and linkages)

Scenario analyses are essential to looking forwards and valuing ES effects regarding their integration with and support of human decision-making, and with regard to plausible futures (Daily et al., 2009). The introduced scenarios, which were based on the demographic and economic assumptions of local authorities (representing the maximum range), enabled the valuation of LUC-related ES flows with regard to altering drivers for the simulation period (2008-2030; SDUDEB and SOBB, 2009). Due to the increase in built-up area (primarily for residential use) even under shrinkage (cf. sect. 2.2 and app. IV, Table A-IV-1a), ES improvements on the regional scale are seen for only two ES in the growth scenario and three ES in the shrinkage scenario, which were induced by altered housing decisions and the increase in detached houses related to positive energy-provision values. Except for energy provision, all ES flows showed better values for shrinkage than for growth, as confirmed by the mean ES change rates (+2.3% for shrinkage and -2.4% for growth, cf. Table IV-3). The reasons were a higher increase of urban green space and lower increase of built-up area (Table IV-2). This is additionally confirmed by the mean normalized ESA value (the sum of all normalized ES values) for the entire urban region (for growth 26.47, for shrinkage 26.56, cf. Table IV-2), although providing relatively low differences despite high spatial variation.

As expected, we could show that for a growing urban population, the pressure on ES increases (with the simultaneous increase of ES demands), with possibly negative long-term effects on human wellbeing (Douglas, 2012). Human wellbeing has so far largely been considered with regard to material needs offered by provisioning services (MA, 2005); however, cultural and regulating services are suitable to affect human health and play a critical role for local livability, especially for poor and vulnerable urban dwellers that are the most exposed (Raudsepp-Hearne et al., 2010). Declining (climate) regulating services, as observed for urban growth, might for instance increase environmental stressors, such as urban heat or air pollutants (Douglas, 2012; MA, 2005; Scherer et al., 2014). The more positive ES flows under urban shrinkage are not, by implication, necessarily improving urban quality of life; in contrast, urban shrinkage might reduce public revenues, with potential negative economic and environmental effects on human wellbeing (Haase et al., 2012). Thus, ES flows should always be considered in a wider socioeconomic context.

We considered ES linkages (synergies, trade-offs and loss) and provided supporting information on regional and land-use related qualities by uncovering the sensitivities of single land-use transitions and by showing the regional dispersion of ES linkages (Figure IV-5 and app. IV, Figure A-IV-3).On the regional scale considering all ES, linkages were more positive for the shrinkage scenario, with a higher rate of synergies and a lower rate of ES loss, even though the maximum rate of ES loss was attributed to urban shrinkage (Figure IV-4). The pairwise comparison of ES linkages helps in solving conflicts between competitive ES, as was particularly evident for energy versus food supply, revealing that a decreasing value of food provision cannot be surrogated by energy provision (Table IV-3). The higher energy-provision rate obtained for urban-growth-affecting ES linkages demonstrated the importance of scenario-based ES linkages to resilient ESA (Butler et al., 2013). The results have the potential to present trends of ES linkages with regards to LUC, which would be useful for communication processes of planners, stakeholders and urban dwellers, but are rather limited in terms of controlling them (without changing the land use), e.g. to minimize trade-offs or to enhance synergies locally, as no ecological interactions are integrated in our land-use approach (Bennett et al., 2009)

The Multi-criteria ESA matrix gives an overview of relevant information in order to evaluate ES flows and linkages regarding the scenario-specific extent (the quality) of observed land-use transitions. The shrinkage scenario proved to be favorable in terms of ES improvement, as numerous urban brownfields that originated in dense residential or industrial uses were transformed into new urban green spaces with superior ES qualities. Additionally, the extent of positively related land-use transitions was generally higher while being lower for negatively related transitions. Also, contrasting urban development trends, such as reurbanization and suburbanization, could be compared. Both showed equally moderate ES loss; suburbanization, however, is quantitatively and regionally critical, as it yields the most total LUC, with space-consumption rates almost three times higher than reurbanization (Table IV-5 and app. IV, Table A-IV-5). Local effects and differences between scenarios were found for the whole region at slightly higher rates in the hinterland than in the inner city due to relatively high rates of suburbanization, revealing stronger ES impact due to urban growth (cf. app. IV, Figure A-IV-4). The scenario-based results presented in this study focus on LUC (including its drivers) and do not provide other factors causing flows of single or multiple ES (Daily et al., 2009); with consequences for the observed ES linkages (sect. 4.3).

4.3 Contribution to a more general system understanding

The combination of LUC and ES modeling provided insights in the functional interrelation of socioeconomically and demographically driven LUC and the associated effects on multiple ES within an urban-to-periurban region (cf. Haase et al., 2012b). The LUC model covers the demographic dynamics of a diverse urban population (households) that makes complex residential decisions in the urban environment. This environment is controlled by planners, who mediate between different human interests (of households and businesses) and the environment. Sensitivity analysis revealed that population decline neither consequently nor immediately affects residential or ES supply (cf. Table IV-3). We showed that regional ES flows are especially sensitive to the occurrence of urban green areas (forests, green spaces) and agricultural area and to a lower extent to residential LUC.

The low explanatory power of total population shifts derives from the fact the urban development depends on numerous complex factors (cf. Batty, 2007 and sect. 2.2). One of them is the demographic composition, which can influence urban developments at equal population numbers and by that influence ES. In our results we showed that, for instance, an increase in single households with high consumption of per-capita living space increases residential land consumption to the extent that even under population decline land consumption continued. Analogous to observed development trends in Europe, our results revealed that population aging accelerated the subsequent individualization and by that land use consumption and ES loss (Buzar et al., 2007; Haase et al., 2007). Another critical economic factor is the construction of new residential land that does not necessarily reflect the real needs or demands, as was shown by the recent real-estate crisis in several countries.

We found that human-decision-driven LUC (including urban dwellers and planners and businesses) provide satisfying explanations for urban ES flows, especially on the regional scale, and thus should be integrated in scenarios addressing urban ES, as it presents one of the major pressures for the urban ecosystem (Alcamo and Henrichs, 2008; Seppelt et al., 2012). The exceptional improvement of ES within the growth scenario (energy provision) and improving ES trends for shrinkage underline the added value of such scenarios by revealing the complexity of cause-and-effect relationships between LUC and ecosystem services, despite existent uncertainties (explained below and in sect. 4.2).

An additional benefit to support system understanding would be to match data on ES supply with data on ES demand and to analyze in more detail the cause-and-effect relationships between human-decision-driven LUC and ecosystem services (Burkhard et al., 2012; Seppelt et al., 2012). Accordingly, ES effects and potential consequences for human wellbeing should represent a feedback of human decisions within causal feedback loops so that, in turn, these consequences for human wellbeing change human decisions iteratively, e.g. in terms of residential choice or planning decisions (Figure IV-1). Such relations should be further investigated, although requiring detailed knowledge of individual or group-specific preferences, perception and sensitivities to define thresholds for decision-making (Batty, 2007).

ES correlation results provided information on ES linkages and indicate land-use related interdependencies (Table IV-4). On average, negative correlations defined trade-offs and positive correlations defined positive or negative synergies. However, these results provide only a basic scheme of how land-use-related ES are connected and where high potentials for trade-offs and synergies lie with regard to land-use transitions that are based on the regional specifics of considered land uses. To manage the relationships among ES the hidden mechanisms (whether ES interact with the same drivers, or interact among themselves) have to be revealed (Bennett et al., 2009; Daily et al., 2009).

4.4 A tool to assist participation and planning?

The proposed model combination can be utilized by local planners to estimate future ES flows from plausible and planned land-use changes in the context of regional and local effects. The integration of different scenarios allows for a comparative assessment of potential impacts for the entire region. For a simple valuation of local land-use decisions, the proposed ESA lookup table (Table IV-5) can be applied. An example given for the Berlin region is the construction of the new BBI airport, which was assessable in terms of multiple ES effects. Results can also be presented in maps showing the multiple normalized ESA changes indicating the anticipatory risk (app. IV, Figure A-IV-4). Together with the findings of empirical patterns of ES linkages (Table IV-4), model results might promote the development of strategies to mitigate ES loss and foster positive synergies—for instance, through precautionary land-use decisions. These should be adapted to local conditions to improve ES in areas with serious impacts. Conversely, areas of excellent ES provision can be identified and protected (Bart, 2010; Daily et al., 2009).

In the first attempt, we used uniform weighting for the integrative ESA; however, the meaning and the necessity of certain ES indicators might be judged differently under specific conditions or in specific regions. For instance, regions with higher exposure to urban heat stress rely more on climate-regulating services than regions in cold climates (Scherer et al., 2014). Expert knowledge, local decision makers and stakeholders (including urban dwellers) thus need to be integrated as a prerequisite for successful implementation of decision support with regard to ES improvement (Chan et al., 2006; McIntosh et al., 2011; Rawlins and Westby, 2013). The prioritization of ES requires accurate knowledge of who profits from which ES to which extent combined with a sophisticated local-specific understanding of ES linkages, e.g. to successfully define actions that provide synergies for different stakeholders (Elmqvist et al., 2013). Once again, the demand for ES should be integrated to provide further information on population distributions and vulnerability to adapt to ES losses or improve human wellbeing (Burkhard et al., 2012). In that context, the focus on urban neighborhoods could raise broader participation of urban stakeholders, and seems promising for community integration. The development of PES schemes could balance and prioritize stakeholder-linked ES and other economic interests (Huberman, 2009; Rawlins and Westby, 2013). Urban green spaces, which provide several regulating and provisioning services, play a crucial role in that (Elmqvist et al., 2013; Haase et al., 2012b).

The transferability of the multi-criteria ESA is limited by the fact that the normalization process for the ESA depends on regional land uses and their specific ES values defining the range. An inter-regional or national comparison of the applies ESA could be provided by defining, for instance, European maximum and minimum values of land-use related ES that are then used the normalization.

5 Conclusions

In this study, we estimate the effect of demographic and socioeconomic shifts and consequent land-use changes on ES flows and linkages using a combination of LUC and ES- modeling techniques. The empirically driven model combination verifies the dynamic link of household behavior and urban ES and enables scenario-based comparisons regarding effects of ES on the regional and the local scale and thus offers information for different decision levels. The consideration of land-use related ES linkages is suitable to reveal synergies and trade-off of competitive ES. Within a multi-criteria ESA, we address ecosystem protection in regard to the quality and the quantity of potential ES effects due to future land-use transitions. These findings are presented in a lookup table for urban decision makers and stakeholders in order to communicate human-driven environmental impacts. The study bears a lot of potential for a participatory approach but this has not been realized yet. The paper also contributes to the understanding of the complex cause-and-effect relationship between human decisions, land-use patterns and ecosystem services and provides new ways of judging urban growth and shrinkage in terms of their environmental impact and potential. For that purpose, natural and social science must be linked. In general, this challenging but important task is needed to understand the complexity of urban dynamics and the functional linkages of human decision-making and wellbeing. The effectiveness of diverse planning measures on ES supplies must be continuously tested on different scales. . The proposed model combination is transferable to other Central European urban regions, with the addition of some regional specifics. The model requires specific information on demographic shifts, housing preferences and the housing market in the case of varying urban structure types. The ES-quantification models are easily adaptable to similar urban regions of Central Europe.

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The supplementary material offers further information and results.

Chapter V:

Synthesis

1 Main conclusions

Using a combined model approach, different human decisions were investigated in order to analyze their respective effects on the urban system. Within this approach, reasoned land-use change (LUC) and its consequent effects on the urban pattern and the provisioning of ecosystem services (ES) could be uncovered. For this purpose, the joining of different system perspectives was essential, such as a demographic, a socioeconomic or ecologic ones. Interdisciplinary work is the key to understanding and to managing urban complexity, which becomes especially crucial when it comes to the link to human wellbeing.

By testing different scenarios with respect to their multiple consequences, the simulation model revealed its practical relevance. In this way, lessons could be learned about the system functionality, which showed distinct potential to support decision-making in urban planning by uncovering specific functional chains. The scenario-based simulation results provided causal understanding of negative effects, in terms of urban pattern and ES change related to processes attributable to specific human decision-making. The insights of the effects due to human decision-making can help to prevent the negative effects of eligible policies without having to experience them. Mark Twain (1835-1910) said: ”Good decisions come from experience. Experience comes from bad decisions”. When relating the decision-making process to urban planning, good decisions are those that promote resilient, sustainable and efficient urban planning with respect to human wellbeing and health. Adapting Twain's quote to this context, a comprehensible example could be the decision in Germany to promote human welfare and increase living space via the creation of a grant system for first-time home buyers, which was implemented in 1996 and one of the largest government subsidies to date (BGBI, 2005). The result was that the process of suburbanization was reinforced and accompanied by negative environmental effects, such as enormous land consumption and increased individual traffic and associated emissions (BUND, 2008; Rodt et al., 2010). Decreasing population numbers accompanied by increasing vacancy rates in the inner cities finally led to the decision to scrap the grant scheme (BUND, 2008). With a suitable simulation model including the appropriate parameters (such as presented in this thesis), “the experience” could have been drawn from the model simulation results, encouraging “good” decision-making straight away.

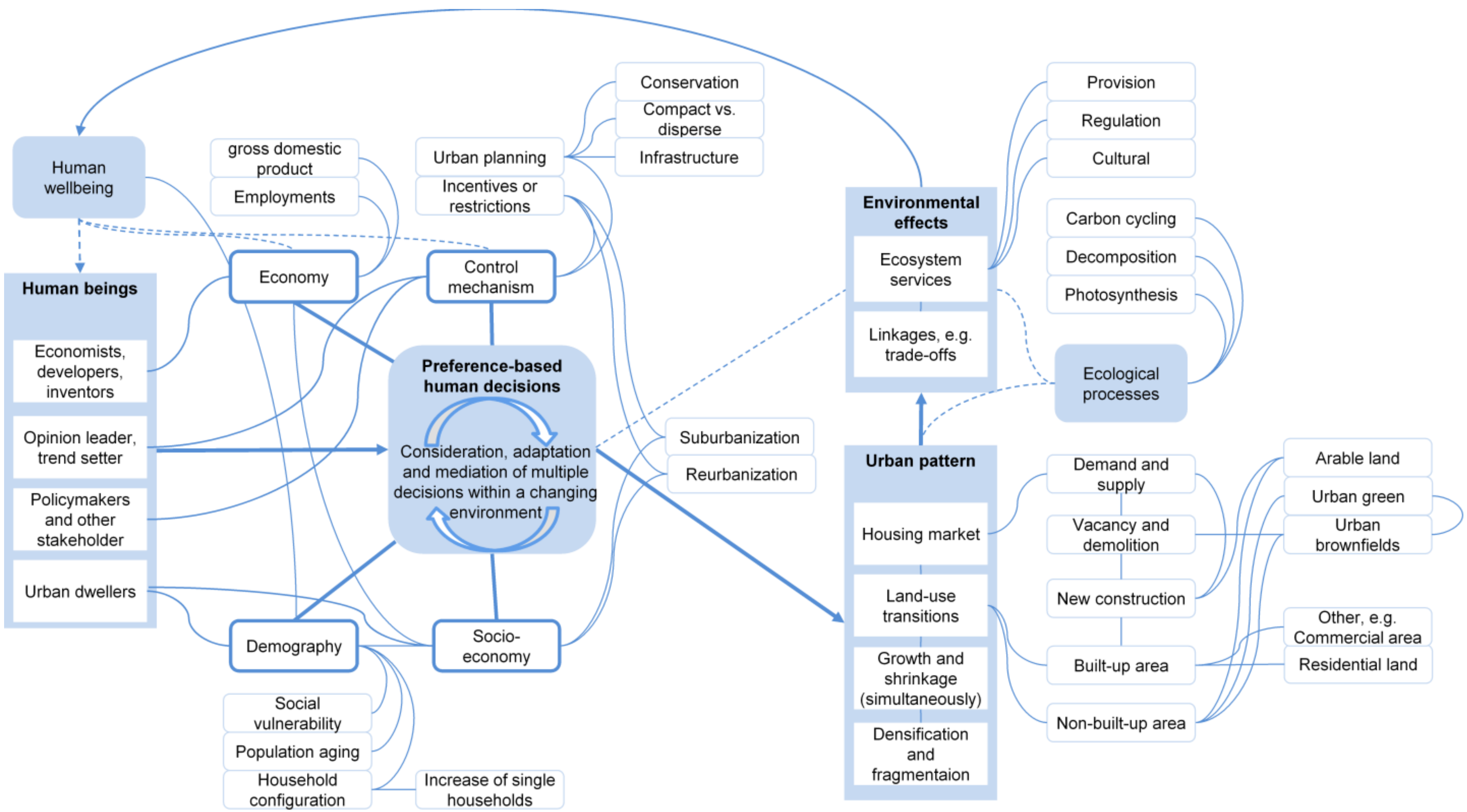

Figure V-1. Systematic overview of the considered urban system and its interrelated components and functional chains; dotted lines represent links that need to be further researched

Figure V-1 gives a systematic overview of the considered system components and interrelations, which will be referred to at different points in the conclusions. The following subsections are according to the overall research questions.

1.1 Model suitability

<u>*1. Overarching research question:*</u> *Is a combined model approach suitable to uncover urban system dynamics?*

To answer this question, the aspects considered in the evaluation of model suitability need to be clarified. In accordance with the research question, three subcategories are examined: (1) the model's suitability (related to content) in reproducing LUC and current urban processes, based on relevant human decision-making and model requirements (2) the improved model quality and validity with regard to the technical application under a combination of different model approaches, compared to traditional models, (3) the benefit of the combined model, with regard to the production of comprehensive and meaningful results, that could be relevant to political decision makers. These parts are presented within the next paragraphs under inclusion of the insights from chapter II, III and IV.

a. *What are the requirements for including reasoned human decision-making and current urban processes, such as urban growth and urban shrinkage?*

To cover the relevant processes and decisions, the participating actors of the system had to be identified and integrated into the model, together with their specific process-influencing decisions and factors, in an interconnected manner. The precondition was fundamental system knowledge from historical observations (cf. sect. I-4) and literature review as a basis for the definition of the intended system components and parameters (e.g. Alberti, 2008; Barredo et al., 2003a; Batty, 2007; Benenson and Torrens, 2004; Brade et al., 2009; Burkhard et al., 2010; Buzar et al., 2005; Douglas, 2012; Forman, 2008; Haase et al., 2012a), considering that the model can only be as good as the existing insight into the depicted system (Shilling et al., 2005). The urban system from the urban to peri-urban extent defined the system boundary (Ravetz et al., 2013). The manifold processes influencing the urban system are introduced in chapter I. Both system boundary and the variety of urban processes are well-represented by the study region (cf. chapter I-4).

All exogenous system influences through global processes such as climate change, or endogenous influences through spontaneous environmental disturbances such as natural disasters, were not considered. The predominant element influencing the system is the human factor, which has numerous land-use impacts which increase proportionally to the urban population (Alberti, 2008). Consequently, the integration of population dynamics is an elementary model component.

The urban population of Berlin and the urban to peri-urban population of Berlin's surroundings were structured into representative age groups, with respective migration trends and trend-influenced fertility and mortality rates, and linked by migration dynamics. To gain more insight into the demographic structure of the population, the population amounts per age groups were transferred into lifestyle-oriented household types. This enabled a more precise and causal consideration of the process of demographic change, including population aging, family decline and the increase of smaller households (cf. II-3.1). Accordingly, the population development was attributable to complex demographic relations and not only simple change parameters.

The urban system is to a high degree shaped, influenced, and formed by numerous, interrelated human activities. Thus, the most relevant activities regarding spatially-related environmental effects had to be identified. They are, in turn, attributable to respective actors that make decisions based on several influencing factors (Haase et al., 2012a).

Urban dwellers compose the biggest group of actors and decide individually on housing locations, employment, consumer goods and recreation (Colwell et al., 2002; Forester, 1987; Whitehead, 1999). The group of developers and investors respond to expressed demands within a demand supply function, eventually deciding to increase the supplied goods and services along with the area in the city needed to offer them, e.g. by transforming land from non-built-up to built-up area, or vice versa. Spatial transition is controlled by planning actors, who implement via land-use and zoning plans the future designation of new development or recreation areas, based on current processes and their effects. They also enforce top-down political decisions by implementing centrally directed changes in planning, as is the case with new transportation routes (Dutta, 2012; Forman, 2008). This includes the airport transitions in the case study region.

Due to the fact that the life function habitation (housing) with its resulting implications on residential land is the most important and most effective activity in terms of extent (Alberti et al., 2007), (app. V, Table A-V-2), its causal derivation was a necessary requirement for the model. For that purpose, a market-oriented residential choice algorithm was developed by integrating residential preferences related to household types representing similar socioeconomic specifics and decision patterns. Residential preferences were derived from relevant decision variables determined in studies of housing satisfaction, resulting in eight variables such as housing cost, security, education among others (Haase et al., 2005; Lauf et al., 2012c), (cf. II-3.1).

Together with the underlying demographic development, living space demand could be generated as a function of residential decision-making and living space supply. The demand-dependent supply, which describes the stock in the housing market, was defined as the sum of the typical and predominantly available residential types characterized by their structure and density (cf. Figure I-2), as well as by the respective decision variables (as used on the demand side) which dynamically change under demand shifts, e.g. the increase in housing cost under demand increase. Thus, demand and supply contain a closed feedback loop, which increased the dynamics of residential decision-making. In order to realize demand-related supply shifts in terms of growth or shrinkage, the housing parameters new construction, vacancy (a function of depletion and reuse) and demolition (a function of vacancy) were integrated. The resulting living space supply per residential type was then transformed into respective land use areas, applying the floor space index (Lauf et al., 2012c), (cf. II-3.1).

Human activities related to the life-function work are spatially relevant for the supply of job locations, which are related to developments in the economic, agriculture, manufacturing and service sectors (Capello and Nijkamp, 2004). Accordingly, the quantitative land uses of commercial, industrial and public and private services were calculated based on the gross value added (GVA) per economic sector, the regional gross domestic product (GDP), and the demand of the total population. Agricultural land is a function of change in these built-up classes (cf. sect. II-3.1; app. IV, Table A-IV-1a).

Probably the most popular human activities refer to the life-function of recreation that, to a large extent, is associated with the call for urban green spaces which provide abundant recreational ES (Douglas, 2012). The class urban brownfields was found to represent a transitional class which could potentially lead to new urban green space, if it was accessible and not otherwise requested. This is in part due to the supporting natural successional processes (De Sousa, 2003), (cf. chapter IV). Thus, urban green space provision was considered to depend on the development of urban brownfields, which stated a function of new construction and demolition of urban built-up uses (cf. II-3.1).

In addition to the passive land-use classes that were considered to be constant during the spatial allocation of quantitative LUC (e.g. water bodies or infrastructural areas), all non-built-up classes—namely arable land, pasture, shrubs and trees, forest and open space—were considered as a function of the actively changing built-up land use classes described above (including urban brownfields and urban green space), in accordance with the real processes of urbanization (Benton-Short and Short, 2008). The superordinate control element is urban planning, e.g. by designating specific development paths or conserving certain areas. Following this, the spatial translation of the varying activity-based decisions was realized in a CA, using the Metronamica software (RIKS, 2013).

In this process, the present land use configuration, the respective requirements on infrastructural accessibility and planning were considered. Neighborhood relations between pairs of land-use classes representing either the effects of attraction or repulsion were integrated using distance-decay functions, which were derived from the overall land-use distribution (cf. sect. II-3.2; Figure III-1). The infrastructural requirements on the modal split for each actively changing land-use class were integrated according to their meaning and distance, which also resulted in distance-decay functions (cf. sect. II-3.2 and app. V, Table A-V-1). For this we used the street network, distinguishing between federal roads and autobahns, and the access points to public transportation, distinguishing between regional train traffic stations and local train traffic stops, including metro, tram and city train stations and stops (Figure IV-2; app. V, Table A-V-1). All these factors regarding accessibility, neighborhood relations, planning, and quantitative LUC resulted in a transition potential map for each class, from which an overall land-use map maximizing the respective potentials was created (RIKS, 2013), (cf. sect. II-3.2).

Manifold urban processes were detected through the analysis of spatial land-use dynamics, which was carried out using simulations at different points in time. These processes included suburbanization, with an increase in decentralized low-density residential area; reurbanization, with an increase in centrally-located dense residential areas; and urban growth or shrinkage (cf. sect. V-1.1c, chapter III). For an improved and more detailed understanding of the decision-related spatial effects in the urban to peri-urban region, suitable tools had to be applied to characterize urban pattern dynamics. To this end, landscape metrics and process-related urban form parameters were utilized on the basis of the entire region and pre-defined sub-areas (cf. Table III-2).

Beyond that, the simulation results were used to determine the environmental relevance of specific decisions causing land-use dynamics, by applying the concept of ES and ES assessment (ESA) related to the model outputs (i.e. land-use maps), (cf. chapter IV). Relevant ES and ascertainable indicators were selected, under the inclusion of various spatial statistics, determined, and finally, normalized within an overall ESA, in order to analyze multiple ES and their linkages (cf. Table IV-1; Table IV-2; Table IV-5).

The uncertainties revealed in the model are discussed in the following section, which discusses the technical suitability and validity. Useful decision feedback for improving the reproducibility of the system (not considered thus far), additional beneficial model functionality, and the possibilities of other model concepts, are discussed in the outlook of the thesis (chapter V-2).

b. Is the model qualitatively sound?

It was possible to successfully test the quality of the combined LUC model, including system dynamics (SD) and cellular automaton (CA). A meaningful and expedient conclusion regarding model quality generally requires a strict separation of observed (input) parameters (used for the model calibration), and observed (output) parameters (used for the model validation), in comparison with simulated parameters (Agarwal et al., 2002; Van Vliet, 2009). The validation posed a challenge because of the large extent of the study region, which crossed the administrative borders of Berlin and reached into the federal state on Brandenburg. This led to spatial data difficulties in terms of temporal consistency. Due to the excellent provision of statistical data in both federal states, the non-spatial SD model was tested initially, before testing the combined model (cf. sect. II-3.4).

The SD model was calibrated, taking data from the period between 1992 and 2001 to determine specific model variables and trends (cf. sect. II-3.4 and II-4.1). The validation was done for the time step 2007 in the simulation period 2001-2007, while acknowledging and critically discussing the fact that short simulation periods result in comparably better results (Van Vliet, 2009). Mean relative deviation, linear correlation and regression analyses were taken into account for the evaluation, resulting in convincing results for the development of population, household types and residential types. An unexpected trend revealed that with increasing model depth (analogous to an increasing dependency from other factors), the approximation to observed data improved (Figure II-3; app. II, Figure A-IIb-1 and A-IIb-2). Additionally, the SD model had already been successfully tested in another urban region under the same conditions (Lauf et al., 2012c), increasing the acceptance of the model in terms of quality.

The spatially explicit CA model was validated through the application of two land-use maps, available for the entire region. Due to a higher temporal resolution of land-use data for Berlin, the study region was divided along the Berlin city border and only data for Berlin were used for the model calibration, which represents 30% of the entire region. This step is justified due to the fact that the whole region includes urban to rural characteristics with relatively dense cities in the surroundings (e.g. Potsdam), and rural characteristics within the Berlin city border, with large agricultural and forested areas (cf. Figure III-1).

Land-use data between 1992 and 2007 were considered for the calibration. The above mentioned neighborhood effects, described as distance-decay functions, were calibrated by optical interpretation, analysis of cell transitions and recommendations from Metronamica for the calibration process (RIKS, 2007). For the calibration of the accessibility parameters, the mean distance of the land-use classes to the road and rail networks was analyzed. Urban planning was integrated using current land development and zoning data for the entire region (Table II-1).

The validation of the combined model included the mean absolute percentage error (MAPE) and mean relative deviation (MRD), as well as kappa values, which were calculated after the simulation run of 15 years (1992-2007). Due to several uncertainties in using these stand-alone values without any reference, a null model was used to compare the proposed model with a conventional CA model (Pontius Jr. and Petrova, 2010), (cf. sect. II-3.4). In doing so, a higher agreement could be achieved in the tested parameters, and the added value regarding the explanation for the improved land-use patterns was revealed (cf. Figure II-4).

Consequently, the proposed model combination provides a technical and content-based information improvement due to the integration of the above-described model functionality. It represents the decision-making process of relevant actors, which is characterized by highly dynamic model components due to the integrated feedback loops.

Another qualitative aspect refers to the individual model techniques of SD and CA. By combining both SD and CA, the model benefits from respective advantages, and at the same time reduces individual disadvantages, such as the weak capability of spatial explicitness for SD or the relatively weak integration of dynamic behavior in CA (cf. sect. I-2.1 and I-2.2). In addition to the higher degree of accuracy and itemization of modeled LUC compared to other CA (revealed with the null model), the model results could be compared to another cellular approach using the urban growth model SLEUTH (Heinsch et al., 2012). For calibration in SLEUTH, methods of spatial statistics are applied to a minimum of four historical land-use maps, while predominantly ignoring causal relations. The reduction from different built-up uses to only one class provided poorly differentiated knowledge in terms of LUC and does not allow for the simulation of urban shrinkage processes. These facts speak in favor of the proposed LUC model.

Transferability was considered as well, as it is a crucial aspect when evaluating model quality (Batty, 2007). As already mentioned, the SD model was transferred to the city of Leipzig with relatively little effort and provided conclusive results (Lauf et al., 2012c). Only local census data were required to be analyzed. The CA model implemented within the Metronamica software was solitarily applied in numerous studies with highly diverse study areas (Aljoufie et al., 2013; RIKS, 2013; Stanilov and Batty, 2011; Van Delden et al., 2007), thus confirming its transferability. One of the most challenging tasks when applying the Metronamica model was confirmed to be the extremely sensitive calibration process of the neighborhood functions (Hewitt et al., 2014; Van Vliet et al., 2013), (sect. V-1.2). The adaptation of the integrated residential decision-making process from the combined model to cities considerably different from European cities, however, was challenging due to the amount of data evaluation required when defining the integrated model parameters (cf. e.g. Figure III-2). Thus, a good data infrastructure is called for (Lakes et al., 2011).

The spatial resolution of the CA consists of a grid cell size of 50 x 50 m, which represents a good compromise between a high local resolution and the spatial extend of the region (cf. sect. I-4). In this way, detailed analyses regarding urban pattern shifts and environmental impact (on ES) due to LUC were enabled on the local and the regional scale (chapter III and IV). The respective methods applied in chapter III and IV in addressing the urban pattern and the ESA (based on LUC) do not require explicit tests to judge the quality of the respective calculation models. The use of landscape metrics and other urban form indicators validly depict accepted spatial statistics to describe the urban pattern (e.g. Schwarz, 2010; Zhou et al., 2011). The calculation of ecosystem service indicators was based on simple non-dynamic calculation models, similarly to other studies (Haase et al., 2012b; Kroll et al., 2012). Their plausibility was discussed with regard to results from other studies (cf. sect. IV-4).

c. *What are the benefits of the proposed model?*

The presented LUC model allows for the reproduction of currently relevant urban processes related to actor-based decision-making, such as those observed in many European cities. These include demographic change, urban growth and urban shrinkage, reurbanization and suburbanization, LUC (including the loss of arable land or the increase of urban green space), the decreasing compactness of the urban pattern or the loss of ES (e.g. Brade et al., 2009; Kasanko et al., 2006; Turok and Mykhnenko, 2007), (cf. sect. III-1).

Due to the causal linkages within the model and the integration of demographic, economic, socioeconomic and planning-related variables, the effects of interrelated and interdependent processes can be explored. Sociospatial processes (e.g. residential and accessibility preference shifts), planning modifications (e.g. changes in zoning maps or traffic infrastructure) and aspatial processes (such as population decline, population aging, the increase of smaller households or economic changes (including deindustrialization)) can be simulated and evaluated according to their spatial effects, e.g. in terms of land use or urban pattern change, as well as in terms of their associated environmental effects (i.e. ecosystem service changes), (cf. chapter III and IV).

This was only possible through the integration of the (most) relevant actors and decisions contributing to urban change. The strength of SD for revealing complex dynamics provided the model basis for the causally explicable LUC, especially in terms of residential LUC, predominantly affecting the urban system (cf. sect. V-1.1a). With that, the detailed classification of residential land use enabled the revelation of residential choice and housing market processes. Furthermore, it enabled the analysis of detailed land uses changes that later enabled detailed analyses of the consequent urban patterns and ES shifts along the urban to peri-urban gradient. Thus, a high level of detail regarding urban dynamics can be revealed under the model.

The integration of housing parameters (new construction, vacancy and demolition) and the dynamically-changing transition class urban brownfields made it possible to reveal urban shrinkage and urban growth processes. This is a considerable difference from conventional LUC models that are mostly solely limited to urban growth (Batty, 2007). The reproducibility of both processes becomes crucial in the context of several European cities development's, which are on the edge to downturn (e.g. Haase et al., 2013). The model is able to provide insight about the origin, pattern and effects of urban shrinkage, thus closing existing gaps of the relevant cause-effect-relationships (cf. chapter III and IV).

The connection of the LUC model to (1) an urban pattern analysis method, and (2), an ESA model (both indicator-based and repeatable), makes it possible to affiliate urban pattern and ES shift to human-induced processes. The normalization process integrated in the ESA model also allows it to interlink multiple ES and to evaluate these linkages in terms of synergies, trade-offs or multiple loss, which is a crucial necessity to correctly judge the human-induced impact on the environment (Haase et al., 2012b). The assignment of ES to each land-use type, presented in a look-up table, allows for the distinguishing of the ES effects of equal human activity. For instance in terms of housing it matters which residential type you choose, e.g. a high rise building complex has a different effect than a detached house (cf. Table IV-2).

The ascertained model quality confirms the models usage for analytical purposes, in the form of scenario analyses. Modifications in the initial model parameters enable one to test manifold scenarios to provide insights into the system's functionality. Possible future developments under specific scenarios could support decision-making for planners or politicians, so that undesirable developments or potential risks could be recognized early, allowing for the development of early mitigation or adaptation strategies, e.g. through incentives or restrictions, or reversely, positive developments, e.g. in terms of the promotion of ES provisioning (cf. sect. III-4 and IV-4).

1.2 Improved system understanding?

2. Overarching research question: How does scenario analysis contribute to increase system understanding?

To improve understanding of the system, scenario analyses were used in order to test crucial inherent system interrelations. The 22 year simulation period (2008 to 2030) represented a compromise of reliability and sufficient scenario perspectives (cf. sect. III-2.2). The applied scenario assumptions represent different parameter modifications, based on the knowledge of previous changes and the knowledge of important system drivers (cf. sect. I-2 and I-4). Contrasting demographic and economic assumptions were focused upon in order to compare the effects of urban growth and urban shrinkage in the urban-to peri-urban system (cf. chapter III and IV). Furthermore, the observed baseline scenario (BB)processes were increased to test exceeding development trends, such as population aging or reurbanization (chapter III). Additionally, not as yet introduced scenarios were created to test (1) the relevance of current planning decisions on land-use development (Lauf et al., 2012b), and (2) the meaning of shifts in accessibility preferences towards public transportation (Lauf and Schoenduwe, 2011). Finally, scenarios were combined to reveal the integrated system response of growth and shrinkage assumptions, i.e. regarding effect intensification or extenuation. An overview of all integrated and tested scenarios is given in Table V-1.

Due to the chosen systemic approach (cf. Figure V-1), the scenarios could be utilized to examine differing decision processes affecting housing-market-related residential choice, land consumption and LUC, the spatial urban patterns and ES changes. In this context, complex cause and effect relations became identifiable. To answer the above-raised research question, two aspects were considered, (1) the identification of common and deviating trends urban change until 2030, and (2) the analysis of model sensitivities and general systemic interrelationships.

Table V-1. Overview of all scenarios applied and tested using the proposed model approach; the listed drivers refer to Figure V-1 indicating the system context

Baseline (B)	**FB**	Free Baseline, like BB but without planning restrictions (except for the airport transition), enabling a more "free" development (driver: control mechanism)
	BB	Basic Baseline, development under planing restrictions and integration of the basic accessibility parameters, cf. Table A-V-1 (App. V)
... baseline development following a forward projection of demographic and economic trends, cf. chapter I-4	**AB**	Accessibility Baseline, like BB, but with implications of increased accessibility demand for public transportation (driver: socioeconomy or control mechanism), cf. Table A-V-1 (App. V)
	OB	Overaging Baseline, like BB, but with an increase of elderly people (driver: demography), cf. Table III-1 (chapter III)
	RB	Reurbanization Baseline, like BB, but with a preference increase for central living (driver: socioeconomy or control mechanism), cf. Table III-1 (chapter III)
Growth (G)	**FG**	Free Growth, like BG but without planning restrictions (except for the airport transition), enabling a more "free" development (driver: control mechanism)
... increment of the baseline development of demographic and economic trends, according to Table III-1 (chapter III)	**BG**	Basic Growth, development under planing restrictions and integration of the basic accessibility parameters, cf. Table A-V-1 (App. V)
	OG	Overaging Growth, like BG, but with an increase of elderly people (driver: demography), cf. Table III-1 (chapter III)
	RG	Reurbanization Growth, like BG, but with a preference increase for central living (driver: socioeconomy or control mechanism), cf. Table III-1 (chapter III)
Shrinkage (S)	**FS**	Free Shrinage, like BS but without planning restrictions (except for the airport transition), enabling a more "free" development (driver: control mechanism)
…reduction of the baseline development of demographic and economic trends, according to Table III-1 (chapter III)	**BS**	Basic Shrinkage, development under planing restrictions and integration of the basic accessibility parameters, cf. Table A-V-1 (App. V)
	OS	Overaging Shrinkage, like BS, but with an increase of elderly people (driver: demography), cf. Table III-1 (chapter III)
	RS	Reurbanization Shrinkage, like BS, but with a preference increase for central living (driver: socioeconomy or control mechanism), cf. Table III-1 (chapter III)

a. *Which common and deviating scenario developments can be observed between 2008 and 2030?*

Under the applied scenarios, both common and contrary processes could be observed. A summarized overview of simplified scenario-based system behavior is given in Figure V-2, assisting the detection of generalizable functionality within the complex urban system and revealing scenario-based system specifics. At first, the common, scenario-independent developments are revealed, to give an indication of generalized system response.

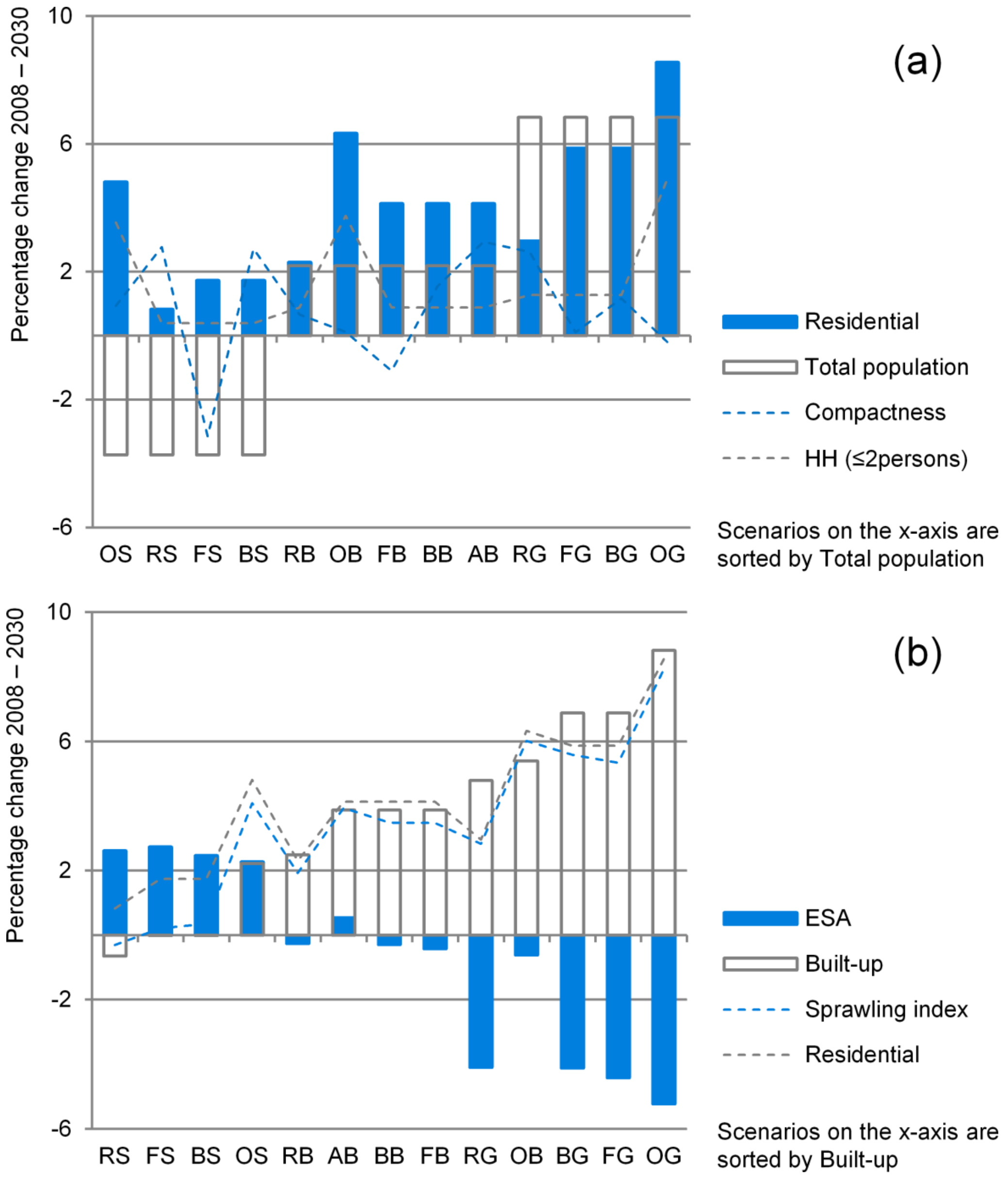

Figure V-2. Scenario specifics indicating general system interrelations; (a) regarding changes of demography, residential patterns and residential area; and (b) regarding changes of residential patterns, built-up area and the summarized ESA value

<u>Common development trends:</u>

An important and consistent change within the simulation period was the politically driven cross-cutting decision on the area-intensive airport substitution and transition. The two former airports Tegel and Tempelhof were given up and the airport Schönefeld was integrated into the newly built airport Berlin Brandenburg International (BBI), which was directed by planning decisions under inclusion of demographic and economic restraints (e.g. BF, 2010), (cf. Figure III-6; Figure V-1). This development was associated with considerable environmental effects, e.g. regarding local ES (cf. Table IV-5) and actors' location decisions due to new development opportunities (cf. Figure III-6), and gave evidence to the exceptional significance of planning decisions on urban and environmental change.

Another similarity refers to the pattern of residential development. In all scenarios, including the shrinkage scenarios (of population decline), the total supplied residential area increased until 2030, although revealing partially different dynamics (cf. Figure V-2). This was due to two observations, (1) the delayed model reaction towards demand shift on the supply side of about 10 years, e.g. in a supply reduction trough demolition only after a critical vacancy rate is reached, which is similar to the adaptation processes in real housing markets (Whitehead, 1999), (cf. sect. II-5); and (2) the agreeing demographic trends of the SDT with an increase in smaller households (≤2 persons, with 9% for BB), fostered by the increase of elderly people (>45 years, with 17% for BB), and associated with the decline of family households with children (9% for BB), (cf. app. V, Figure A-V-2). As a results, the per capita living space increased (at 1.1% for BB), which increased the residential demand and consequently the supplied residential area as well (3.8% for BB), (cf. app. V, Figure A-V-5). On these grounds, the amount of residential land can only partly be linked to the total population development, as indicated in Figure V-2, but rather depends on additional factors such as demographic specifics (e.g. SDT) and residential decisions (e.g. towards urban compactness).

One crucial and consistent residential dynamic became clear for all scenarios: the simultaneous occurrence of demand-controlled growth and shrinkage in different residential land uses (cf. app. V, Figure A-V-3a). The low perception of living in suburban villages or prefabricated multi-story housing resulted in a decline in the supply (Kabisch, 2005), (cf. app. V, Figure A-V-5); whereas all other uses represented an increase in supply. Consequently, differentiated residential developments based on preference-driven residential decisions occurred independently from superordinate scenario assumptions (e.g. growth or shrinkage). These residential trends found expression in differing urban processes, as described hereinafter.

The dominant increase of decentralized low-density residential area (detached housing) was due to the low floor space index (FSI; cf. Figure III-5; app. V, Table A-V-3). This development characterizes the process of suburbanization, which proceeded in all scenarios, albeit with decreasing tendency (app. V, Figure A-V-3a). The accompanied transition of non-built-up area (mainly of agricultural land) predominantly occurred in the inner periphery at the city edge, along existing urban structures. This had characteristic effects on ES provisioning, such as a reduction in regulating or an increase in recreational ES, resulting in similar regional ES changes across the scenarios (cf. Table IV-2; app. V, Figures A-V-4(a), A-V-10, A-V-21). This process represented the biggest interference with the urban system in terms of size (Table IV-5), which was confirmed in all scenarios (app. V, Figure A-V-3a), even in the inner-city-directed reurbanization scenarios.

Furthermore, an equal but opposite trend to the aforementioned one was the increase in central-located dense residential areas, such as inner-city blocks (cf. app. V, Table-A-V-3). This process of reurbanization was less pronounced in terms of area effectiveness, because of the generally lower expansion possibilities due to the high housing-stock density in central locations, and the obviously lower land consumption as living space increased, due to a relatively high FSI. The reurbanization process was mainly driven by the increase of smaller households (cf. sect. III-3.1). The spatial implementation occurred mainly on former urban brownfields that partly originated within the simulation period, resulting in compaction of the inner city (app. V, Figure A-IV-21). The local effects obtained on ES were lower than expected and showed to be comparable in terms of degradation to those obtained for the typical suburbanization pattern; for suburbanization high ESA values were almost kept and for reurbanization moderate ESA values were almost kept (sect. IV-3.2.3).

The development of intermediate residential uses—a transitional process for both aforementioned processes—turned out to be the most significant one in terms of living space alteration. This development included the (most noticeable) increase in the land use residential park, the (weaker) increase in villas and a simultaneous decrease in prefabricated multi-story housing (cf. app. V, Figure A-V-3a). The spatial extent of the corresponding LUC was only slightly lower than that obtained for suburbanization; however, with more living space realized at equal land-use extent (cf. FSI, Figure III-5). Only in the scenario RS did the strong decrease of prefabricated multi-story housing result in an overall decline of intermediate residential area (app. V, Table A-V-3).

The spatial implementation revealed a predominant occurrence of intermediate residential uses in the outer city and the inner periphery (app. V, Figure A-V-21). The development of intermediate residential uses showed a strong link with the development of elderly people (cf. sect. III-4).

However, there is traditionally a high continuance of elderly in decentralized low-density residential areas (after their children move out), linked to clear advantages in terms of well-being and health and promoted by good ES provisioning. However, this is also linked to substantial disadvantages due to the high dependency on car ownership, with individual transportation mostly representing the only transportation possibility, which is associated with high costs both fiscally and environmentally due to increased CO2 emissions (Douglas, 2012; Martins, 2012; Namdeo et al., 2011; Rosenberg and Everitt, 2001; Temelová and Dvořáková, 2012). In the case of age-related driving unfitness, this dependency could lead to serious limitation in accessing human activities and social contacts, eventually leading to social isolation (Fésüs et al., 2008). Additionally, the maintenance of large properties implies a high effort and high costs in old age.

In contrast, the inner city is characterized by excellent accessibility to all public and private services, while providing the lowest provisioning rate of ES (Elmqvist et al., 2013; Temelová and Dvořáková, 2012) and is the most affected by environmental stressors, such as noise, pollution and heat waves as climate change proceeds (Dugord et al., 2014; Honold et al., 2012).

In conclusion, intermediate residential uses confirm, from a strategic point of view, a compromise between good accessibility to public and private services and wellbeing promoted by ES provisioning, and therefore might depict the ideal future form of housing for the elderly regarding building structure and their spatial distribution within the urban region (cf. sect. III-4 and 5).

All these above-revealed processes in combination resulted in a representative spatially-influenced urban pattern from the urban to the peri-urban region, which was characterized by increasing effects with increasing distance to the city center (app. V, Figures A-V-10 to 14 and Figure A-V-21).

The overall consideration of ES using ESA revealed a decline of ES provisioning due to the increase of built-up area in all scenarios (cf. Figure V-2). Unexpectedly, energy provision and recreation showed to be positively influenced by the increase of residential area (app. V, Figure A-V-4(a)). The reason was the calculation basis for respective ES indicators. Recreation was represented by close-to-home green space provision, which increased due to the proximity of (mainly) new decentralized low-density residential areas to forested green areas at the city edge. Energy provision revealed a relatively high rate of photovoltaic devices for detached housing, which resulted in a positive development due to the increase of detached housing (cf. Table IV-2).

Deviating development trends:

Despite the equalities and similarities revealed, significant scenario differences were obtained, which are summarized in here according to the fields of demography, land use, urban pattern and ES (cf. app. V, Figures A-V-1 to 21 and Tables A-V-1 to 4). The differing scenario implications presented in Table-V-1 affected human decision-making and resulted in quantitative shifts in residential and other built-up uses, either by demographic (OB, BG, BS), economic (BG, BS) or residential preference shifts (RB), or resulted in shifts in the spatial allocation of built-up areas (FB,AB). Also, the effects of combined scenario assumptions were revealed (FG, FS, OG, OS, RG and RS).

An overview of the effects of individual (uncombined) scenario assumptions compared to the Basic Baseline scenario is given in app. V, Figure A-V-6, which summarizes significant system parameters. Very high percentage changes, e.g. for capita living space, are due to low change rates in BB (app. V, Figure A-V-5).

The effects of exceeded population aging (OB) showed to influence residential supply more than total population changes (BG, BS). Population aging (OB) and population growth (BG) revealed the highest land consumption rates, which were confirmed by an increased sprawling index, resulting in the reduction of compactness, accompanied by mostly negative effects on ES, especially for BG (cf. app. V, Figures A-V-6 and 13 and Table-A-V-3).

The scenarios RB and BS revealed positive effects, confirming the expectation that urban shrinkage and reurbanization reduce urban sprawl and are associated with ES increase (cf. app. V, Figures A-V-6 and 15 and Table-A-V-3). Additionally, the sociospatial process of reurbanization increased the compactness of urban build-up. Despite its benefits regarding land consumption and ES, reurbanization has to be viewed critically in terms of the processes involved, which potentially lead to increasing housing prices, gentrification and displacement (Bromley et al., 2007), as well as in terms of increasing built-up density that certainly intensifies heat stress events (cf. III-4).

The AB scenario showed a considerable increase of urban compactness due to the preferred allocation of residential areas close to public transportation access points, which improved regional ES provisioning (cf. app. V, Figures A-V-1, 6 and 12 and Table-A-V-3). This development speaks in favor of promoting the use of public transportation and attaching stricter conditions to the use of individual transportation, especially since it already comprises the highest environmental burden in the inner city (cf. Figure IV-3.).

The FB scenario revealed a significant loss of urban compactness and by that demonstrated the relevance of urban planning. However, the spatial preferences under an exclusion of planning restrictions might support current planning decisions by pointing out probable and suitable sites for new development, especially since no significant effects on ES were obtained (cf. app. V, Figures A-V-11, 6 and 7).

The individual scenario assumptions were combined to test the multiplying effects of the previously described scenario assumptions under growth and shrinkage conditions (cf. Table V-1). The influence of growth and shrinkage on the basic (BG, BS) and free development (FG, FS) scenarios showed to be relatively equal, representing the likely and expected maximum range of respective parameters in 2030 according to the growth and shrinkage assumptions (cf. Table III-1). Accordingly, a relatively high demographic deviation (~10%) showed relatively moderate differences in LUC (~5%) and ES change (~2%), (cf. app. V, Figure A-V-8).

For exceeding assumptions of population aging (OG,OS), the characteristics of demographic change strengthened under growth and shrinkage conditions leading to a cumulative effect on LUC, with a considerable deviation in the increase of intermediate residential uses between growth and shrinkage. Due to the comparatively high negative effects in OG and OS, the deviation in urban pattern and ES parameters is relatively low when comparing both scenarios. Among all scenarios, OG revealed the highest effects on the urban system (cf. app. V, Figures A-V-7 and 8 and Table A-V-3).

The exceeding assumption of reurbanization under growth and shrinkage conditions revealed contrasting effects on residential living space (less for growth, higher for shrinkage), resulting in a common reduction of total residential area under increase of centrally-located residential uses. Both scenarios revealed comparatively low negative effects. Among all scenarios, RS revealed the lowest effects on the urban system (cf. app. V, Figure A-V-4 to 8 and Figures A-V-18 and 19).

Chapters III and IV focus on the comparison of growth and shrinkage and reveal detailed information on the observed findings regarding urban pattern relations (chapter III) and regarding the impact on ES and ES linkages (chapter IV). Further information on the examined system parameters comparing all scenarios, with special attention to the implication of urban growth and urban shrinkage, is given in app. V.

a. *What are the major system sensitivities and which system relationships can be drawn from the scenario analyses?*

The chosen system approach (cf. Figure-V-1) allows one to imply a functional chain of demography-driven decision-making regarding land-use demand, under the inclusion of other factors and drivers, such as planning, economic conditions, preferences and initial housing parameters. This results in spatially explicit LUC that implies specific effects on the urban pattern and the provision of ES.

The effectiveness of driver changes was tested using simple sensitivity analyses that reveal the sensitivity of targeted parameters towards driver change (e.g. chapter III, eq. 1; chapter IV, eq. 19). Sensitivity analyses represent a widely used procedure for delivering valuable information on model behavior that are attributable to general system functionality (Dhawan, 2006; Sterman, 2002).

Under the application of the proposed and combined LUC model, residential supply was a main driver of LUC, which again showed to be moderately sensitive towards total population change; whereas the population was revealed to be very sensitive to shifts in fertility, mortality and migration parameters, with migration shift representing the highest effectiveness (cf. sect. II-5; Figure V-2; app. V, Table A-V-2).

The residential supply was additionally sensitive towards the FSI (defining the transition of living space to residential area) and the demand-driven housing parameters. These parameters (construction, demolition and vacancy) were found to be extremely sensitive, because their initial values direct the subsequent housing development until demand shift led to (possibly delayed) alterations (cf. sect. II-5).

A more detailed consideration of the demographic processes revealed that residential supply was sensitive towards small, elderly and family household development with significant impacts on single residential land-use types (cf. Figure III-11). Besides demography, economic parameters (e.g. GDP and employment data) represented crucial system drivers, especially for all non-residential built-up developments.

The spatial allocation of LUC applied by the Metronamica software revealed to be very sensitive regarding the integrated transition rules used to implement the neighborhood functions (Hewitt et al., 2014; Van Vliet et al., 2013), and thus require sufficient expertise within the calibration process.

The urban pattern showed to be sensitive towards different parameters in various ways with significant differences regarding growth and shrinkage and with varying characteristics along the urban to peri-urban gradient. Urban sprawling and dispersion were especially sensitive towards population aging and decline in household size, revealing a positive relation. Against that, urban compactness was especially sensitive to residential preference shifts towards central living, especially under growth conditions. Results revealed that this process was effectively increasing residential concentrations in the inner city and reducing the fragmentation of built-up areas in the outer city (Figure III-11; app. III, Table A-IIIc-1).

The sensitivity of ES towards other system parameters was shown in chapter IV. ES change was confirmed to be obviously driven by LUC, but also indirectly by population shifts that induce LUC (MA, 2005). However, ES were only weakly sensitive to population shifts due to the described model functionality, showing the relevance of other drivers affecting LUC in varying ways. Towards final LUC, ES reacted strongly sensitive, which found expression in the chosen ESA approach that is based on land-use transitions (cf. Table IV-3).

To reveal generalized relationships between relevant system parameters conclusively, their percentage changes between 2008 and 2030 were jointly considered for all 13 scenarios within correlation and bivariate regression models. As a result, systemic insights could be revealed regarding parameter dependencies and about the explanatory power of pairs of parameters, which could explain their respective relations. The sensitivities obtained largely found expression in the correlation and regression results shown in Table V-2.

The results shown in Table-V2 summarize the revealed functionality of the urban system and confirm the benefit of a systemic approach insofar that population and demographic shifts could provide adequate explanation for the occurrence of LUC, to a lesser extent for urban pattern change and partly very conclusive results for ES change.

The color distribution in the table descriptively shows the multiple impacts of LUC on the urban pattern and ES provisioning that were pursued within this thesis. New insights were accrued from the convincing explanatory power of ES change by urban pattern change, even along the urban to peri-urban gradient. The results prove, concurrent with other studies, the increasing ES pressure due to urban concentration and compaction, especially in the inner and outer city, and the loss of ES associated with urban sprawling (Bolund and Hunhammar, 1999; Haase et al., 2012b; Kroll et al., 2012; Tratalos et al., 2007) Above that, the high coefficient of determination between different ES, confirm the meaning of ES linkages and interactions, with regard to synergies, trade-offs and loss (cf. chapter IV).

Finally, the functional understanding gained from the urban system was translated into a simple functional chain, breaking down the existing complexity into a comprehensive and easily communicable scheme.

Table V-2. Condensed correlation and regression results between relevant system parameters; given signs reveal the correlation characteristics; a detailed presentation of respective values in given in App.V (Table A-V-5)

		Total population	HH ≤2 person	Child HH	Elderly HH (>45y)	Residential living space	Capita living space	Built-up	Residential area	Central-located dense	Inter-mediate	Decentralized low-density	Non-built-up	Agricultural	Green and forest	Sprawling index, SI	SI_ inner city	SI_ outer city	SI_ periphery	Compactness, ED·(-1)	(-)ED_ inner city	(-)ED_ outer city	(-)ED_ periphery	Fragmentation, PD	PD_ inner city	PD_ outer city	PD_ periphery	MEAN ESA	Energy provision	Food provision	Emissivity index	PMV index	Net carbon storage
		Demography				*Land use*										*Urban pattern*												*Ecosystem service*					
Demography	HH ≤2 person	(+)																															
	Child HH	(+)	(-)																														
	Elderly HH (>45y)	(+)	(+)	(-)																													
Land use	Residential living space	(+)	(+)	(-)	(+)																												
	Capita living space	(-)	(+)	(-)	(+)	(+)																											
	Built-up	(+)	(+)	(-)	(+)	(+)	(-)																										
	Residential area	(+)	(+)	(-)	(+)	(+)	(+)	(+)																									
	Central-located dense	(+)	(+)	(-)	(+)	(+)	(-)	(+)	(+)																								
	Inter-mediate	(+)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(+)																							
	Decentralized low-density	(+)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(+)	(+)																						
	Non-built-up	(-)	(-)	(+)	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)																					
	Agricultural	(-)	(-)	(+)	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(+)																				
	Green and forest	(-)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(+)	(+)																			
Urban pattern	Sprawling index, SI	(+)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(-)	(-)	(-)																		
	SI_inner city	(+)	(+)	(+)	(+)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(-)	(-)	(-)	(+)																	
	SI_outer city	(+)	(+)	(-)	(+)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(-)	(-)	(-)	(+)	(+)																
	SI_periphery	(+)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(-)	(-)	(-)	(+)	(+)	(+)															
	Compactness, ED·(-1)	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(+)	(+)	(+)	(-)	(-)	(-)	(-)														
	(-)ED_inner city	(+)	(+)	(+)	(+)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(-)	(-)	(-)	(+)	(+)	(+)	(+)	(-)													
	(-)ED_outer city	(+)	(+)	(+)	(-)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(-)	(-)	(-)	(+)	(+)	(+)	(+)	(-)	(+)												
	(-)ED_ periphery	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(+)	(+)	(+)	(-)	(-)	(-)	(-)	(+)	(-)	(-)											
	Fragmentation, PD	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(+)	(+)	(+)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(+)										
	PD_inner city	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(-)	(-)	(-)	(+)	(+)	(+)	(+)	(-)	(+)	(+)	(-)	(-)									
	PD_outer city	(-)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(+)	(+)	(+)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(+)	(+)	(-)								
	PD_periphery	(+)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(+)	(+)	(-)	(-)	(+)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(+)	(-)							
Ecosystem service	MEAN ESA	(-)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(+)	(+)	(+)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(+)	(+)	(-)	(+)	(+)						
	Energy provision	(+)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(-)	(-)	(-)	(+)	(+)	(+)	(+)	(-)	(+)	(+)	(-)	(-)	(+)	(-)	(-)	(-)					
	Food provision	(-)	(-)	(+)	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(+)	(+)	(+)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(+)	(+)	(-)	(+)	(+)	(+)	(-)				
	Emissivity index	(-)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(+)	(+)	(+)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(+)	(+)	(-)	(+)	(-)	(+)	(-)	(+)			
	PMV index	(-)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(+)	(+)	(+)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(+)	(+)	(-)	(+)	(+)	(+)	(-)	(+)	(+)		
	Net carbon storage	(+)	(+)	(-)	(+)	(+)	(-)	(+)	(+)	(+)	(+)	(+)	(-)	(-)	(-)	(+)	(+)	(+)	(+)	(-)	(+)	(+)	(-)	(-)	(+)	(-)	(-)	(-)	(+)	(-)	(-)	(-)	
	Recreation	(-)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(-)	(-)	(-)	(+)	(+)	(+)	(-)	(-)	(-)	(-)	(+)	(-)	(-)	(+)	(+)	(-)	(+)	(-)	(+)	(-)	(+)	(+)	(+)	(-)

- $R^2 < 0.25$ or p-value > 0.05
- $0.25 \le R^2 < 0.5$
- $0.5 \le R^2 < 0.75$
- $R^2 \ge 0.75$

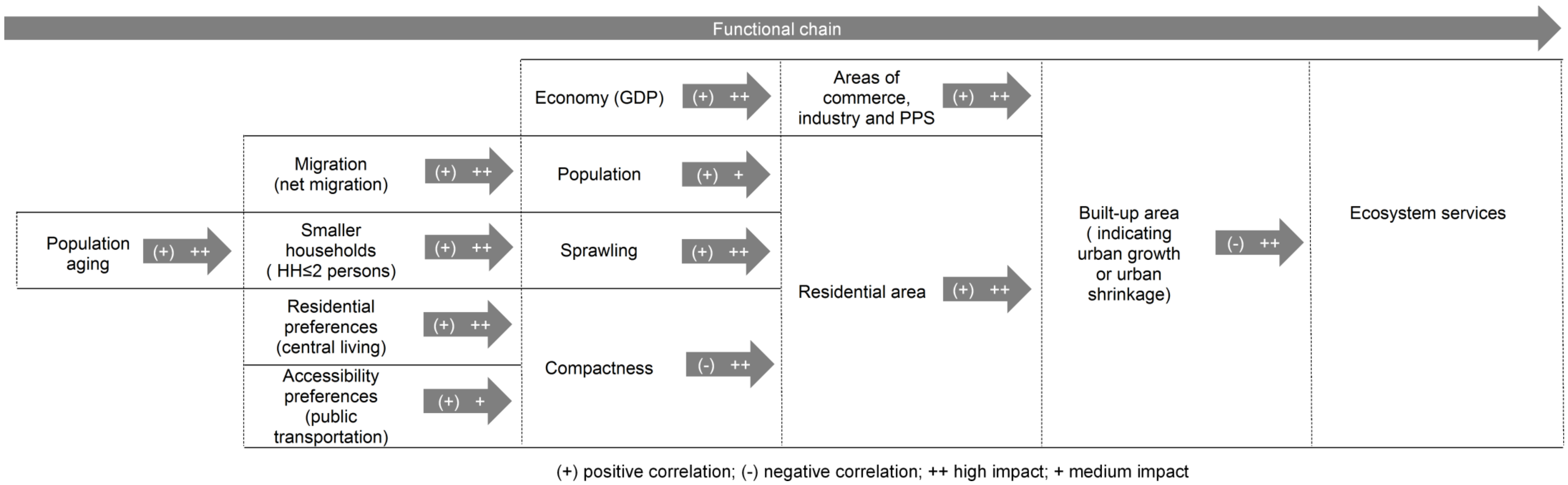

Figure V-3. A summarizing functional chain of urban system dynamics, from demography to ES change

2 Outlook

In the outlook of this thesis the focus is on the remaining research gaps and on the provision of possible approaches to close them. A closer look at Figure V-1 represents the so far not considered (missing) links within broken lines, which help to reveal interfaces for further research in conjunction with the presented systemic approach addressing the complex urban system.

The proposed model would additionally benefit from a closed feedback of decision-induced environmental effects connecting back to human decision-making. However, the fact that human decision–making is influenced by multiple biophysical patterns and dynamic processes (Alberti, 2008) implies that further evidence and explicitness is needed regarding their effects on human behavior. This is quite challenging, especially on the individual scale, as negative effects are often only recognized when it results in personal disadvantages, e.g. in terms of wellbeing (Douglas, 2012; Namdeo et al., 2011; Uejio et al., 2011), (cf. Figure V-1: missing link). It requires environmental awareness and widespread knowledge of the multiple (partly slowly) decreasing ES, in which a societal perspective on cultural values might increase participatory forces affecting decisions-making (Bai et al., 2010; Hewitt et al., 2014; Rawlins and Westby, 2013). Accordingly, cultural needs, environmental perception and the valuation of nature might lead to changed decisions aiming at conservation, and thus need to be continually investigated through qualitative and quantitative studies.

One example illustrating this link is the city of Stuttgart (Germany), where in 2010 people from different social classes manifested to prevent the conversion and extension of the local main station (Dietrich, 2013). The main reason was the enormous building cost for the city; however, the protest was triggered by the targeted cutting of 200 year old tree populations in the neighboring Schlossgarten park, which became symbolic for the protest. Protesters chained themselves to the trees or constructed tree houses to stop the felling, resulting in the summoning of an external and independent expert group and leading to a compromise that most trees were transplanted (Dietrich, 2013).

Such processes of bottom-up participation reveal the power of human decision-making in affecting political or planning decisions through an environmental consensus, in which detailed (scientifically-based) information are not necessarily required. Participatory decision-making represents a powerful instrument and is the key to environmental justice and fair planning (Bai et al., 2010; Matthies et al., 2007).

Despite the enormous progress in ES research (e.g. providing land-use-based information on ES), revealing ES linkages, including critical cause and effect relationships (as presented in this thesis), policymakers and planners are still obstructed against including ES tools for decisions-making (Crossman et al., 2013). The reasons for these restraints are partly understood and still need to be constantly revised in order to improve existing ESA models aiming-at a broader future implementation. The obstacles are due to missing standards in ES approaches, resulting in different models, scales, and target units and not-fully-integrated ecological processes behind ES (Seppelt et al., 2012), (cf. Figure V-1: missing link).

The integration of ecological processes on continuous spatial scales should be implemented in order to assess ES from a single tree to the regional and eventually global scale. In this manner the required functions for the provision of interlinked ES and those provided by interlinked ES could be considered systematically and thus be protected more efficiently (Elmqvist et al., 2013; Huberman, 2009).

For decision-making aiming at conservation, which is the only alternative in view of limited resources and the increasing necessity of resilient cities, economic-based schemes are needed to integrate ES tools into existing planning instruments, such as broadly applied environmental impact assessments (Huberman, 2009; Liu et al., 2008). To accomplish that, the evaluated effects on multiple ES (regarding trade-off, synergies and losses) under the inclusion of the required and provided ecological functions need to be considered with regard to their scale-effectiveness. This encompassing tool should be applicable to evaluate any kind of environmental impact relevant for planning, and needs to finally result in a monetary value that enables the full compensation of multiple ES effects in proximity, at the moment before loss (including acquisition costs and expenditure of human labor), (cf. Bastian et al., 2012; Daily et al., 2009).

Such an economic-based ES tool would effectively promote and increases urban resilience and maintains ecosystem services and functions (Seppelt et al., 2012) by launching the reconsideration of a cost-intensive decision (in terms of ES effects) and accordingly balance environmental degradation. One of the biggest obstacles for the implementation of ES tools is per se the market-oriented system that demands perpetual growth, e.g. by investors developing new residential areas. Only a unique implementation on a broader scale, such as on the European level, can promote such tools, under consideration of respective regional conditions. This could balance the economic disadvantages that might occur due to higher development prices or different ecosystem performance. However, these system-inherent constraints indicate the weaknesses of a technocratic perspective.

A bridging tool to feed back the negative effects of destructive human activities into altered decision-making is the integration of PES (payment for ES), which is effectively working under specific (urgent) threats with considerable environmental effects, and promotes the participatory integration of stakeholders (Tallis et al., 2009), with examples such as water contamination or emission trading. However, PES are limited to local effect regulation, and are not used as universal decision-making tools. (Chan et al., 2006; Tallis et al., 2009).

Another aspect rarely considered is the dynamics of ecosystem service, e.g. the decline of regulating services in a forest without being spatially affected due to pollutants, invasive species or fluctuations in water provision. ES dynamics are crucial for making assumptions on the resilience of cities with regard to disturbance (Adger, 2000) which becomes important for a holistic view of the socio-ecological system, integrating human vulnerability and its capacity to adapt to environmental changes (Gallopín, 2006). This implies detailed comprehension of the effects of ecosystem degradation on human wellbeing and particularly on health, which is bound to ES provisioning (Douglas, 2012), (cf. Figure V-1: missing link; sect. I-2.3). Such an attempt requires medical studies to identify the effects on the physical and psychological health resulting from (multiple) stressors due to environmental burdens not compensated by ES, e.g. air and water contamination, noise and also heat (waves), (Epstein and Mills, 2005; Honold et al., 2012).

One of the major future challenges, especially for urban dwellers, is climate change (Epstein and Mills, 2005; Haines et al., 2006). The individual vulnerability toward heat stress is highly dependent on the personal medical history, lifestyle, socioeconomy (adaptive capacity) and age (Benzie et al., 2011), which shows the aggravation of climate change in terms of proceeding population aging. Moreover, the hazard of increasing heat stress is additionally increased in urban regions due to urban pattern characteristics, showing increasing tendencies towards the city center due to increasing compactness and building density, resulting in centrally-located urban heat islands (Dugord et al., 2014). This indicates the increasing need for accessible cooling landscape elements, e.g. parks or watersides (Arnfield, 2003; Mathey et al., 2010).

Both the increase in vulnerability and hazards expedite heat stress risk and related health effects with incalculable consequences in the future. Therefore, these processes, which are linked to the urban system, need to be revealed systematically. The presented approach in this thesis is applicable for revealing possible urban futures with regard to the urban pattern and for revealing the potential effects on heat stress hazard under the consideration of climate-relevant ES, e.g. in terms of thermal emission. Thus, it is possible to determine the future increase of heat stress vulnerability in terms of population aging, but only on the regional scale.

In this context, it would also be advantageous to reveal residential decision-making under the inclusion of actor-defining features, such as age, in a dynamic and spatially explicit approach. This could be realized by applying another model technique suitable for revealing multiple interlinked actors' decisions: agent-based modelling (ABM). The advantage of ABM compared to CA is that decision-making can be directly based on interactions with other agents. Agents are able to enlarge their knowledge and learn from each other and adapt their decisions to other actor's decisions or to feedbacks of environmental effect. However, ABM quickly becomes too complex for integrated and detailed LUC modeling (Lauf et al., 2012c).

The further and necessary systemic progress of urban and urban ecosystem research irrevocably depends on it being interdisciplinary, due to the enormous complexity of urban systems. The future challenges require a continuous adaptation and adjustment of the applied models to understand the system functionalities under changing conditions. To address and improve future human decision-making with new system understanding, the inherent system complexity needs to be reduced to determinable, understandable and simple relations.

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Appendix

Presentation of a contributing research article: Simulating demography and housing demand in an urban region under scenarios of growth and shrinkage

Abstract

After the fall of the Berlin wall in 1989, demographic decline and urban shrinkage has brought massive changes in housing stock in East German cities. Urban planners and policy makers face complex problems caused by the resulting vacancies and demolitions and the handling of urban brownfields in the inner city. At the same time, cities are under the ongoing pressure of suburbanisation. Because existing models mainly focus on demographic and urban growth and their impact on housing stocks, we present a simulation model that is able to compute both growth and shrinkage processes. We uncover nonlinear dynamics and feedbacks between demography, housing preference and supply of housing space. The simulation results show that despite population decline, the increasing number of single households leads to a growing total housing demand in the central parts of the study area. Beyond this area, residential vacancies in multi-storey housing segments will remain regardless of population growth. At the same time, the simulations show that despite population shrinkage and an overall oversupply of flats, there is a negative net-demand of flats in affordable prefabricated housing estates as the percentage of low-income households increases. These findings will help planners modify or adapt their visions of the residential function in shrinking cities and to adjust current programmes of renewal and restructuring.

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1 Introduction

The simultaneity of demographic change, suburban growth and inner-city shrinkage is a challenge for urban planners and policy-makers in post-industrial, modern societies in both Europe and the US (Batty, 2001; Champion, 2001; Kasanko et al., 2006). This situation is particularly true for cities that were situated behind the iron curtain and entered a phase of extreme population dynamics after 1990 – that is, rapid and massive inner-city out-migration along with suburban net-growth (Kabisch, 2005). A vivid example of these developments is the city of Leipzig, Germany. The city is representative of a wider range of large, post-socialist cities in Eastern Germany, but also Central Eastern Europe (Banzhaf et al., 2007; Haase et al., 2007).

Apart from population losses due to labour-migration into the western part of Germany, the main reason for the simultaneity of sprawl and shrinkage is a quantitative and qualitative change of the urban demography and respective housing-demand-patterns. In addition to typical suburbanites, such as family households, we increasingly find "non-traditional" household types, such as cohabitating flat-sharers and single-parent families or patchwork families with specific housing preferences (a.o. Bösch-Supan et al., 2001; Buzar et al., 2007). The absolute and relative growth of the latter was found to foster the current reurbanisation processes in inner-city residential areas (Buzar et al., 2007; Haase, 2008), whereas the former drives the ongoing sprawl (Couch et al., 2005).

However, such changing housing demand patterns due to demographic changes are far from just a phenomenon in former socialist countries; throughout Europe, the population is getting older and the share of traditional family households is decreasing (Kaa, 1987, 2004). Meanwhile, population decline in urban regions is a trend across Europe (Kabisch & Haase, in press). However, these effects are not well represented in urban simulation models because the models focus predominantly on urban sprawl and growth (Schwarz et al., in press).

Simulation models can help us understand these complex dynamics and derive scenarios for the future (Verburg et al., 2004). In this study, we develop a simulation model for urban regions with a focus on two identified missing links: demographic changes in household types and simultaneous growth and shrinkage. In doing so, we aim at uncovering feedbacks between both declining and growing housing development. In both cases we account for ageing population, respective housing preferences and their impact on the housing stock.

Because urban planning and housing companies both look for projections of future housing demand based on new demographic and household behaviours (Jessen, 2006), new knowledge of the above-mentioned feedbacks is crucial. Therefore, our study pursues the following objectives:

1. Building a model that covers dynamics and feedbacks between population development, households, residential demand and housing supply within an urban region.
2. Revealing feedbacks between population (growth and shrinkage), household preferences, residential demand and housing supply, including vacancies.
3. Answering the following questions posed by urban planning:
   - Does a shrinking city face ongoing residential land consumption?
   - Does a growth of one-person households increase the housing demand?

The paper is organised as follows. After introducing the problem of modelling urban housing demand under conditions of demographic change, section 2 provides details of the modelling approach, the software chosen and the case study of Leipzig. The model components and equations are discussed in section 3 before coming to the major results (section 4) and their discussion in section 5. The paper closes with an outlook concerning future amplifications of the model.

2 Modelling demographic effects on housing demand

4.1 State-of-the-art in urban causality modelling

A variety of simulation models for urban land use changes have been developed to assist in urban planning (see reviews by EPA, 2000; Berling-Wolff and Wu, 2004; Haase and Schwarz, 2009). Four different urban modelling approaches can be distinguished: (1) system dynamics; (2) spatial economics / econometric models; (3) cellular automata; and (4) agent-based models. (1) System dynamics models are – in their standard application – not spatially explicit. Rather, the structure of combining stocks, flows and feedback mechanisms leads to a set of differential equations (Sterman, 2000). The outcome of these equations can be simulated, given values for parameters and initial conditions (for urban system dynamics, see, e.g., Forrester, 1969; Haghani et al., 2003a, b; Raux, 2003). (2) Spatial economics / econometric models (e.g., Nijkamp et al., 1993; Mankiw and Weil, 1989) mainly examine demography and household-driven demand-supply relations in urban regions, such as housing market developments. (3) Land use change models use cellular automata with 2-dimensional grids. Each cell symbolises a patch of land, and change rules depend on empirical data regarding land use changes in the past and on suitability and zoning regulations (e.g., Verburg and Overmars, 2007; Landis and Zhang, 1998a, b; Engelen et al., 2007). Cells change states simultaneously according to the same rules, and the state of a cell in time t solely depends on the state of the neighbouring cells in t−1. (4) Agent-based models consist of autonomous individuals (agents) that are usually located on a spatially explicit grid. The agents perceive their environment and interact with one another (Parker et al., 2003). In urban land use models, they represent, for example, households relocating their homes (e.g., Strauch et al., 2003; Salvini and Miller, 2005; Ettema et al., 2007; Loibl et al., 2007; Waddell et al., 2003).

Shrinkage poses challenges for these simulation models because the models are mostly developed for growing cities in industrialised countries. To expand such simulation models to cover urban shrinkage, two additional factors need to be included: (1) residential vacancy as an output variable; and (2) the processes of deconstruction and demolition of vacant residential areas. Few existing simulation models explicitly include the vacancy and demolition of residential housing stock (e.g., Forrester, 1969; Sanders & Sanders, 2004; Eskinasi and Rouwette, 2004).

4.2 A new system model approach

Building on the findings of section 2.1, we decided to construct a new urban simulation model that is able to capture both population growth and shrinkage. Although our new model is calibrated using regional statistics and survey data from the urban region of Leipzig, the model approach itself is applicable to other urban regions with a comparable mix of traditional and non-traditional household types (Haase & Haase, 2007).

System dynamics represent an appropriate tool for identifying causal-feedback-loops occurring in an urban region and building a respective model. We have chosen the system dynamics approach for the following reasons:

(1) In a system dynamics model, specific variables interact in the form of causal feedback loops, which, depending on their polarity, change the system state in a (largely) non-linear way (Forrester, 1971, 1979; Dhawan, 2006; Sterman, 2002). For both growth and shrinkage, including feedback loops in a model is important: on the one hand, growing industrial or residential areas might grow even faster because they attract more growth; on the other hand, a declining residential area may become more unattractive for residents already living there, thus causing even faster decline.

(2) System dynamics models are, in general, not spatially explicit, although sectors or other spatial units can be introduced into such models (Sanders and Sanders, 2004). When setting up a new

model approach, working with aggregate, non-spatial data to capture the main causal relations is, in fact, a good starting point. For modelling shrinkage, these data provide another clear advantage, as empirical data on the spatial distribution of vacant residential or commercial areas are difficult to find.

(3) System dynamics models are suitable, and are often used, for deriving scenarios and future projections (see examples in Eppink et al., 2004; Forrester, 1969; Onsted, 2002; Raux, 2003; Sanders and Sanders, 2004). Simulating simultaneous urban growth and shrinkage is extremely helpful for scientists as well as practitioners when estimating future land use changes as well as the demand for residential land. In our model, population development (input variable) affects the demand on housing areas, which (indirectly) depends on factors such as housing costs and urban green spaces (system parameter). These factors, in turn, lead to a modification of variables such as housing area and housing vacancy (output variables). Expressed mathematically, system dynamics models consist of differential equations that are estimated for each time step (in our model, once per year). The model presented was implemented using the modelling environment Simile (version 4.7) by Simulistics (Simulistics Ltd., 2007). Simile provides a graphical user interface and is based on C++ (Muetzefeldt and Massheder, 2002; Muetzelfeldt, 2002). The specifications of our model in terms of variables and equations are given in section 3.

4.3 The case study

The region of Leipzig, Germany, was chosen as an example of the quantification of causal loops. Leipzig is a stagnating-to-shrinking rural-urban region of half-a-million inhabitants located in Eastern Germany. The compact, monocentric urban region holds one of the largest Wilhelminian (1890-1918) housing estates in all of Germany and one of the largest socialist prefabricated high-rise housing complexes (Haase & Nuissl, 2007).

In the nineteenth century, Leipzig experienced a period of vibrant industrial growth, making it the country's fourth largest city when it reached its population peak of more than 700,000 in the early 1930s (Couch et al., 2005). During the socialist period, between World War II and 1990, the city's population declined.

Since the German reunification, the development of Leipzig has mainly been influenced by de-industrialisation, further population losses and residential vacancies. During the 15 years after the reunification, the city lost about 100,000 inhabitants (1989: 530,000; 1998: 437,000). In 2006, Leipzig had 505,000 inhabitants. Simultaneously with the population decline, urban sprawl emerged at the city's periphery. Scattered commercial and residential development occurred in the surrounding rural landscape (Nuissl and Rink, 2005).

Leipzig has a quasi-radial structure. The Wilhelminian-era multi-storey housing estates form the inner residential ring around the town's centre. A second ring consists of mixed residential-industrial areas characterised by multi-storey row houses and villas. As a third ring, single houses and residential parks follow along the urban-to-rural gradient adjacent to the villages of the suburban and rural surroundings.

3 The model

3.1 Structure

The system considered in our model represents a city and its close surroundings. Here we find typical urban structure types (UST) as described in section 3.2. Structurally, the model distinguishes demand and supply.

The model uses population and household dynamics to compute a household-preference-driven housing demand. The respective supply, represented by the housing stock of each UST, in turn influences this demand. Based on the demand-supply ratio, residential vacancy and demolition of houses is determined in addition to new construction of houses. Thus, components for shrinkage and growth are included. In the following, the model components are introduced in more detail (Figure 1).

Population is dynamically estimated by fertility, mortality and migration and is classified by age classes, which are then classified into different household types (HHT; eqs. 1 and 2). Households have specific preferences regarding the desired housing area, such as surrounding urban green spaces, housing costs, house type, social characteristics of the neighbourhood and crime rates (cf. Figure 1).

In total, seven HHTs (see below for more details) decide on their living spaces based on their specific preferences. If there is not enough demand for a certain UST, the living space is abandoned and it becomes a residential vacancy. A vacant housing space, if not demanded, is demolished and the area converted to open land. If the demand for a certain structural type increases, the open land is then converted into a new housing area by construction. Figure 1 shows that a change in the supply side, reflected in the real estate, affects the housing conditions of a UST, which again influences the housing demand. Thus, the feedback from supply to demand is considered.

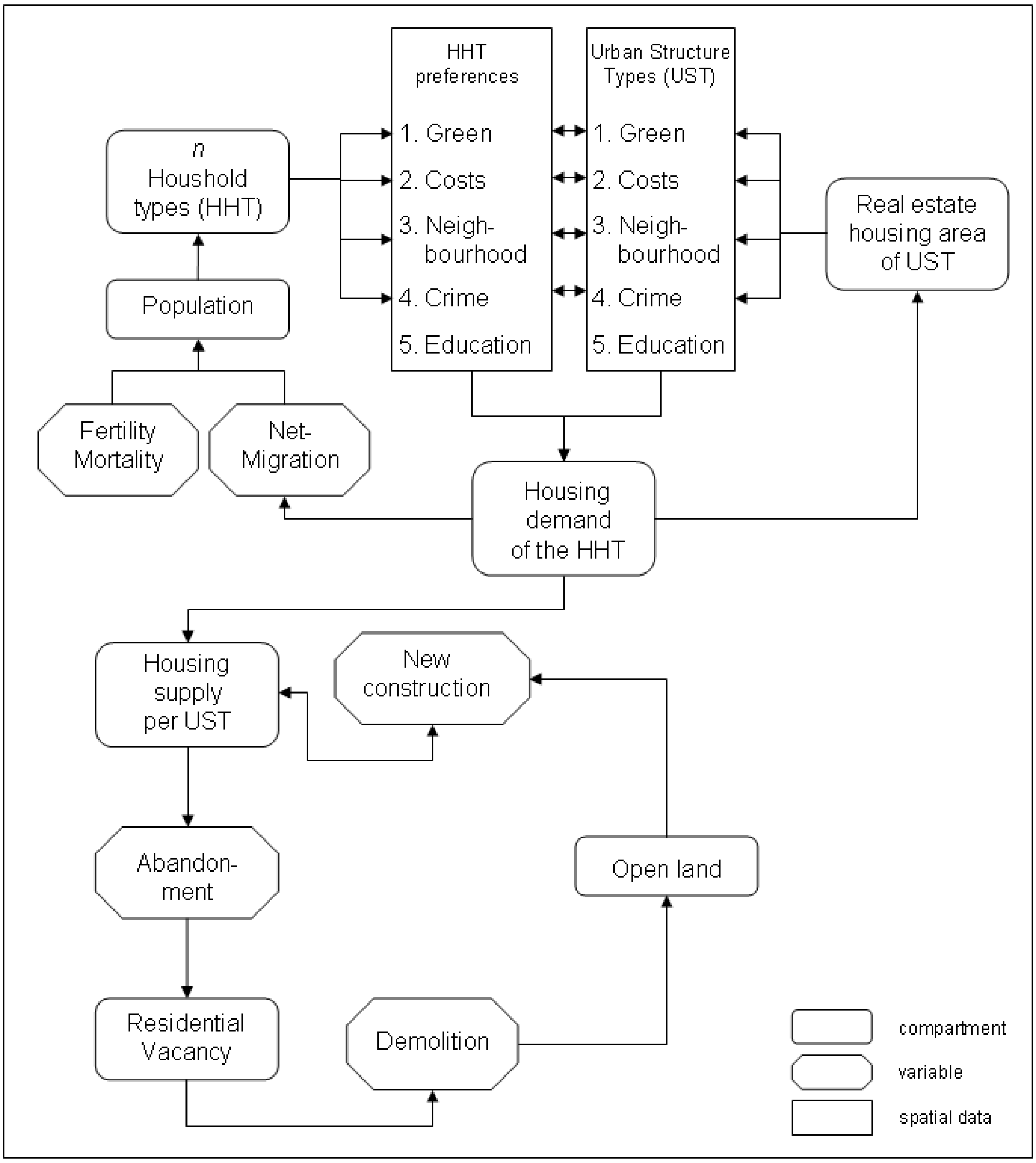


Figure 1. Simplified model structure including the main model components

3.2 Model components

Population

One of the main components of the simulation model is the total population number *P*, which depends on the temporal dependence *dP/dt* of total fertility *F*, mortality *μ* due to life expectancy and net-migration. Individuals may enter a population cohort *i* of a region, either by birth *F*P* or in-migration *I*. The exchange of persons between cohorts is unidirectional from younger to older cohorts; this is reflected in the ageing process, which is represented by the aging rate *A*. Leaving a cohort occurs by ageing, out-migration *O* or dying $\mu_i * P$, coded as the cohort output as follows:

$$\frac{dP_i}{dt} = \sum_{i=2}^{3} F_i \cdot P_i - \mu_i \cdot P_i + I_i - O_i + A_{i-1} \cdot P_{i-1} - A_i \cdot P_i \qquad (1)$$

with $F_{1,5-8} = 0$, $\mu > 0$, $I, O > 0$.

Households

Empirical research has shown that household characteristics significantly influence the specific housing demand per person (Buzar et al., 2007). Therefore, the aggregation of individual elderly person classes into households is relevant, especially in terms of residential preferences. Households vary considerably in form and size, and this variety increases even within the context of demographic change (Kaa, 2004). As households become smaller and less stable, they become more subject-oriented, and living arrangements are adapted to individual narratives (Buzar et al., 2005; Ogden and Hall, 2000).

Households have been classified according to type based on recent empirical data for different European cities: families with dependent children; elderly one-person households and couples (co-habitation); and so called ‘new’ or ‘non-traditional’ household types, namely, young one-person households, young couples or cohabitation households, single-parents and unrelated adults sharing a common flat (Buzar et al., 2007). In the model, the household types *HHT* at a point in time *t* are coded as the following distribution matrix *M(t)* of these seven HHTs (eq. 2):

$$HHT_k = (M_{ki} + N_k) P_i \text{ with } k = 1 \ldots 7 \qquad (2)$$

M(t), the distribution matrix, has a linear trend *N(t)* according to the changes that are assumed to come along with demographic changes due to the second demographic transition, such as an increase of single households and a decrease of the classical family household (cf. Kaa, 2004).

A specific mean income MI_k is also assigned to each household (Haase, A. et al., 2005) (a.o. determines the preference for large houses, flats and green space). Due to limited empirical data, an income variation is randomly created, whereas a threshold determines to which preference set an HHT is given priority (Figure A1). A household with high income is less restricted by the price of a flat and looks more at housing conditions such as green space availability or security.

Urban Structure Types (USTs)

We coded eight urban structure types that are representative of European urban regions, including the core city and the periurban area (Ravetz, 2000). For the core city, these USTs are town centre (1); Wilhelminian-era, old built-up blocks (inner city housing estates) (2); multi-storey row housing estates (built-up in the 1960-70s) (3); prefabricated multi-storey housing estates (from socialist times) (4); villas (5); residential parks (mainly small, uniform single houses) (6); and single houses (7). The periurban area is represented by suburban villages (8).

Housing preferences

The concept of residential segregation suggests that household patterns do not occur by accident, but can be related to the attractiveness of a place *j* depending on housing preference variables (Gober, 1990; Wegener and Spiekermann, 1996; Kemper, 2001). Next to income as a household type specific variable, the real estate market in the form of space availability/supply *SS*, the building state *BS*, and the costs of buying or renting a flat or a house *C*, play an important role. Moreover, the direct social and environmental neighbourhood are decisive for a residential choice (Haase et al., 2008).

In the model, crime rate *Cr*, green supply *G*, surroundings *Su*, social neighbourhood *So*, centrality *Ct* and education facilities *E* represent the neighbourhood. Rules for housing demand and its magnitude based on preference variables were derived from different questionnaire surveys conducted in Leipzig to identify housing satisfaction (Haase, 2008; Haase et al., 2005; Kabisch, 2005). The availability of such housing satisfaction data is crucial for model transfer to other urban regions (cf. section 2.1).

Based on a ranking of the relative importance of neighbourhood characteristics for residents according to the surveys, we chose a simple additive weighting for coding the attractiveness of a place for each household. The variable's importance of each HHT is included according to their estimated importance and weighting. Additive weighting assumes the additive aggregation of the criterion values, which are normalised into non-dimensional values ranging between 0 and 1 to make them comparable by means of the value functions. The residential attractiveness of a place RA_{kj} to live is coded as given in eq. 3:

$$RA_{kj} = CtP_k \cdot CtC_j + SuP_k \cdot SuC_j + CP_k \cdot CC_j + BSP_k \cdot BSC_j + CrP_k \cdot CrC_j + EP_k \cdot EC_j + GP_k \cdot GC_j + SoP_k \cdot \sum_{j=1}^{7} (SoC_j \cdot SoPM_k) \quad (3)$$

Multiplication of the household's specific preferences (*k*) and the given site conditions of the neighbourhood (*j*) produces a maximum preference and an initial probability of the household distribution within the eight USTs. Preference variables such as *CtP* or *SutP* are static parameters, while condition variables such as *CtC* or *SutC* depend on the demand–supply relation (app., Figure A1). Rising living costs of a UST may have a negative effect on its attractiveness and, by implication, on the UST demand.

Depending on the number of persons per household, we calculate the number of housing demand agents DP_{kj} (eq.4) and the respective housing area demand in hectares (eq. 5):

$$DP_{kj} = RA_{kj} \cdot HHT_k \qquad \text{with } \frac{dDP_{kj}}{dHHT_k} \geq 0,\ t > 0 \qquad (4)$$

$$DLS_{kj} = \frac{LSC_k \cdot DP_{kj}}{10000} \qquad \text{with } \frac{dDLS_{kj}}{dDP_{kj}} \geq 0,\ t > 0 \qquad (5)$$

LSC_k is the housing area per capita in m^2. DLS_{kj} represents the demanded living space for each HHT *k* and UST *j.* The supplied living space SLS_j is calculated using the newly built-up area co_j, flat abandonment and depletion of housing stock df_j, demolition dl_j and re-filled vacancies ru_j, which are considered because of reurbanisation trends (Buzar et al., 2007):

$$\frac{SLS_{kj}}{dt} = \sqrt{co_k \cdot DLS_{kj} - df_k \cdot DLS_{kj} - dl_k \cdot DLS_{kj} + ru_j \cdot DLS_{kj}} \qquad \text{with } t > 0 \qquad (6)$$

The residential vacancy V_j is determined by the annual demolition rate dl_j. The parameters co_j, df_j, dl_j and ru_j are all highly influenced by the demand for living space DLS_{kj}. The demand adaption as a consequence of changing supply is regulated by the changing condition variables of each UST, such as housing costs or crime rate (Figure A1). Here, further testing and more empirical data are necessary for a precise validation. Any causal loop from housing supply to household structure has not yet been considered.

Finally, the net-demand on housing area is (eq. 7):

$$NDLS_j = DLS_j - SLS_j \qquad (7)$$

Vacancies and demolition

In the case of non-satisfaction of a household's residential demands, out-migration increases. The share of residential vacancy increases simultaneously in the parts of the city that do not fulfil, or only partially fulfil, the housing requirements of the households (Kabisch, 2005). Vacancy occurs either in the form of single dwellings within a house or completely vacant housing estates (100% vacancy). We further assume that, according to the life-cycle or 'ageing' process of a residential house, a house proves to be uninhabitable after being vacant for over five years, and both maintenance and reconstruction costs far exceed the rental income from new residents (in low income areas of Leipzig). Houses that have a more attractive urban structure type can be re-filled (cf. eq.14). The resulting demolition dl_i rate is coded accordingly in the model (see appendix). The open land, which partially reflects the space supply for new construction, changes as a consequence of the total newly-built areas and the total demolished living space at time *t*. A complete description of the model variables, including all initial values, can be found in the appendix.

3.3 Calibration and validation of the model

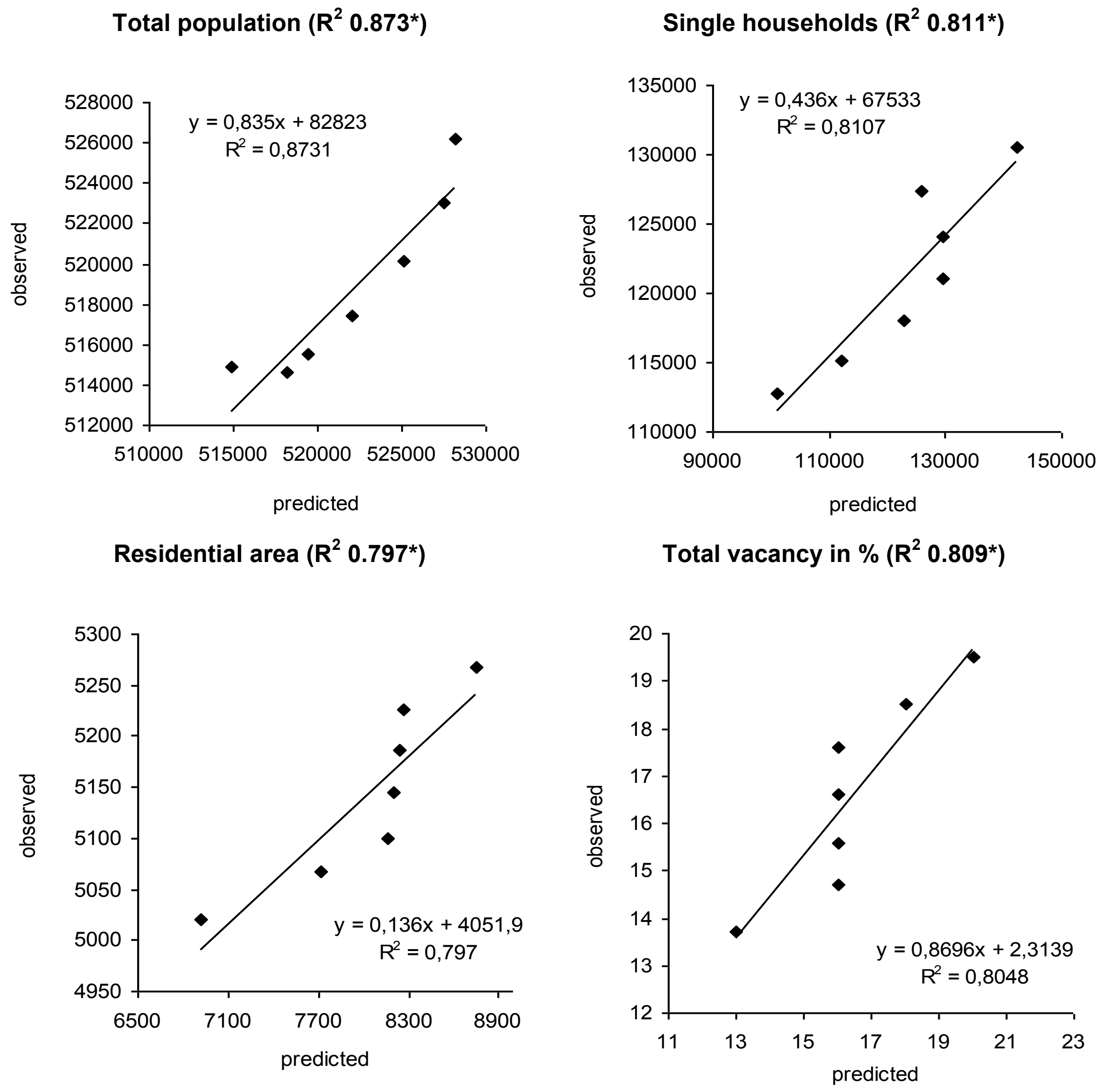
Before running different population scenarios, the model's functionality was tested to verify its quality. A time series produced by the model (with real data inputs) was compared to data from the case study. Table 1 provides an overview of all model variables used for model calibration. The data were taken from municipal statistics for 2005 (City of Leipzig, Saxony; Table 1).

Table 1. Variables used to calibrate the model (all initial values can be found in the appendix)

Population	Household types	Housing market
Population (P_i)	Distribution matrix (DM_{xk})	City area (CA)
Fertility (F_i) + trend* (FT_i)	Housing preferences (CtP_j, SuP_j, CP_j, BP_j, CrP_j, EP_j, GP_j, SoP_j)	Site conditions (CtP_k, SuP_k, CP_k, BP_k, CrP_k, EP_k, GP_k, SoP_k)
Mortality (M_i) + trend* (MT_i)	Mean income (MI_j)	Housing area (SLS_k)
In-migration (IM_i) + trend* (TOM_i)		Vacancy (V_k)
Out-migration (OM_i) + trend* (TOM_i)		Open land (SS)
		Number of floors (St_k)
		Housing floor density (FSM_k)

* derived from statistical data from 1999-2005

Using independent census data, that is time series of municipal statistics from 1992-2005 (City of Leipzig, 1993-2006), the major variables of the simulation model could be validated. Figure 2 reports the regression coefficients and curves obtained. For all variables tested, they show that the model results are in good and significant accordance with the statistical data (R-square >0.7). To confirm that the validation of the model was correct and did not relate to the calibration data, two independent data sets were used (the calibration using federal census data, the validation using municipal census data).



** $p < 0.01$ * $p < 0.05$ (t-test)

Figure 2. Regression coefficients obtained during the model validation using municipal statistics (issued by the city of Leipzig, 1993-2006)

3.4 Scenarios

In the introduction, we posed several questions concerning how housing demand and supply and residential vacancy would be affected if the population in an urban area either grows or declines. In accordance with these questions, a scenario matrix was set up for population growth, population shrinkage and baseline development (representing a continuation of current population development trends). These factors were based on the major demographic variables the model uses, such as fertility, mortality, net-migration and percentage of single and family households. These variables predominantly shape the current population dynamics of an urban region (Table 3). The simulations cover a time horizon of 25 years (2005-2030 for each of the scenarios).

Table 2. Calculation of fertility, mortality, net-migration, percentage young one-person and family based on municipal and regional statistics

	Scenarios		
	shrinkage	baseline	growth
Fertility (F)	*F= (F0*FT)*(-0.2)*	*F= (F0*FT)*(0.8)*	*F= (F0*FT)*(2)*
Mortality (M)	*M= (M0*MT)*(-0.2)*	*M= (M0*MT)*(0.8)*	*M= (M0*MT)*(1.5)*
In-Migration (IM)	*IM= IM0+IMT*(-1)*	*IM= IM0+IMT*(1)*	*IM= IM0+IMT*(1.01)*
Out-Migration (OM)	*OM= OM0+OMT*(-0.95)*	*OM= OM0+OMT*(0.96)*	*OM= OM0+OMT*(1.01)*
% Single households (S)	*S= S(t-1)*(1+0.002*t)*	*S= S(t-1) +S*0.008*t*	*S= S(t-1) +S*0.002*t*
% Families (Fa)	*Fa= Fa(t-1)* (1+0.002*t)*	*Fa= Fa(t-1)+Fa*0.008*t*	*Fa= Fa(t-1)+Fa*0.002*t*

Note: FT=measuref fertility rates, 1999-2005; MT=measured mortality rates, 1999-2005; IMT and OMT=measured migration rates, 1999-2005.

4 Results and discussion

4.1 Population development

The results of the scenarios show a differentiated picture for population development. Starting with today's urban population (514,904), the baseline scenario shows a non-linear but gradual population growth (564,585) until 2030 (Figure 3). In the shrinkage scenario, however, the population number falls remarkably (again non-linear) to under 400,000. Assuming a constant increase of fertility and net-migration, the population rises above 640,000 residents in 2030. Within just 25 years, the difference between the growth and shrinkage scenarios accounts for more than one-fourth of the current total population number.

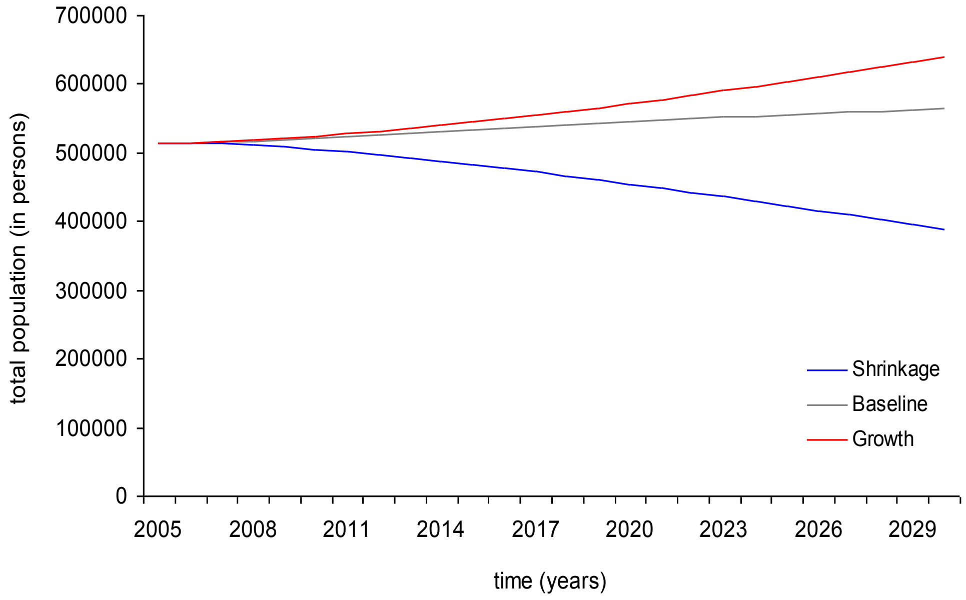


Figure 3. Total population in persons for baseline, growth and shrinkage scenarios

When looking at the development of the age class, the baseline, growth and shrinkage scenarios differ considerably. Using the indicator of the young- (share of inhabitants <20 years old divided by the share of inhabitants >60 years) and old-age dependency rates (1/young-age dependency), we see that the young-age dependency in each of the three scenarios decreases – which means that the urban region will age. A considerable increase in the old-age dependency rate can be found in the shrinkage scenario: more than 2.5 persons >60 years equals one person <20 years. Figure A3 (app.) reports that in the shrinkage scenario, the decrease in population accelerates after 2015. Due to an aging population, the housing preferences and demands of elderly people will attract special attention to future housing markets (Kaa, 2004; Buzar et al., 2007).

4.2 Household development

The growth of the total number of households in both the baseline and growth scenarios is caused by an increase in the number of persons living in single households (young and elderly) (Figure 4). This result is in accordance with current observations of household number (Buzar et al., 2007), which is assumed to be caused mainly by on-going individualisation trends (Ogden and Hall, 2000). The growth scenario, in particular, reports a non-linear growth of young single households, which no doubt has implications on the need for housing area. After an initial increase, the number of single households decreases in the shrinkage scenario. Compared to the increase of persons living in single households, the number of family household members dramatically decreases in all three scenarios. Conversely, the number of single-parent families increases in both the baseline and growth scenarios (Figure 4).

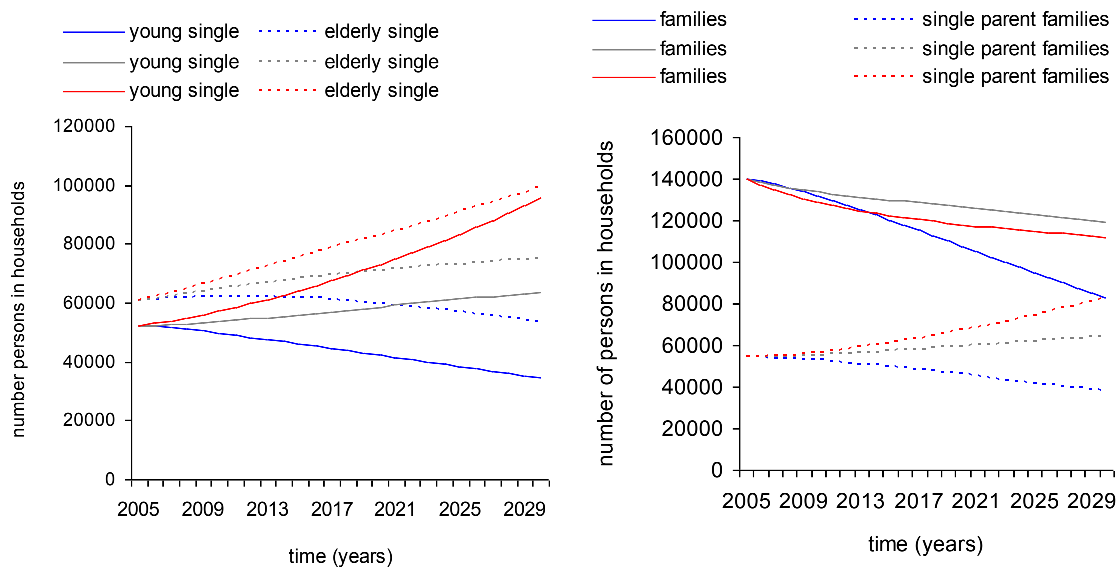


Figure 4. Development of the number of persons living in young and elderly single households compared to those living in family households with children. Blue = shrinkage; grey = baseline; red = growth

4.3 Housing demand and supply

Figure 5 depicts the net-demand-supply from 2005-2030. We see a completely different picture for the growth and shrinkage scenarios: whereas the housing supply exceeds the respective demand in times of population shrinkage, in times of population growth, the housing supply dramatically decreases (assuming that individual living space will not be reduced) (Priemus, 2003).

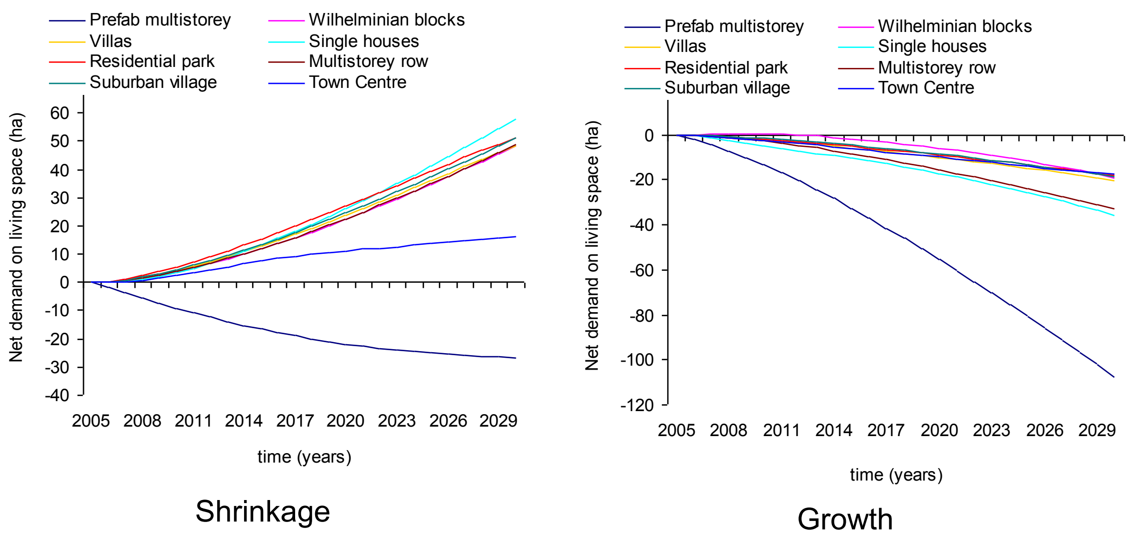


Figure 5. Net demand-supply-relation on living space in the different urban structure types for the growth and shrinkage scenarios

In the growth scenario, an undersupply of prefabricated multi-storey houses is simulated, something that would not be expected based on the low perception of this urban structure type today (Kabisch et al., 1997). In the simulation, there is a growing interest in affordable flats by low-income and single-parent family households that can be provided by prefabricated large housing estates. As Figure 5 shows, the undersupply levels-out by about 30%. In all other urban structure types, an oversupply is computed even for the growth scenario, although there is a high preference by most of the households for single houses, Wilhelminian-era built-up houses or residential parks and villas. The sharp decrease in housing demand is caused by the reduction of the population by >100,000 residents by 2030 in the shrinkage scenario, which can neither be moderated by an increase in the number of households nor by the demolition of vacant houses.

4.4 Vacancies and demolition of residential supply

As discussed in the introductory section, residential vacancy is a major issue in urban land use development, particularly under conditions of shrinkage, is a consequence of an oversupply of living space (apartments, houses). Figure 6 gives an idea of the proportions of residential vacancy in the different urban structure types.

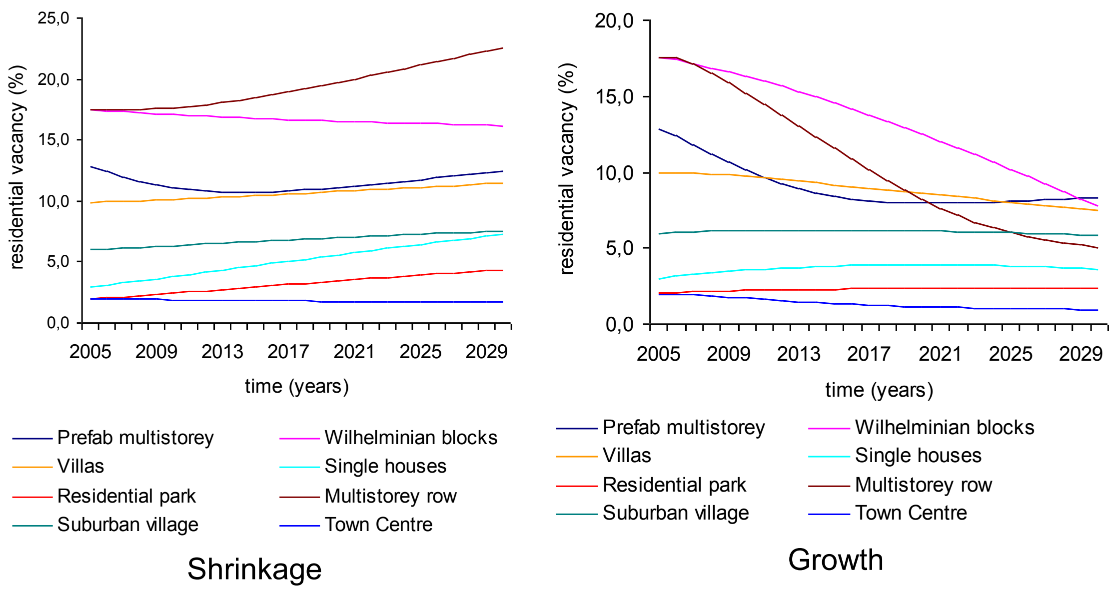


Figure 6. Residential vacancy in the 8 urban structure types for the growth and the shrinkage scenarios

The overall share of vacancy increases in the shrinkage scenario up to 13% by 2030, whereas it falls to 6% in the growth scenario (starting with 12.3% in 2005). Even in the baseline scenario, residential vacancy will decrease to 9.1%. In the growth scenario, demolition predominantly impacts the proportion of residential vacancies in the prefabricated multi-storey housing estates, as they are less attractive than other USTs for single and family households with a higher income (and for most of the urban planners). This result somehow contradicts the discussed undersupply of prefabricated housing shown in Figure 5, and it makes clear that current demolition policies underestimate the demand for affordable flats in such prefab housing estates caused by a future increase of low-income household types.

The reduction of vacancy in the inner-urban Wilhelminian-era blocks mainly results from their rising attractiveness for a growing number of households. Demolition does not occur in single housing areas. Therefore, we find a slight increase in single house vacancy in the shrinkage scenario. There is no empirical evidence from European urban regions that single houses are demolished on a larger scale even if vacancy appears (Kasanko et al., 2006).

The total residential area of the urban region, summing up demand and supply on living space as well as residential vacancy moderated by demolition measures, shows again a highly divergent picture. The graphs in Figure 7 show that Leipzig will face an increase in the total residential area in the case of population growth, which means that the urban region will expand and, assuming a constant or even increasing living space per capita, further land consumption will take place. In the baseline scenario, remaining residential vacancies and low population growth lead to smart urban growth.

In the urban shrinkage scenario, residential land will decrease (in the model, this leads to an increase in open land) in cases when all residential areas that are unused are given back to nature (Figure 7). Open land consumption does not happen in the baseline scenario. Here, the surplus in residential land compared to the start of the simulation in 2005 is buffered with a densification of the existing urban space and an infill of vacancies. We observe a dramatic decrease of open land in the growth scenario.

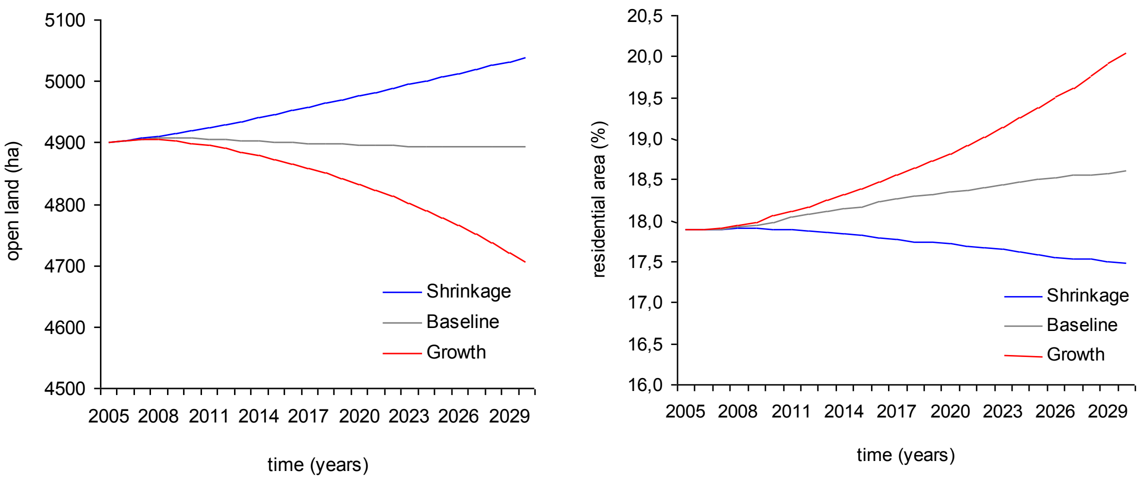


Figure 7. Development of open land and residential area in the three scenarios: baseline, growth and shrinkage

Figure 7 further shows that an alteration in the distribution of households – that is, according to the second demographic transition, an increase of single households and the reverse development for family households – has an impact on the growth/decline of the total residential area.

5 Conclusions

Based on the results of the new simulation model, we can show a range of interesting trajectories concerning how population dynamics under demographic change will affect housing demand and the supply of residential and open land in an urban region. The results of the population projections show that currently shrinking cities and urban regions can expect very different futures; further decline is only one of them. In accordance with recent findings on reurbanisation, trends in urban regions formerly faced with population decline (Turok and Mykhnenko, 2008; Storper and Manville, 2006), in both baseline and growth scenarios, indicate that urban regions might again "recover" from a phase of decline.

The model shows strong and weak segments of the housing stock related to two important urban processes: demographic change and new household types as well as urban growth and shrinkage. The results shown here can help planners better understand housing preferences and the feedbacks between those and the housing supply (= housing stock).

Do shrinking cities face further residential land consumption? Does a growing number of single-person households lead to an increase in the overall housing demand? In two of these scenarios (baseline and the growth), we state an increase of single households, both younger and elderly. This increase leads to an increase in the total housing demand in both scenarios (cf. Figures 3 and A4). Compared to this, In the shrinkage scenario, neither the number of single households nor the housing demand increases. In Leipzig, we note an increase in the total number of households up to 2007. However, the expected increase in housing area weakens and is expected to abate within the coming years.

As shown in the summarising Figure 8, a growing number of single households leads to an increasing demand of living space and residential land taken in both total population growth and shrinkage scenarios due to the positive trend of per capita living space. A total decline in population does not "solve" the land consumption problem of urban regions as long as per capita demands are rising and individualisation leads to an increase in total household numbers (Karsten, 2003; Lee et al., 2003).

	Population	Singles	Vacancy	Resid. Land	Open Land
Growth	↗	↗	↘	↗	↘
Baseline	↗	↗	→	→	→
Shrinkage	↘	↘	↗	→	→

Figure 8. Major trends of the growth, baseline and shrinkage scenarios

The results of our model show that young single households could play an important role in new, inner-city development in the Wilhelminian-era ring – that is, the process of reurbanisation – as inner-city urban structure types, in particular, are positively influenced by an influx of young single households. This effect may be crucial to overcoming residential vacancies in inner-city areas. Young singles, especially, demand a “functional social and cultural life”, which is offered in the inner city (Favell, 2008). In addition, it was shown that the development of family households implies the direction of single-house progress linked to future land consumption. In contrast, if the decrease in family households continues, previous sprawling processes at the city’s periphery can be expected to freeze.

Of particular interest for urban planners are the housing demand and respective land use development trends. The former high vacancy rates of Leipzig’s inner-city will balance the growing demand of a living space of 36 hectares, and continuing demolition will even lead to a reduction of the residential area by 10 hectares by 2020 (baseline; Table A 2). Therefore, a high potential for open spaces and greenfield expansion exists, which could enhance the attractiveness of the inner-city. The rising demand for inner-city Wilhelminian-era USTs, which define the urban image, requires a reduction of the demolition rate (despite existing vacancies). With decreasing growth sprawl affecting residential areas, detached houses will still increase by 38 hectares by 2020, while enormous 108-hectare areas will become available due to demolition in the segment of prefabricated multi-storey houses (shrinkage; Table A1). This trend elucidates the high brownfield exploitation capability for new construction, which can prevent further space consumption and sealing.

Another possible way of using our model is combining it with a spatial cellular automaton to uncover local dynamics. The presented model delivers population dynamics and housing demand, including internal causal feedback loops on the regional scale, to avoid simple empirical trend implications.

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The article contains supplementary material that is available on the journal homepage; among other it includes a detailed description of all model variables and equations, a detailed graphical model description and additional results

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Appendix I regarding Chapter I

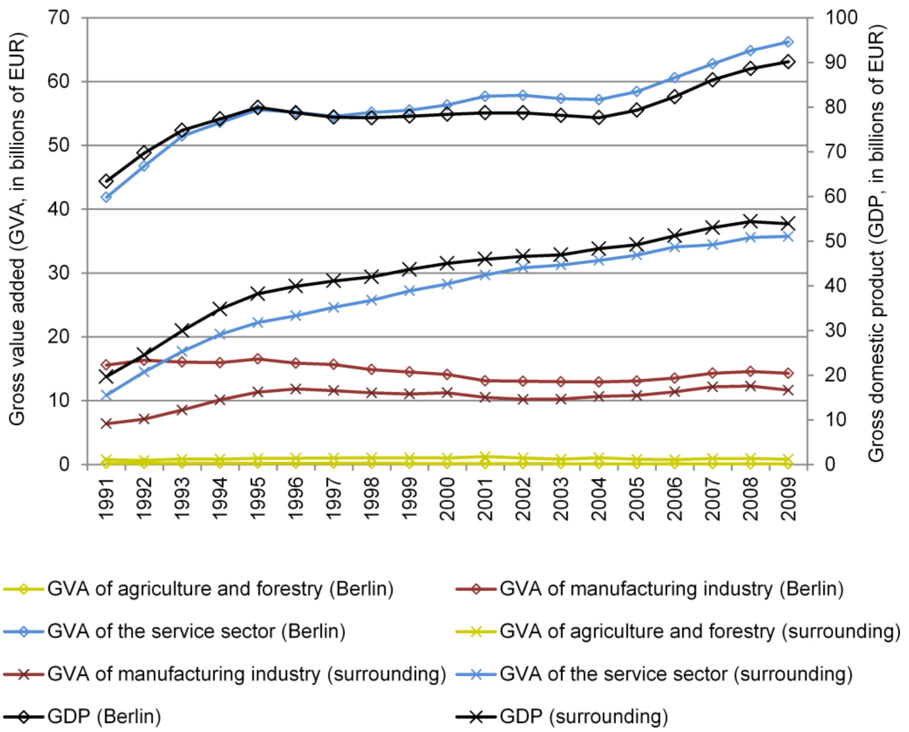


Figure-A-I-1. Economic development in Berlin and its surrounding between 1991 and 2009

Appendix II regarding Chapter II

App. II-A: List of all trend variables and initial parameters for the SD model

Indices

x=[0-15,16-25,26-35,36-45,46-55,56-65,66-75,75+]; age cohorts in years

k=[young singles, elderly singles, young childless couples, elderly childless couples, families, single parents, flat sharers]; household types

j=[Multi-story prefab, Wilhelminian blocks, villas, detached houses, multi-story row, residential park, village]; residential land uses classified as urban structure types

Population

$P1_x$=[542144,385228,667612,518955,498149,386984,243206,233114]; Residents of Berlin

$P2_x$=[141027,90180,127934,119577,103442,103678,55002,39905]; Residents of Berlin's surroundings

$F1_x$=[0.00003,0.02762,0.02568,0.00527,0.00006,0,0,0]; Fertility of age cohorts for Berlin

$F2_x$=[0.000028,0.015458,0.014703,0.001890,0,0,0,0]; Fertility of age cohorts for Berlin's surroundings

$M1_x$=[0.00058,0.00074,0.00108,0.00220,0.00569,0.01150,0.02651,0.11530]; Mortality for Berlin

$M2_x$=[0.00033,0.00083,0.00103,0.00270,0.00537,0.01224,0.02716,0.11009]; Mortality for Berlin's surroundings

$IM1_x$=[15787,28437,37996,17344,7873,4333,2557,1509]; Immigration to Berlin

$IM2_x$=[1572,2277,3410,1957,933,370,217,303]; Immigration to Berlin's surroundings

EM_x=[13010,15682,28881,16507,7690,4258,2020,1657]; Emigration from Berlin

$EM2_x$=[1415,2047,2785,1980,808,476,185,146]; Emigration from Berlin's surroundings

$RM2_x$=[0.0038,0.0031,0.0041,0.0037,0.0027,0.0018,0.0008,0.0011]; Migration from Berlin to surroundings

$RM2_x$=[0.0067,0.0215,0.0132,0.0064,0.0043,0.0029,0.0037,0.0042]; Migration from surroundings to Berlin

$F1Trend_x$=[0.099*log10(time(1))+1.1248,0.0367*log10(time(1))+0.903,0.0079*log10(time(1))+1.0151,0.0265*log10(time(1))+1.013,-0.01*log10(time(1))+0.9984,0,0,0]

$F2Trend_x$=[0.0514*log10(time(1))+0.9132,0.0203*log10(time(1))+0.9587,0.01575*log10(time(1))+1.08293,0.0725*log10(time(1))+1.0205,-0.036*log10(time(1))+0.9924,0,0,0]

$M1Trend_x$=[0.0226*log10(time(1))+0.9324,0.026*log10(time(1))+0.91,-0.017*log10(time(1))+0.9774,-0.021*log10(time(1))+0.9957,-0.008*log10(time(1))+0.976,-0.003*log10(time(1))+0.9858,-0.029*log10(time(1))+1.024,0.007*log10(time(1))+0.965]

$M2Trend_x$=[0.0237*log10(time(1))+0.9744,-0.029*log10(time(1))+0.9785,-0.061*log10(time(1))+1.0339,0.014*log10(time(1))+0.9177,-0.028*log10(time(1))+1.0115,-0.009*log10(time(1))+0.9722,-0.004*log10(time(1))+0.9786,-0.005*log10(time(1))+0.9877]

$IM1Trend_x$=[0.0051*log10(time(1))+0.953,0.0227*log10(time(1))+0.9699,0.016*log10(time(1))+1.0145,-0.041*log10(time(1))+1.0516,-0.041*log10(time(1))+1.052,-0.013*log10(time(1))+1.0181,-0.019*log10(time(1))+1.008,-0.005*log10(time(1))+1.0255]

$IM2Trend_x$=[-0.006*log10(time(1))+1.0394,-0.001*log10(time(1))+1.021,-0.11*log10(time(1))+1.1599,-0.148*log10(time(1))+1.2409,-0.128*log10(time(1))+1.2102,-0.089*log10(time(1))+1.2233,-0.118*log10(time(1))+1.2773,-0.063*log10(time(1))+1.1703]

$EM1Trend_x$=[0.012*log10(time(1))+0.966,0.0228*log10(time(1))+0.9758,0.005*log10(time(1))+1.0064,-0.014*log10(time(1))+1.023,-0.021*log10(time(1))+1.0283,-0.029*log10(time(1))+1.064, 0.044*log10(time(1))+1.067,-0.038*log10(time(1))+1.0625]

$EM2Trend_x$=[0.0398*log10(time(1))+0.9567,0.0471*log10(time(1))+0.9757,0.032*log10(time(1))+1.059,-0.07*log10(time(1))+1.1175,-0.069*log10(time(1))+1.1368,-0.031*log10(time(1))+1.063,-0.056*log10(time(1))+1.133,0.005*log10(time(1))+1.039]

$RM1Trend_x$=[-0.077*log10(time(1))+1.2766,-0.067*log10(time(1))+1.2528,-0.086*log10(time(1))+1.2679,-0.082*log10(time(1))+1.2744,-0.063*log10(time(1))+1.2294,-0.076*log10(time(1))+1.2695,-0.112*log10(time(1))+1.3505,-0.051*log10(time(1))+1.2449]

$RM2Trend_x$=[0.0643*log10(time(1))+0.9999,0.048*log10(time(1))+0.9783,-0.00001*log10(time(1))+1.0864,0.0114*log10(time(1))+1.0657,-0.022*log10(time(1))+1.1092,-0.004*log10(time(1))+1.0687,0.0209*log10(time(1))+0.9652,0.0305*log10(time(1))+0.97]

Households

M_{xk}=[[0,0.22,0.24,0.22,0,0,0,0],[0,0,0,0,0.21,0.23,0.29,0.4],[0,0.11,0.18,0.27,0,0,0,0],[0,0,0,0,0.34,0.64,0.61,0.3],[0.7,0.3,0.28,0.35,0.35,0.09,0,0],[0.3,0.13,0.12,0.11,0.1,0.04,0,0],[0,0.24,0.18,0.05,0,0,0.1,0.3]]; Matrix defining population transition from age cohorts to HHT

P_k=[0.05*log10(time(1))+0.999,0.010*log10(time(1))+0.99,0.05*log10(time(1))+0.999,0.01*log10(time(1))+0.99,-0.05*log10(time(1))+1.001,0.06*log10(time(1))+0.9995,-0.009*log10(time(1))+1.0001]; Household structure dynamic

PA_k=[0.15,0.12,0.08,0.09,0.02,0.01,0.2]

PZ_k=[0,0.1283,0.1516,0.1272,0.0749,0.119,0.27]

PC_k=[0.3263,0.1819,0.1381,0.0647,0,0.0986,0.0813]

PB_k=[0,0.1306,0.1691,0.1193,0.0847,0.1303,0.2265]

PS_k=[0.0947,0.1279,0.0841,0.1529,0.2722,0.1347,0]

PE_k=[0.3149,0.1198,0.1101,0.0846,0,0.077,0.2101]

PG_k=[0,0.1062,0.075,0.1797,0.3122,0.1262,0.0684]

PL_k=[0,0.113,0.122,0.1674,0.2561,0.1712,0.0137]

PN_k=[0.2642,0.0923,0.1502,0.1044,0,0.143,0.13]

NM_{kk}=[[0.208,0.042,0.208,0.042,0.167,0.167,0.167],[0.048,0.238,0.048,0.238,0.190,0.190,0.048],[0.217,0.043,0.217,0.043,0.174,0.174,0.130],[0.048,0.238,0.048,0.238,0.190,0.190,0.048],[0.111,0.111,0.111,0.111,0.222,0.222,0.111],[0.111,0.111,0.111,0.111,0.222,0.222,0.111],[0.235,0.059,0.235,0.059,0.059,0.059,0.294]]

MI_k=[gaussian(element([HHT],1),920,50),gaussian(element([HHT],2),970,50),gaussian(element([HHT],3),1892,50),gaussian(element([HHT],4),1708,50),gaussian(element([HHT],5),2226,50),gaussian(element([HHT],6),1283,50),gaussian(element([HHT],7),844,50)]; Mean income per household type

PW=[2,3,8,2,4,2,3,3,2] if MI_k<[920,970,1892,1708,2226,1283,844], else PW=[2,3,8,2,4,2,3,3,2]; Preference weighting of 9 housing preference variables depending on mean income shifts

<u>Residential land use classes</u>

SRA_j=[3748,7379,4514,38508,250,7431,5436]; Supply residential area in ha

RD_{jk}=[[0.165,0.157,0.092,0.170,0.219,0.115,0.083],[0.150,0.109,0.077,0.225,0.163,0.110,0.167],[0.007,0.108,0.107,0.301,0.313,0.072,0.093],[0,0.088,0.071,0.266,0.468,0.078,0.029],[0.007,0.154,0.077,0.171,0.413,0.151,0.026],[0.135,0.140,0.116,0.165,0.169,0.118,0.155],[0.109,0.113,0.081,0.209,0.353,0.113,0.023],[0.136,0.167,0.105,0.155,0.216,0.131,0.090]]; Initial residential distribution of *k* in *j*

VR_j=[8,15,10,2,2,10,7]; Initial vacancy rates in%

AS=6000; Available space for built-up areas in ha

LSC_k=[54,54,37.5,35,31,35,37]; living space consumption per HHT in m²

FSD_j=[0.7,1,0.4,0.1,0.6,0.6,0.3]; Quotient of total stacked living space and plot size

SL=1.25; conversion factor from living space to residential area (access roads, parking spaces, wall thickness etc.

$Stories_j$=[8,4.2,3.2,2,4.5,5.5,3.4]

co_j=[0,0.002,0.002,0.005,0.02,0.0008,0.0001]

dp_j=[0.0025,0.0012,0.0006,0.0007,0.0002,0.0008,0.002]

dl_j=[0.003,0.0002,0.00008,0.00004,0.00008,0.0001,0.002]

ru_j=[0.002,0.004,0.0006,0.0005,0.00018,0.002,0.0015]

CA_j=[2,75,10,0,5,15,10]; (Weighted number of cultural conditions)

CZ_j=[0.074,0.175,0.145,0.090,0.095,0.096,0.065]; (Weighted average distance of *j* from center)

CC_j=[5.5,6.5,8.5,7.5,8,7.5,6]; (Mean rent per m²)

CB_j=[0.08,0.1,0.16,0.15,0.14,0.13,0.1]; (Weighted statements of building conditions - studies of housing satisfaction)

CS_j=[1300,1500,1100,800,1000,1200,1100]; (Selected crime rates)

CE_j=[0.14,0.16,0.13,0.05,0.1,0.11,0.07]; (Weighted educational facilities, kindergartens and schools)

CG_j=[5,6,7,8,6,5,9]; (Average close-by green provision per capita)

CL_j=[0.04,0.104,0.114,0.127,0.145,0.112,0.142]; (Weighted tidiness and noise statements - studies of housing satisfaction)

App. II-B: Supplementary information

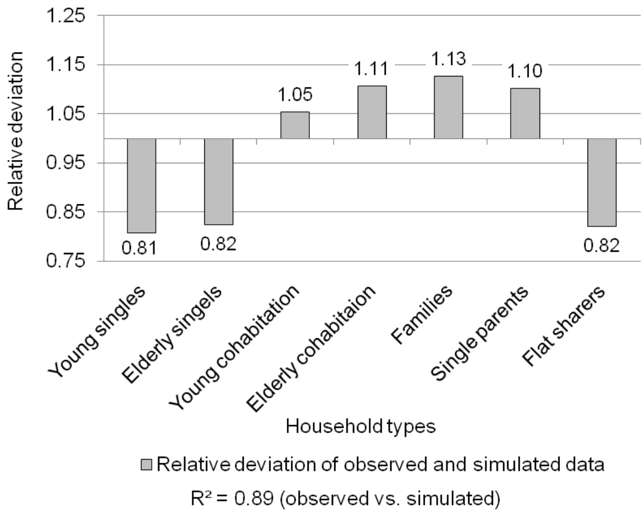


Figure A-IIb-1. Model fit of household dynamics regarding HHT (simulation run 1990-2007)

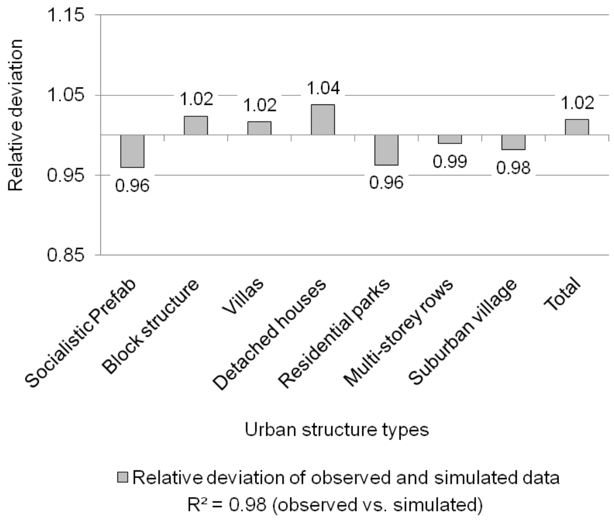


Figure A-IIb-2. Model fit of residential dynamics regarding residential land-use classes (simulation run 1990-2007)

Table A-IIb-1. Overview of residential land use classes; images: Microsoft, 2010 and Google, 2010

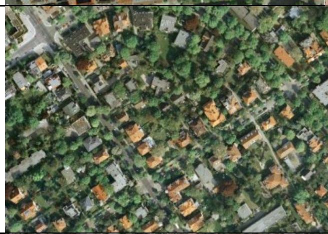
Residential type (Urban structure)	**Structure, Form & Shape**	**Floor-space index**	**Character-istics**
Prefabricated multi-story houses	 	0.7	Predominantly from socialistic times, ≥6 stories, with large patios
(Wilhelminian) blocks	 	1.0	Traditional densely inner-city housing structure
Villas	 	0.4	High quality homes with large gardens
Detached and semi-detached houses	 	0.1	Low-density family homes forming the urban fringe
Residential parks	 	0.6	Modern multi-family houses, straight structured
Multi-story row houses	 	0.6	Often along streets, <6 stories
Suburban village	 	0.3	Mixed and unsorted building structure of low density

Table A-IIb-2. Percentage cell match of simulated and observed residential LUC

	Match	**Mismatch**
Null model	90.4%	6.6%
SD model	93.1%	6.3%

Table A-IIb-3. Cell match of simulated and observed residential LUC

	Null model	**SD model**
In both maps	258933	266796
Only in observed map	18978	18059
Only in simulated map	27635	19772

Table A-IIb-4. Measured and simulated residential change

	Observed	**Null model**	**SD model**
Increase of cells	18929	9894	16838
Relative deviation of cell change	1.00	0.52	0.89

Table A-IIb-5. Cross table of cell state transitions between land-use classes in the time frame 1992-2007, static classes affecting the neighborhood decisions are airport (5196 cells), infrastructure (21335 cells), provision and dumping sites (9373 cells), mineral extraction sites (1642 cells), wetlands (17123 cells) and water bodies (79859 cells)

Map 1992 \ Map 2007	Arable land	Pasture	Shrubs and trees	Forest	Open spaces	Brownfields	Artificial urban green	Prefab multi-story	Multi-story rows	Blocks	Villas	Detached houses	Residential park	Suburban village	Services	Commercial area	Industrial area	Sum Map 1992
Arable land	524112	0	0	0	0	0	0	0	3	3	32	1550	817	91	16	919	0	527543
Pasture	0	288880	0	0	0	0	0	0	8	18	25	2226	1156	132	173	1072	0	293690
Shrubs and trees	0	0	33256	0	0	0	0	0	13	20	13	368	118	17	135	265	0	34205
Forest	0	0	0	677967	0	0	0	0	4	17	49	3108	1752	59	354	1624	0	684934
Open spaces	0	0	0	0	5235	0	0	0	2	1	0	158	35	0	17	117	0	5565
Brownfields	0	0	0	0	0	2853	0	0	11	18	0	63	29	1	172	61	0	3208
Artificial urban green	0	0	0	0	0	0	79194	0	266	542	110	3916	1564	458	1202	1707	0	88959
Prefab multi-story	169	0	0	0	0	0	0	14770	3	0	0	1	8	0	0	0	0	14951
Multi-story rows	0	0	0	0	0	0	0	0	29611	0	0	0	0	0	0	0	0	29611
Blocks	317	0	0	0	0	0	0	0	0	29039	0	17	0	0	0	2	0	29375
Villas	0	0	0	0	0	0	0	0	0	0	18001	0	0	0	0	0	0	18001
Detached houses	0	0	0	0	0	0	0	0	0	0	0	153660	0	0	0	0	0	153660
Residential park	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Suburban village	848	0	0	0	0	0	0	0	0	0	0	35	0	20864	0	0	0	21747
Services	1166	0	0	0	0	0	0	0	0	0	1	35	18	0	20735	1	0	21956
Commercial area	354	0	0	0	0	0	0	0	3	10	0	0	0	0	8	47124	0	47499
Industrial area	1267	0	0	0	0	0	0	0	0	2	1	1	2	0	0	0	25437	26710
Sum Map 2007	528233	288880	33256	677967	5235	2853	79194	14770	29924	29670	18232	165138	5499	21622	22812	52892	25437	3868800

Appendix III regarding Chapter III

App. III-A: Contrasting urban development

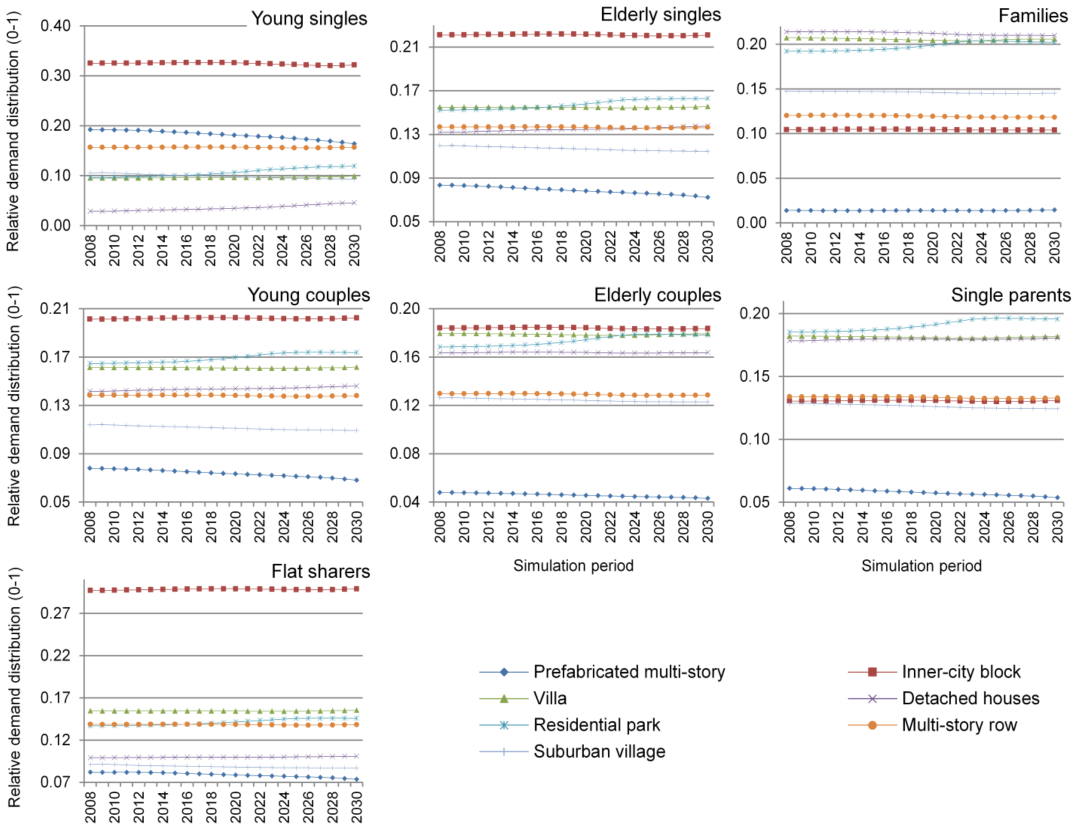


Figure A-IIIa-1. Shifts in housing demand distribution of HHT across residential land-use types (2008-2030), for BG (equal to those of BS) with an annual deviation of max 0.9%, a slight trend of higher demand for residential park and lower demand for detached houses across all HHT

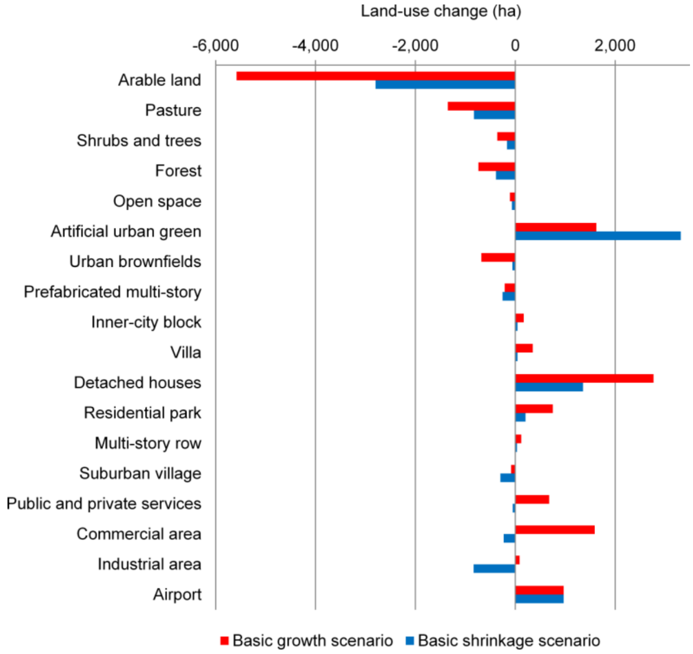


Figure A-IIIa-2. Land-use change between 2008 and 2030 for BG and BS

App. III-B: Exceeding urban development

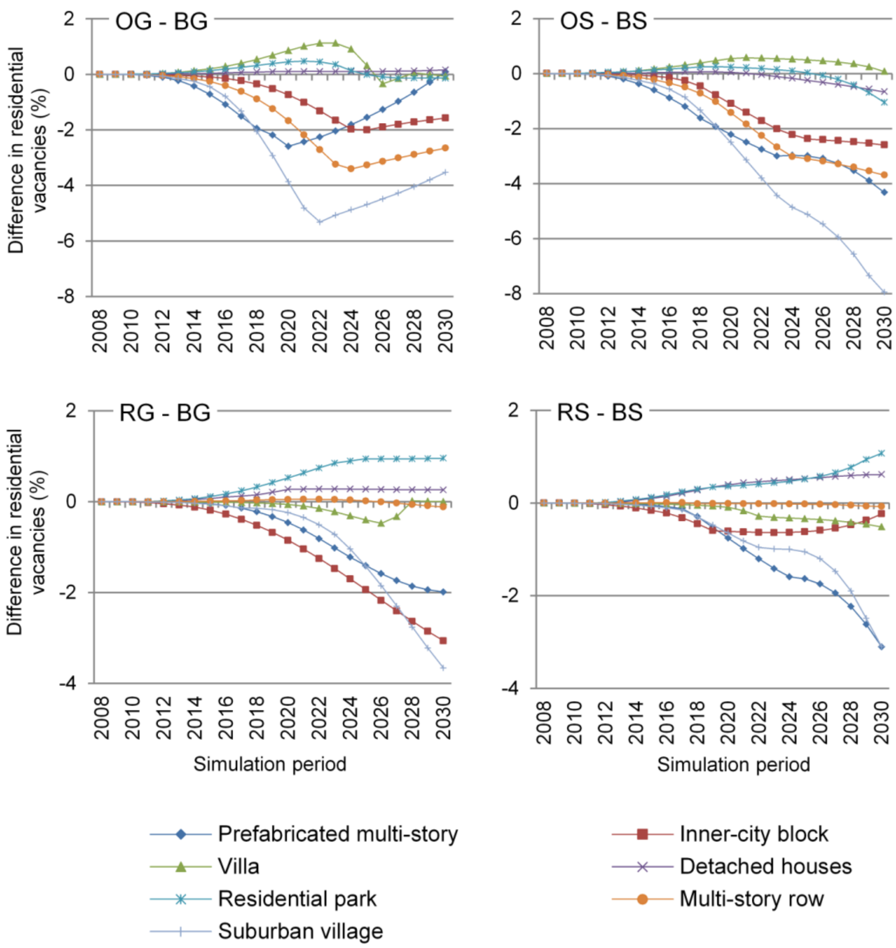


Figure A-IIIb-1. Difference in residential vacancies for exceeding development trends between 2008 and 2030; above: overaging, below: reurbanization

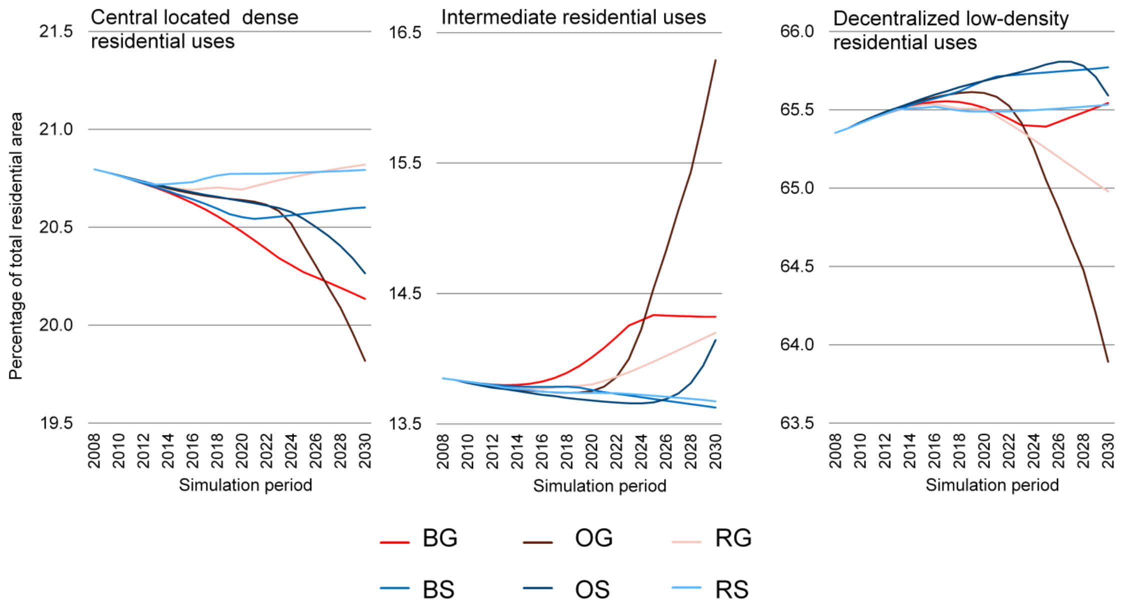


Figure A-IIIb-2. Percentage change in different residential-land-use compositions comparing all scenarios between 2008 and 2030

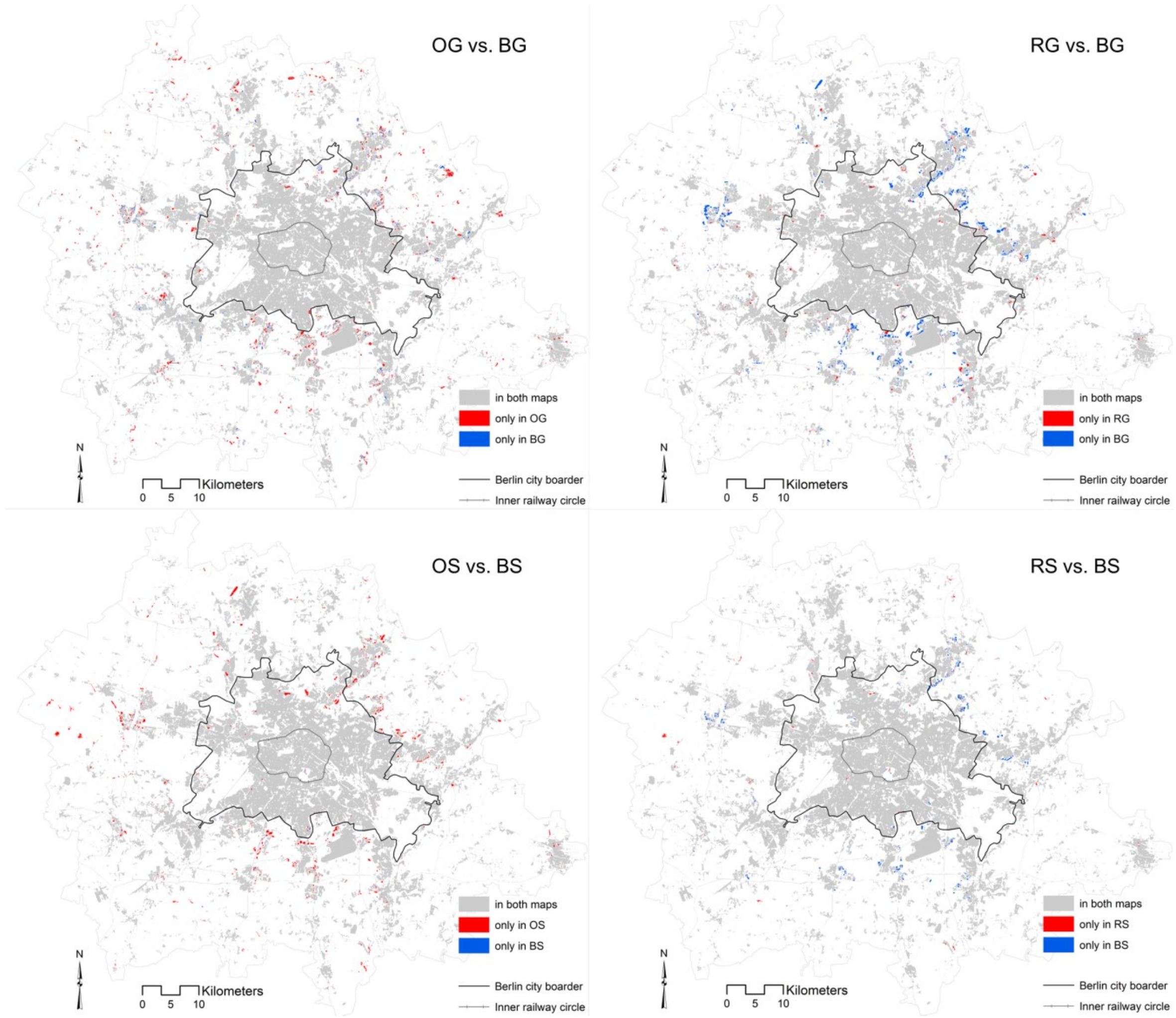


Figure A-IIIb-2. Spatial comparisons of land-uses distribution comparing basic and exceeding developments in 2030

App. III-C: Urban form indicators

Table A-IIIc-1. Sensitivity of urban form indicators towards changing drivers of exceeding urban development, for growth (grey stripes) and shrinkage (white stripes); missing numbers indicate no significance, low significance level under 0.4, medium significance level over 0.4 and under 0.8, high significance level above 0.8.

	Senario drivers	Study area							Built-up areas along the urban periurban gradient: Inner city				Outer city				Periphery					
		SRL	SI	DI	CI	PLAND	ED	PD	SI	DI	CI	PD	SRL	PLAND	ED	PD	SRL	SI	CI	PLAND	ED	PD
Overaging	Elderly	0.2	0.2	-1.1	-0.1	0.2		-0.3		0.2	0.2					-0.2	0.2	0.2	0.1	0.2	0.7	-0.3
		0.4	1.6	0.1		0.4		-0.1			0.2		0.4		-0.1	-0.1	0.4	0.7		0.3		-0.1
	Singels	0.5	0.5	-2.6	-0.3	0.5	0.1	-0.6		0.3	0.4					-0.5	0.6	0.6	0.2	0.5	1.6	-0.6
		0.5	2.2	0.1		0.5	-0.1	-0.1			0.2		0.6		-0.1	-0.2	0.5	1.0		0.5		-0.1
	Family	-0.1	-0.1	0.4		-0.1		0.1		-0.1	-0.1					0.1	-0.1	-0.1		-0.1	-0.3	0.1
		-0.7	-3.4	-0.2		-0.8	0.1	0.2			-0.3		-0.9	-0.1	0.2	0.3	-0.8	-1.5		-0.7	0.1	0.2
Reurbanization	Demand distribution inner-city blocks	0.3	0.3		0.1	0.4	-1.1			0.5	0.5					-0.7	0.2	0.2	-0.5	0.3	-2.8	-0.5
		0.2	-0.4		-0.1	0.2	-0.5	-0.4	0.5		0.5	-0.4				-0.5	0.2			0.2		-0.4
	Demand distribution detached houses	-0.2	-0.2		-0.1	-0.3	1.0			-0.4	-0.5					0.6	-0.2	-0.2	0.5	-0.3	2.4	0.4
		-0.2	0.4		0.1	-0.2	0.4	0.4	-0.4		-0.4	0.4				0.5	-0.2			-0.2		0.4

Appendix IV regarding Chapter IV

Table A-IV-1. Scenario input parameter showing the annual change rates compared to the linear continuation of demographic and economic trends. The model parameters are described in (Lauf et al. 2012a and Lauf et al. 2012c).

Scenario parameters	Growth scenario	Shrinkage scenario
Fertility	1.002	0.997
Immigration	1.003	0.996
Emigraion	0.997	1.004
GDP	1.096	0.904

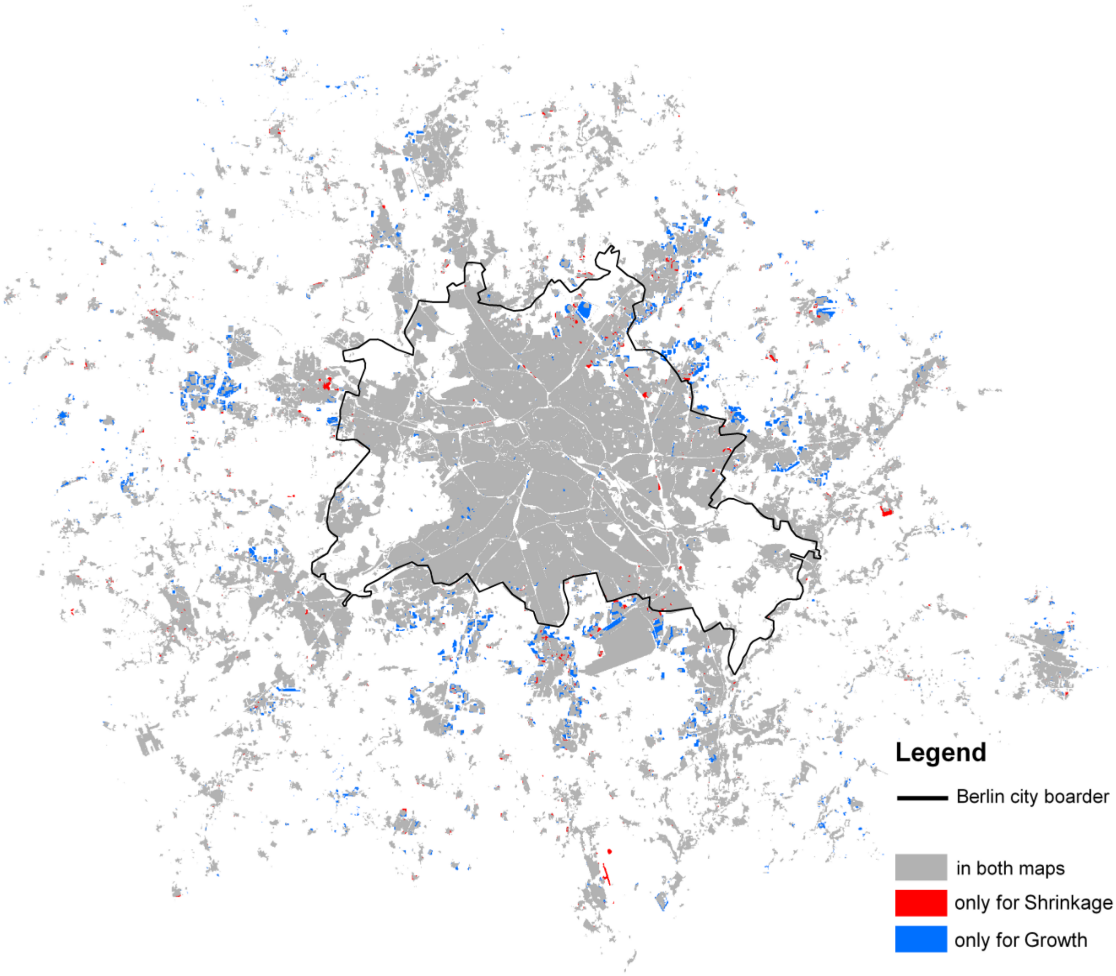


Figure A-IV-1. Land-use map comparisons of the growth and shrinkage scenarios for the year 2030. All built-up areas, urban brownfields and green spaces are considered. The gray area represents all equal land-use states. The red area represents all land-use changes occurring only in shrinkage, and the blue represents all changes occurring only in the growth scenario. The higher rate of urban spread for the growth scenario is clear.

Table A-IV-1a. Land-use transition between land uses from 2008 – 2030 for the shrinkage scenario (grey) and the growth scenario (black) in ha

	Arable land	Pasture	Shrubs & trees	Forest	Open spaces	Urban green	Brown-fields	Multi-story prefab	Inner-city blocks	Villas	De-tached houses	Resid. park	Multi-story rows	Sub-urban villages	Services	Comm. area	Industrial area	Airport	Infra-structure	Supply & disposal	Mineral extraction	Wetlands	Water bodies	Sum 2008
Arable land	126085 123512	/	/	/	/	507 146	48 110	/	1 /	1 50	1454 2862	12 521	2 15	/ 2	1 196	14 468	17 262	1045 1045	/	/	/	/	/	129188 129188
Pasture	3 2	72090 71569	/	/	/	594 296	88 137	/	8 65	2 61	/	14 33	7 61	/ 3	14 147	42 341	14 161	44 44	/	/	/	/	/	72917 72917
Shrubs & trees	1 1	/	8570 8374	/	/	74 67	16 14	/	6 21	2 9	/	6 16	10 22	/ 1	14 104	17 74	3 16	15 15	/	/	/	/	/	8732 8732
Forest	2 /	/	/	170666 170313	/	128 114	146 195	/	3 10	1 21	/	16 22	6 10	/	1 40	18 262	/	64 64	/	/	/	/	/	171049 171049
Open spaces	/	/	/	/	1122 1083	44 25	8 2	/	2 11	/ 1	/	1 5	1 7	/	0 7	2 32	3 11	4 4	/	/	/	/	/	1187 1187
Urban green	28 25	/	/	/	/	20084 20084	/	/	3 3	5 8	/	7 6	/	/	3 4	/	/	12 12	/	/	/	/	/	20141 20141
Brown-fields	113 29	/	/	/	/	744 662	331 345	/	46 43	52 103	/	116 105	18 16	/	47 103	302 363	/	30 30	/	/	/	/	/	1798 1798
Multi-story prefab	1 /	/	/	/	/	196 86	43 32	3502 3546	2 17	4 11	/	8 24	/ 1	/	/	3 41	/	/	/	/	/	/	/	3756 3756
Inner-city blocks	/	/	/	/	/	15 /	10 /	/	7329 7354	0 0	/	/	/	/	/	/	/	/	/	/	/	/	/	7354 7354
Villas	3 /	/	/	/	/	1 2	/ 2	/	/	4533 4533	/	/	/	/	/	/ 1	/	17 17	/	/	/	/	/	4554 4554
Detached houses	2 5	/	/	/	/	19 9	14 10	/	/	0 2	41301 41302	3 3	/	/	1 2	37 42	/	18 18	/	/	/	/	/	41394 41394
Residential park	/	/	/	/	/	2 /	/ 2	/	/	0 5	/	1602 1597	/	/	/	/	/	4 4	/	/	/	/	/	1608 1608
Multi-story rows	2 /	/	/	/	/	8 5	3 4	/	/	0 2	/	/	7546 7548	/	/	/	/	/	/	/	/	/	/	7559 7559
Suburban villages	11 2	/	/	/	/	160 2	121 29	/	/	0 52	/	/	/	5120 5327	/	/	/	3 3	/	/	/	/	/	5415 5415
Services	/	/	/	/	/	108 /	40 /	/	/	1 /	/	/	/	/	5004 5151	/	/	/	/	/	/	/	/	5151 5151
Comm. area	14 9	/	/	/	/	291 21	276 2	/	/	3 7	/	6 10	/	/	1 1	12154 12696	/	95 95	/	/	/	/	/	12840 12840
Industrial area	128 22	/	/	/	/	258 33	446 221	/	1 0	0 40	/	5 2	/	/	/ 1	3 11	5620 6131	29 29	/	/	/	/	/	6490 6490
Airport	/	/	/	/	/	224 218	154 16	/	0 2	0 4	/	21 21	7 3	/	18 78	18 103	/	446 446	/	/	/	/	/	889 889
Infra-structure	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	18 18	5091 5091	/	/	/	/	5109 5109
Mineral extraction	/	/	/	/	/	1 1	/	/	/	/	/	/	/	/	/	/	/	3 3	/	2296 2296	/	/	/	2299 2299
Supply & disposal	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/ /	/	/	399 399	/	/	399 399
Wetlands	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	1 1	/	/	/	4277 4277	/	17111 17111
Water bodies	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	14 14	/	/	/	/	19917 19917	19931 19931
Sum 2030	126390 123606	72090 71569	8570 8374	170666 170313	1122 1083	23458 21768	1743 1120	3502 3546	7400 7525	4602 4907	42755 44165	1815 2363	7596 7681	5120 5333	5101 5833	12609 14433	5658 6580	1862 1862	5091 5091	2296 2296	399 399	4277 4277	19917 19917	534036 534036

Table A-IV-2. Energy provisioning rates per year and land use for different energy segments

Land use	A	E_{sol}	(S_s*P_s)	(S_p*P_p)	E_{wind} (H=2000)	WPP (MP=1.555)	E_{bio}	(Y_b*S_b)
Arable land	129188	0	/	/	26.6	307	18.0	2,325,384
Pasture	72917	0	/	/	3.5	23	17.0	1,239,589
Shrubs and trees	8732	0	/	/	3.8	3	35.0	305,620
Forest	171049	0	/	/	0.1	2	199.6	34,141,380
Open spaces	1187	0	/	/	9.4	1	0.0	/
Urban green space	20141	0	/	/	0	/	45.7	920,444
Brownfields	1798	0	/	/	0	/	0.0	/
Multi-story prefab	3756	18.4	/	19,156	0	/	8.0	30,048
Inner-city blocks	7354	287.6	415,501	172,084	0	/	8.0	58,832
Villas	4554	884.2	1,118,462	/	0	/	1.0	4,554
Detached houses	41394	1406.5	13,904,245	2,268,391	0.3	1	1.0	41,394
Residential park	1608	268.9	103,394	16,723	0	/	8.0	12,864
Multi-story rows	7559	1593.4	3,087,096	258,518	0	/	8.0	60,472
Suburban villages	5415	0	/	/	0	/	1.0	5,415
Services	5151	117.0	31,421	135,986	0	/	5.3	27,300
Commercial area	12840	347.0	/	1,237,776	3.5	4	5.3	68,052
Industrial area	6490	314.6	/	567,226	17.3	10	69.1	448,459
Airport	889	0	/	/	0	/	0	/
Infrastructure	5109	0	/	/	0	/	0	/
Supply and disposal	2299	0	/	/	4.9	1	0	/
Mineral extraction	399	0	/	/	28.1	1	0	/
Wetlands	4278	0	/	/	0	/	0	/
Water bodies	19931	0	/	/	0	/	0	/

Table A-IV-3. Food provisioning rates per year and land use regarding crop, livestock and fish production, grey values show energetic value including crops for fodder production

	F_{crop}	$F_{livestock}$	F_{fish}
Arable land	106.59 (118.64)	1.81	/
Pasture	0.42 (56.86)	8.49	/
Shrubs and trees	8.55	/	/
Water bodies	/	/	0.03

Table A-IV-3a. Detailed list of crop, livestock and fish production, including caloric values and yield, cf. Figure 1 (cf. FAO 2012, Agribusinesses Berlin Brandenburg in SOBB 2012)

Land use	c, l, f	$F_{crop,livestock,fish}$*(A)	$CV_{c,l,f}$	A_c, AF, N_L	Y_c, Y_f, (AP_l-D_l)
Arable land	**grain**				
	wheat	2772314	*13.4*	0.26	61.9
	rye	2373063	*12.8*	0.35	40.8
	triticale*	762133	*13.6*	0.10	43.8
	barely	1401744	*13.3*	0.15	55.0
	oat*	164405	*15.4*	0.03	32.5
	mais*	110825	*3.1*	0.04	74.6
	root crop				
	potatos	199084	*2.7*	0.02	323.7
	sugar beets	265090	*2.8*	0.01	526.0
	legumes				
	peas	6000	*1.2*	0.02	20.1
	beans	87	*2.0*	0.00	19.3
	lupins	62004	*15.6*	0.03	12.1
	oil seeds				
	oil seed rap	1998724	*19.8*	0.22	35.4
	sunnfllower	92025	*12.3*	0.03	20.0
	sum	9326221	67% of A considered for food production		
Pasture	**vegetables**	22928	*1.0*	0.02	201.3
	fruits				
	strawberries	1511	*1.1*	0.00	57.6
	permanent grassland				
	meadow cu	471036	*7.5*	0.19	46.2
	grazing*	414142	*7.5*	0.16	48.5
	harvested green plants				
	green corn	1980140	*2.2*	0.39	319.8
	legumes	36188	*1.2*	0.08	54.5
	grass	391131	*7.5*	0.18	39.9
	sum	24439	80% of A considered for food production		
Assigned to arable land and pasture (fodder production)	**stock breeding**				
	beefs	28418	*6.0*	116131	40.8
	hog	40919	*8.8*	117422	39.6
	sheep	779	*4.9*	15232	10.4
	chicken	4925	*4.9*	1401768	0.7
	eggs	39285	*6.2*	96856084	0.1
	milk	537180	*1.9*	29% beefs	8395.0
	sum	651507	distributed to land uses according to distribution of fodder energy production		
Shrubs and trees	**fruits**				
	apple	56646	*1.9*	0.43	211.6
	pear	996	*2.2*	0.01	107.0
	sweet cherr	3329	*2.1*	0.20	24.7
	sour	2680	*1.8*	0.10	44.7
	plum	3022	*2.1*	0.05	83.7
	small yellow	264	*2.2*	0.00	93.5
	seabuckthо	263	*1.8*	0.02	20.6
	blueberries	1522	*4.8*	0.02	43.9
	currants	22	*2.4*	0.00	10.0
	raspberries	50	*1.9*	0.01	11.4
	sum	68794	41% of A considered for food production		
Water bodies	**fish farming**				
	eel	133	*2.8*	1.00	0.025
	zander	99	*3.7*	1.00	0.014
	pike	108	*3.4*	1.00	0.017
	cisco	39	*4.0*	1.00	0.005
	carp	77	*3.9*	1.00	0.010
	tench	48	*5.6*	1.00	0.004
	others	45	*3.9*	1.00	0.006
	sum	550	100% of A considered for food production		

Table A-IV-4. Carbon emission and sequestration rates per year and land use (cf. Table IV-1; CO2 values were transformed using the factor 0.2727)

Land use	C_{heat}	C_{power}	$C_{traffic}$	$C_{sequest}$
Arable land	/	/	16.0	-0.03
Pasture	/	/	33.2	-0.04
Shrubs and trees	/	/	23.3	-0.13
Forest	/	/	13.7	-0.23
Open spaces	/	/	27.2	-0.31
Urban green space	/	/	25.4	-0.06
Brownfields	/	/	45.7	-0.09
Multi-story prefab	21.4	22.8	52.4	-0.01
Inner-city blocks	27.2	29.1	63.2	0.00
Villas	16.8	17.9	1.1	-0.02
Detached houses	4.0	4.3	20.7	0.00
Residential park	19.0	20.3	6.6	-0.08
Multi-story rows	17.1	16.6	39.4	0.00
Suburban villages	12.0	12.8	58.4	-0.32
Services	27.9	23.0	8.4	0.00
Commercial area	8.3	9.7	7.4	-0.01
Industrial area	26.1	32.4	6.9	-0.01
Airport	0.7	0.4	49.1	-0.11
Infrastructure	/	/	55.8	-0.01
Supply and disposal	6.8	118.9	10.7	-0.05
Mineral extraction sites	/	/	49.4	0.00
Wetlands	/	/	15.6	-1.07
Water bodies	/	/	21.9	-0.01

Table A-IV-4a. Household consumption rates and related carbon emission (cf. Table IV-1, for non-residential built-up land uses we used mean consumption rates per hectare)

	PC_{HHT} (kWh)	HC_{HHT} (kWh)	M_p (g/kWh)	M_h (g/kWh)	HHT (total)
Singles	1500	2786	518.5	261.6	961736
Couple	1400	2600	518.5	261.6	1626864
Family	1091	2026	518.5	261.6	1435208
Flat sharer	1091	2026	518.5	261.6	414286

Table A-IV-4b. Distribution of households across residential land uses

	Singles	Couple	Family	Flat sharer
Multi-story prefab	0.21	0.12	0.02	0.09
Inner-city blocks	0.36	0.23	0.21	0.37
Villa	0.07	0.13	0.09	0.14
Detached houses	0.05	0.25	0.35	0.13
Residential park	0.03	0.04	0.05	0.04
Multi-story rows	0.21	0.15	0.16	0.20
Suburban village	0.07	0.08	0.12	0.03

Table A-IV-4c. Means of transportation and km-frequencies per year and carbon emission per km (SDUDEB 2012, LfUB 2011)

t	F_t (km)	RE_t (kg)
metro	20700945	6.15
tram	19228793	2.48
local train	27404962	9.19
car	11021400000	0.20
truck	1392800000	0.78
bus	89700000	0.80
motorcycle	137400000	0.12

Table A-IV-5. Detailed ESA for all land-use transitions between 2008 and 2030, comparing the scenarios. Red boxes represent especially negative land-use transitions due to at least one of the evaluation attributes; green boxes represent especially positive land-use transitions due to at least one of the evaluation attributes; evaluation attributes in bold indicate highly significant values in terms of ES change; only one value for shrinkage and growth indicates equal values

ES changes	Change of ES assessment value	% of total LUC	
-2	-19.9	0.14	← Shrinkage
	-18.5	4.67	← Growth

LUC 2008 /2030	Arable land	Urban green spaces	Urban brownfields	Inner-city blocks	Villas	Detached houses	Residential park	Multi-story rows	Suburban villages	Services	Commercial area	Industrial area	Airport
Arable land	/	-3 **-19.3** **5.66** **1.31**	**-5** **-24.0** 0.54 0.99	-2 **-31.6** 0.01 **-30.0** 0.00	0 -5.5 0.01 -6.7 0.45	-2 -3.2 **16.24** -2.9 **25.68**	-2 **-19.9** 0.14 **-18.5** **4.67**	-2 -14.2 0.02 -14.6 0.13	/ -4 -14.2 0.02	-3 **-26.6** 0.01 1.76	-3 -21.5 0.16 4.19	-3 **-25.0** 0.19 2.35	**-5** **-19.7** **11.67** **9.37**
Pasture	3 16.9 0.03 0.01	-1 -2.4 **6.63** **2.65**	**-5** -7.1 0.99 1.23	-2 -12.3 0.08 -11.6 0.58	**0** 9.2 0.02 9.9 0.54	/	-2 -3.5 0.15 -3.2 0.29	-2 2.0 0.07 3.7 0.55	/ -4 3.4 0.02	-3 -9.7 0.15 1.32	-1 -4.6 0.46 **3.06**	-3 -8.1 0.16 1.44	-3 -2.7 0.49 0.39
Shrubs & trees	5 16.0 0.01 0.01	-3 -3.3 0.83 0.60	**-5** -8.0 0.18 0.12	-2 -13.1 0.06 -13.0 0.19	2 8.7 0.02 8.6 0.08	/	-2 -4.1 0.07 -3.8 0.14	-2 1.2 0.11 1.6 0.20	/ -4 2.4 0.01	-3 -10.6 0.15 0.93	-3 -5.5 0.19 0.67	-3 -9.0 0.03 0.14	-3 -3.7 0.16 0.13
Forest	-1 7.6 0.02 /	**-4** -11.7 **1.43** **1.02**	**-4** -16.4 **1.63** **1.75**	-1 -21.2 0.03 -21.5 0.09	-1 4.9 0.01 -1.8 0.19	/	-1 -9.9 0.17 / 0.20	-1 -5.2 0.06 -6.4 0.09	/ -3 -6.0 0.00	**-4** **-19.0** 0.01 0.35	-2 -13.9 0.20 2.35	/	-2 -12.0 0.71 0.57
Open spaces	/	2 -0.3 0.49 0.22	-4 -5.0 0.09 0.02	-1 -12.8 0.03 -9.3 0.09	/ 3 13.8 0.01	/	-1 -1.0 0.01 -2.3 0.04	-1 6.5 0.01 5.1 0.06	/	-2 -7.6 0.00 0.06	0 -2.5 0.02 0.29	-2 -6.0 0.04 0.10	-2 -0.6 0.04 0.03
Urban green spaces	3 **19.3** 0.31 0.22	/	/	-1 -8.7 0.03 -9.2 0.03	3 16.6 0.05 16.6 0.07	/	-1 4.3 0.08 -0.7 0.05	-1 2.1 0.00 10.0 0.00	/	-2 -7.3 0.03 0.03	/	/	-2 -0.3 0.14 0.11
Urban brownfields	**5** **24.0** **1.26** 0.26	**4** 4.7 **8.31** **5.94**	/	-1 -5.0 0.51 -4.9 0.38	**5** 16.4 0.58 16.9 0.92	/	1 4.2 1.30 4.9 0.94	-1 8.8 0.20 8.0 0.14	/	-2 -2.6 0.52 0.92	0 2.5 **3.37** **3.26**	/	-1 4.4 0.34 0.27
Multi-story prefab	4 21.9 0.01 /	3 6.3 2.18 7.1 0.77	1 2.5 0.47 2.9 0.28	-1 2.6 0.03 -0.8 0.15	5 24.6 0.04 20.1 0.10	/	**5** 11.9 0.08 8.1 0.21	/ / / 5 12.2 0.01	/	/ 3 -5.9 0.00	3 1.2 0.03 4.1 0.36	/	/
Inner-city blocks	/	1 8.7 0.17 3.7 0.00	1 4.0 0.11 /	/	/	/	/	/	/	/	/	/	/
Villas	0 7.7 0.03 1 12.7 0.00	-3 -16.6 0.01 -11.6 0.01	/ **-5** -16.3 0.01	/	/	/	/	/	/	/	-2 -8.8 0.00 0.00	/	-3 -11.9 0.19 0.15
Detached houses	2 4.9 0.02 2 0.05	-1 -15.1 0.21 0.08	**-5** **-19.8** 0.15 0.09	/	/ -2 -2.8 0.02	/	**-4** -15.1 0.04 0.03	/	/	-5 -16.7 0.01 -21.7 0.02	-3 -17.3 0.41 0.38	/	-3 -14.7 0.20 0.16
Residential park	/	1 0.7 0.03 -4.3 0.00	/ -1 -4.0 0.02	/	/ 4 12.3 0.04	/	/	/	/	/	/	/	-1 -4.6 0.04 0.03
Multi-story rows	2 9.3 0.02 0.00	1 -10.0 0.09 0.04	1 -14.7 0.04 0.04	/	/ 2 6.5 0.01	/	/	/	/	/	/	/	/
Suburban villages	**4** **18.6** 0.12 13.6 0.02	1 -0.7 1.79 -5.7 0.01	**-1** -5.4 1.35 0.26	/	/ **4** 10.8 0.47	/	/	/	/	/	/	/	0 3.9 0.03 0.03
Services	/	2 7.3 1.20 /	2 2.6 0.44 /	/	5 23.9 0.01 / / /	/	/	/	/	/	/	/	/
Commercial area	3 **21.5** 0.16 0.08	0 2.2 3.25 0.19	0 -2.5 3.09 0.02	/	3 18.8 0.03 18.1 0.06	/	-1 6.5 0.06 4.1 0.09	/	/	-4 -5.1 0.01 0.01	/	/	-2 1.9 1.06 0.85
Industrial area	3 **25.0** **1.43** 0.20	2 5.7 2.88 0.30	2 1.0 **4.98** **1.98**	-3 2.0 0.01 /	/ **5** 17.3 0.36	/	1 5.0 0.05 0.02	1 15.8 0.00 0 5.8 0.00	/	/ 0 -1.6 0.01	0 3.5 0.03 0.10	/	0 5.4 0.33 0.26
Airport	5 19.7 0.00 /	2 0.3 2.50 1.96	1 -4.4 1.71 0.14	-1 -3.4 0.00 -1 0.01	/ / / 3 16.9 0.03	/	1 4.6 0.24 0.19	-1 10.4 0.08 0.02	/	0 -7.0 0.20 0.70	2 -1.9 0.20 0.92	/	/
Infrastructure	/	/	/	/	/	/	/	/	/	/	/	/	1 4.7 0.20 0.16
Supply & disposal	/	4 8.1 0.01 0.00	/	/	/	/	/	/	/	/	/	/	0 7.8 0.03 0.03
Wetlands	/	/	/	/	/	/	/	/	/	/	/	/	-1 -11.1 0.01
Water bodies	/	/	/	/	/	/	/	/	/	/	/	/	-2 -3.3 0.16 0.13

Figure A-IV-6. Mapped changes in ES values between 2008 and 2030 for single ES, comparing the scenarios (in one map). Yellow-to-turquoise patches display areas qualitative change (>0-10) in ES for the growth scenario; yellow-to-red-brown patches display areas of qualitative change (>0-10) in ES for the shrinkage scenario

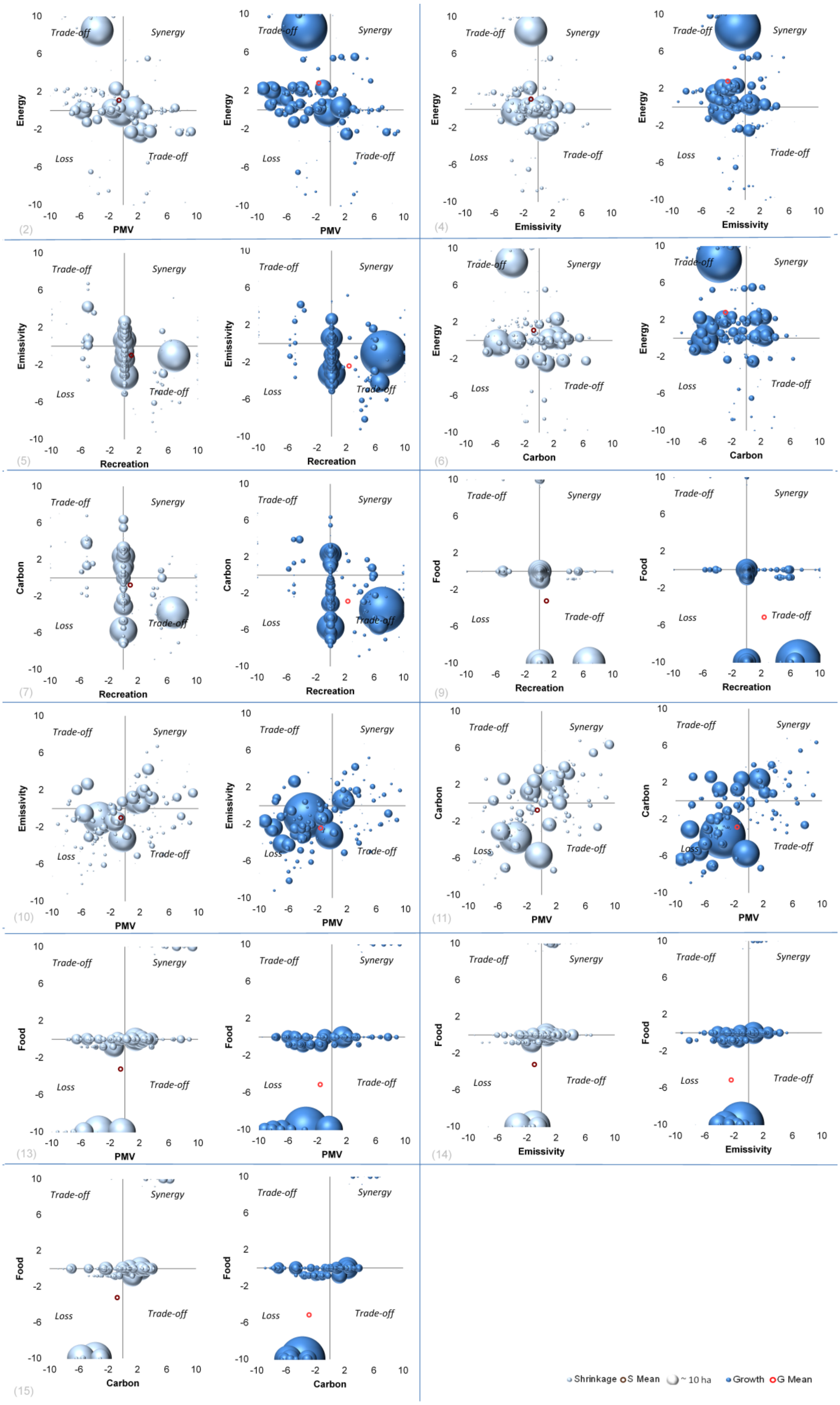


Figure A-IV-3. ES linkages due to obtained land-use transitions and normalized ES changes between 2008-2030 for the remaining ES combinations, with the bubble size representing the summed area size of a specific land-use transition. ES combinations are numbered according to Figure IV-6.

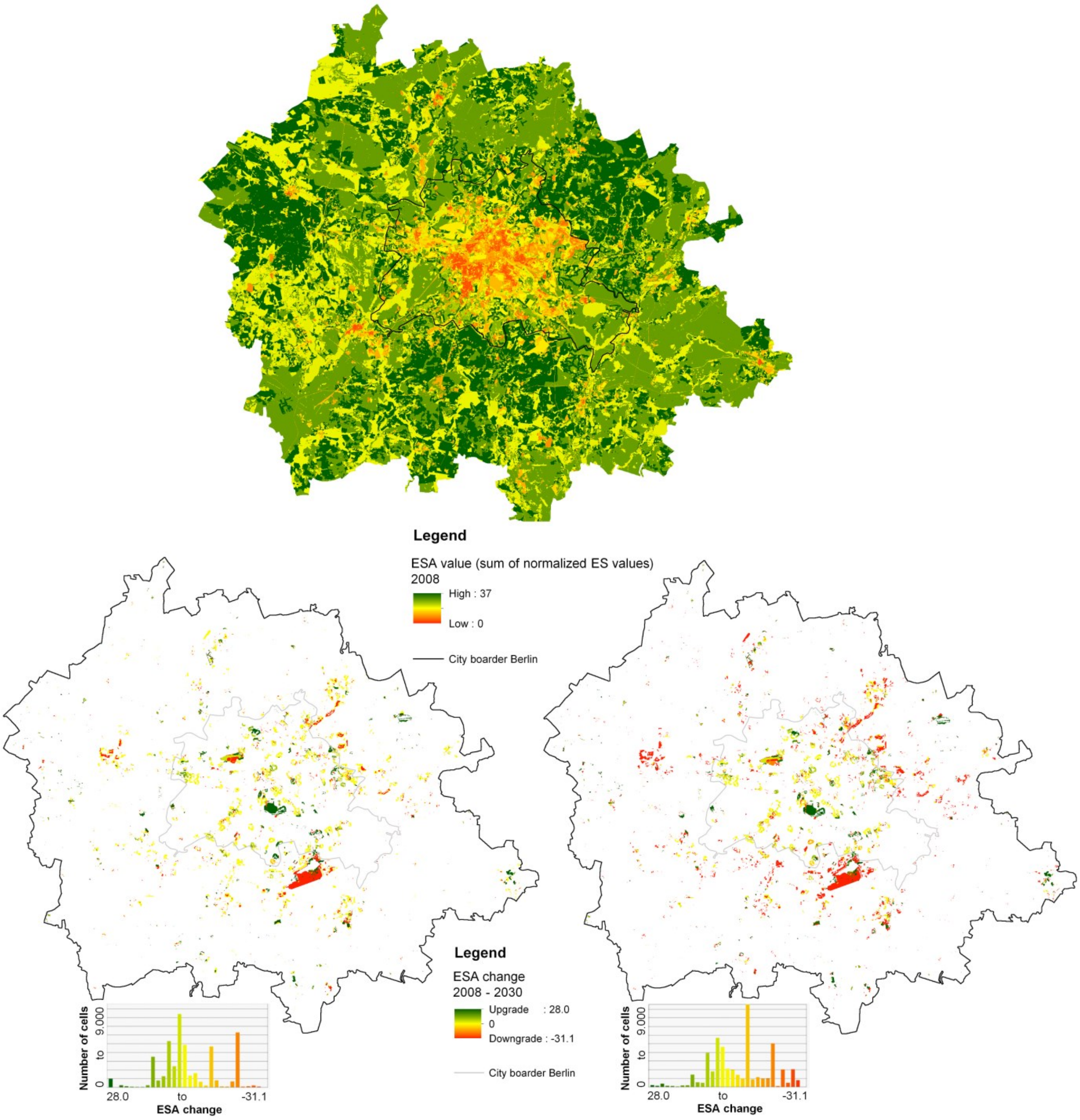


Figure A-IV-4. Decision maps; mapped changes in ESA values for both scenarios between 2008 and 2030. The upper map describes the distribution of ESA values uncovering disadvantaged inner-city areas. The lower maps display the change in ESA values between 2030 and 2008 for the shrinkage scenario (on the left) and the growth scenario (on the right). The changes describe the quality of ES improvement or degradation. Within the histograms, the quantity of ESA changes is shown on the regional scale.

Appendix V regarding chapter V

Table A-V-1. Input accessibility parameters according to the utilization in Metronamica (Riks, 2007, 2013), representing an increasing importance for rail (and public) transport and a loss of importance for road transport

Scenario	Parameter		Urban green space		Brown-fields		Prefabricated multi-story		Inner-city blocks		Villas		Detached houses		Resi-dential park		Multi-story rows		Sub-urban village		Services		Commercial area		Industrial area	
All other scenarios	***Implicit Accessibility***																									
	of built-up area		1		0.9		0.9		1		0.9		0.8		0.9		0.9		0.8		0.9		1		0.9	
	of non built-up area		0.9		0.3		0.5		0.6		0.6		0.6		0.6		0.6		0.5		0.7		0.7		0.6	
	Accessibility to links and nodes		**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**
	Street network	Main street	0.4	50	0.4	15	0.5	25	0.4	20	0.3	-2	0.5	50	0.5	20	0.4	20	0.7	20	0.6	20	0.7	20	0.7	20
		Motorway	0.1	-20	0.4	15	0.2	40	0.3	-5	0.4	-10	0.7	250	0.3	250	0	0	0	0	0	0	0.6	100	0.6	150
	Stations and stops	Local train	0.4	50	0.5	-10	0.2	40	0.1	40	0.2	100	0.3	200	0.3	200	0.3	60	0.3	20	0.1	20	0.5	100	0.5	100
		City train & tram	0.6	50	0.2	-10	0.5	15	0.9	10	0.5	15	0.1	15	0.3	15	0.6	15	0	0	0.7	10	0.6	10	0.1	15
Scenario AB	***Implicit Accessibility***																									
	of built-up area		1		0.9		0.9		1		0.9		0.8		0.9		0.9		0.8		0.9		1		0.9	
	of non built-up area		0.9		0.3		0.5		0.6		0.6		0.6		0.6		0.6		0.5		0.7		0.7		0.6	
	Accessibility to links and nodes		**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**	**RI**	**DD**
	Street network	Main street	0.4	50	0.4	15	0.4	25	0.3	20	0.2	-2	0.3	50	0.4	20	0.3	20	0.6	20	0.5	20	0.6	20	0.6	20
		Motorway	0.1	-20	0.4	15	0.1	40	0.2	-5	0.3	-10	0.5	250	0.2	250	-0.1	0	-0.1	0	-0.1	0	0.5	100	0.5	150
	Stations and stops	Local train	0.4	50	0.5	-10	0.4	40	0.3	40	0.4	100	0.6	200	0.5	200	0.5	60	0.5	20	0.3	20	0.7	100	0.7	100
		City train & tram	0.6	50	0.2	-10	0.7	15	1.1	10	0.7	15	0.7	15	0.5	15	0.8	15	0.2	0	0.9	10	0.8	10	0.3	15

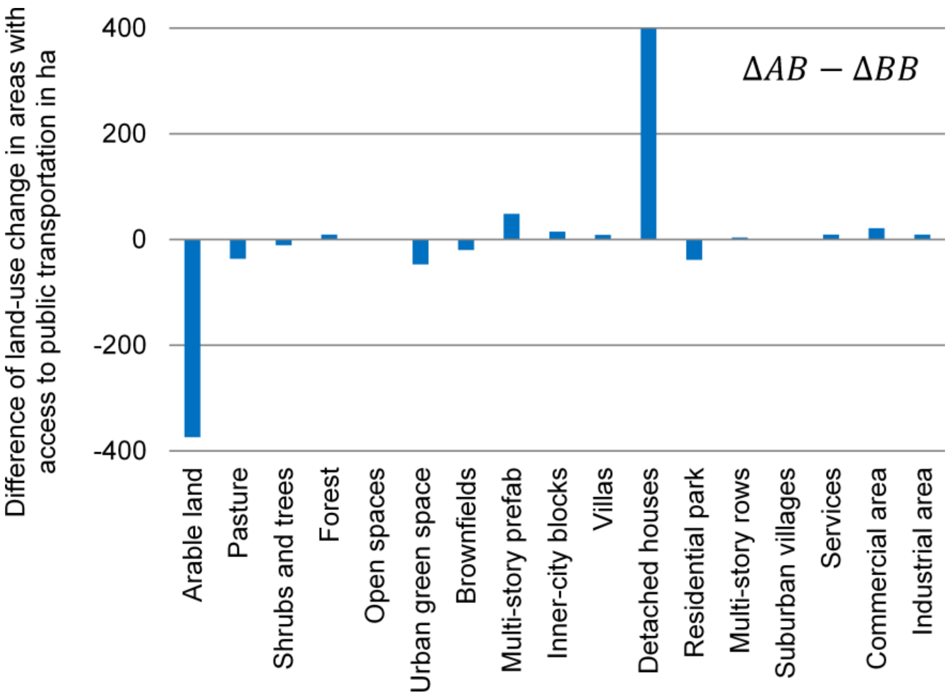


Figure A-V-1. LUC effect in all areas with access to public transportation (2km for regional train stations and 1 km for short distance public transportation stops) for the scenarios AB

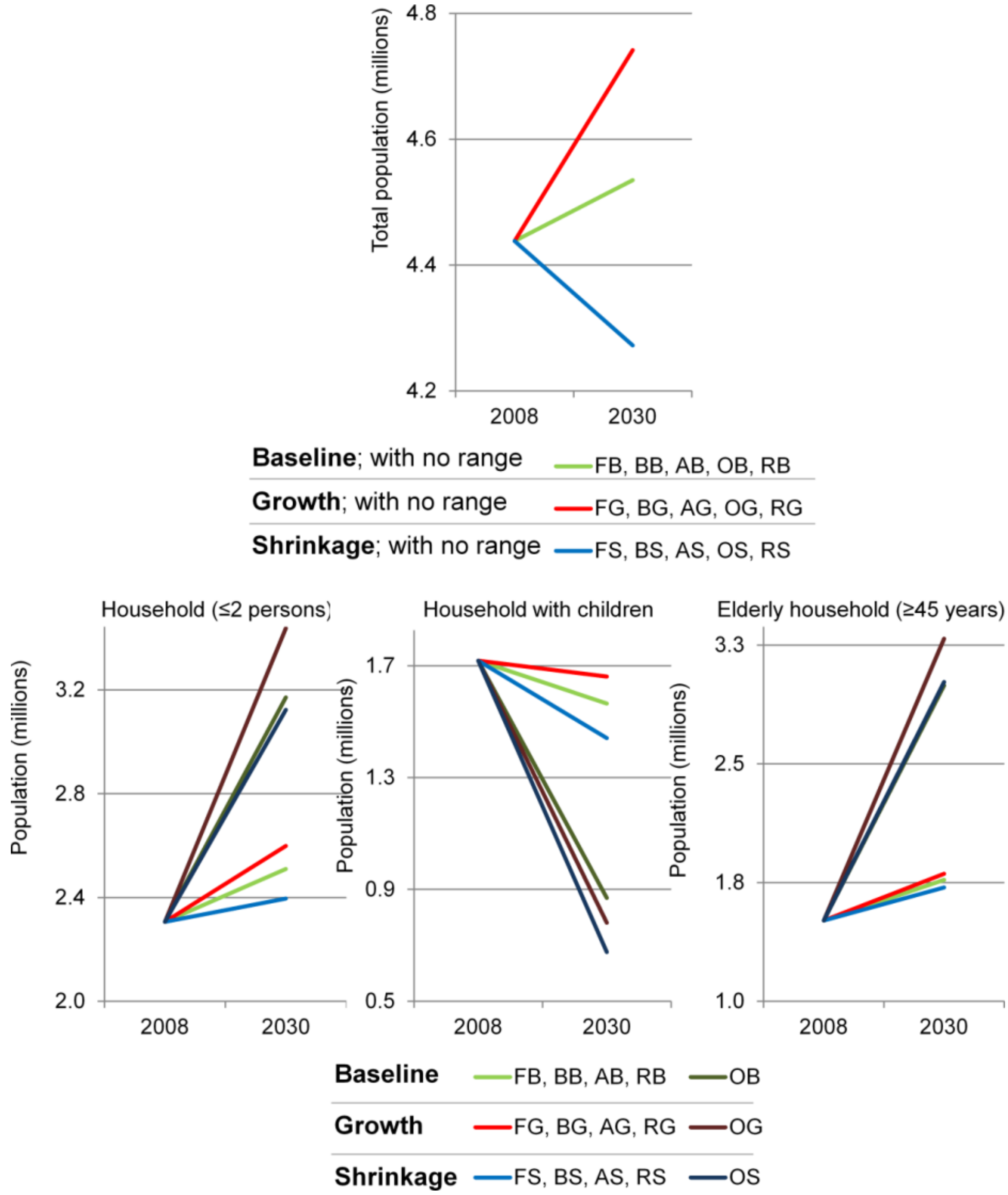


Figure A-V-2. Scenario results of the total population and population numbers per household types between 2008 and 2030

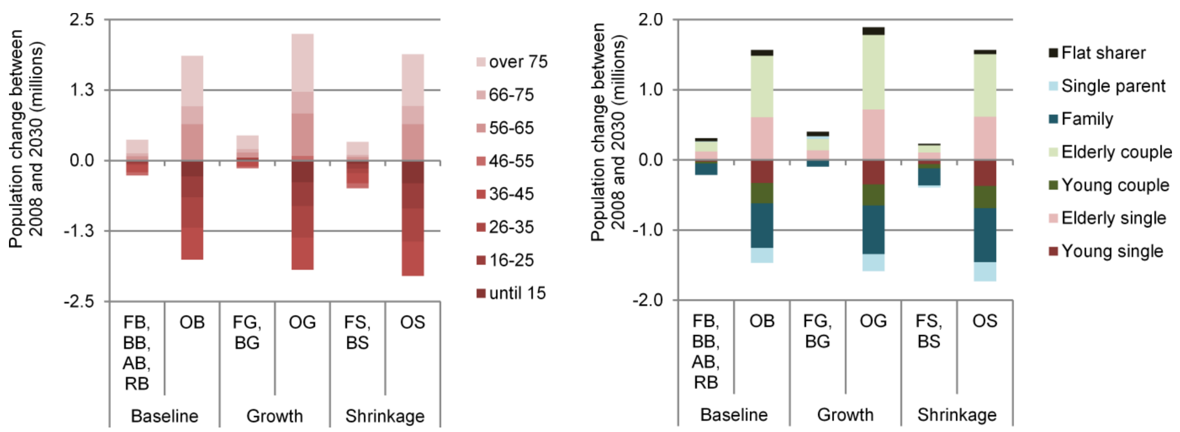


Figure A-V-2a. Scenario comparison of detailed demographic parameters

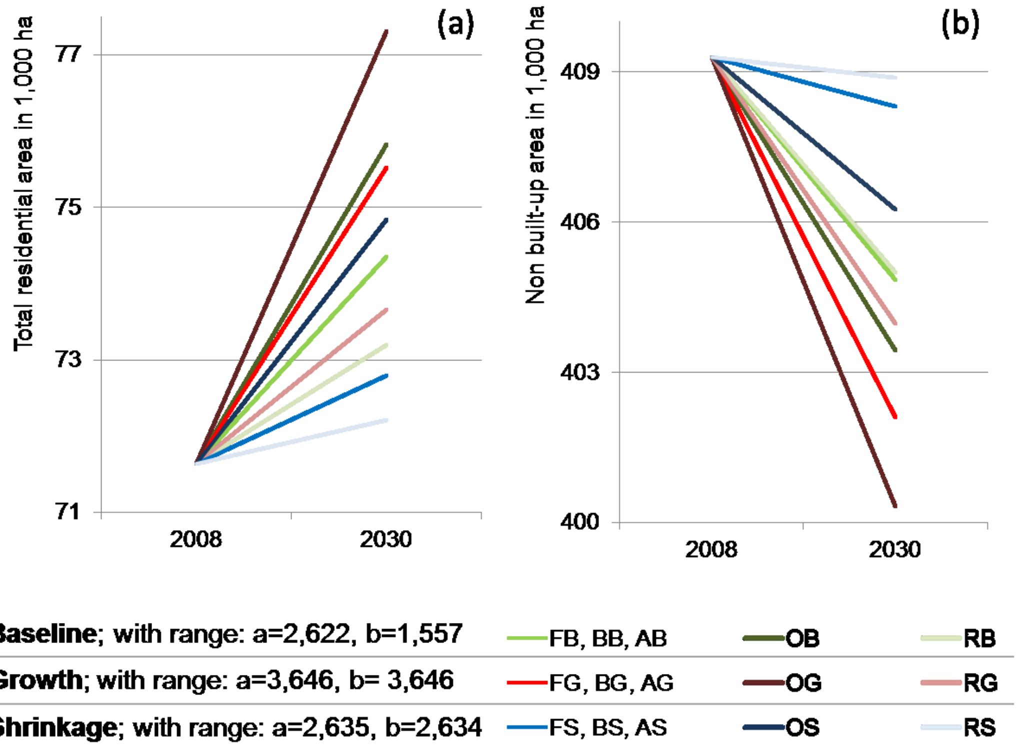


Figure A-V-3. Scenario results of total residential area (a) and total open and green space between 2008 and 2030

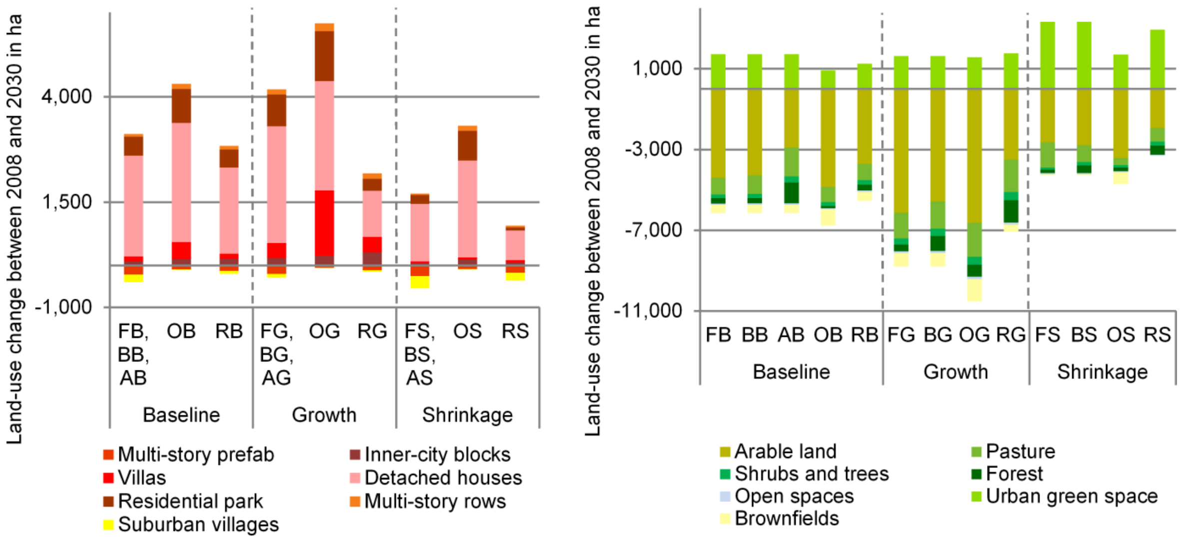


Figure A-V-3a. Scenario comparison of detailed land-use change

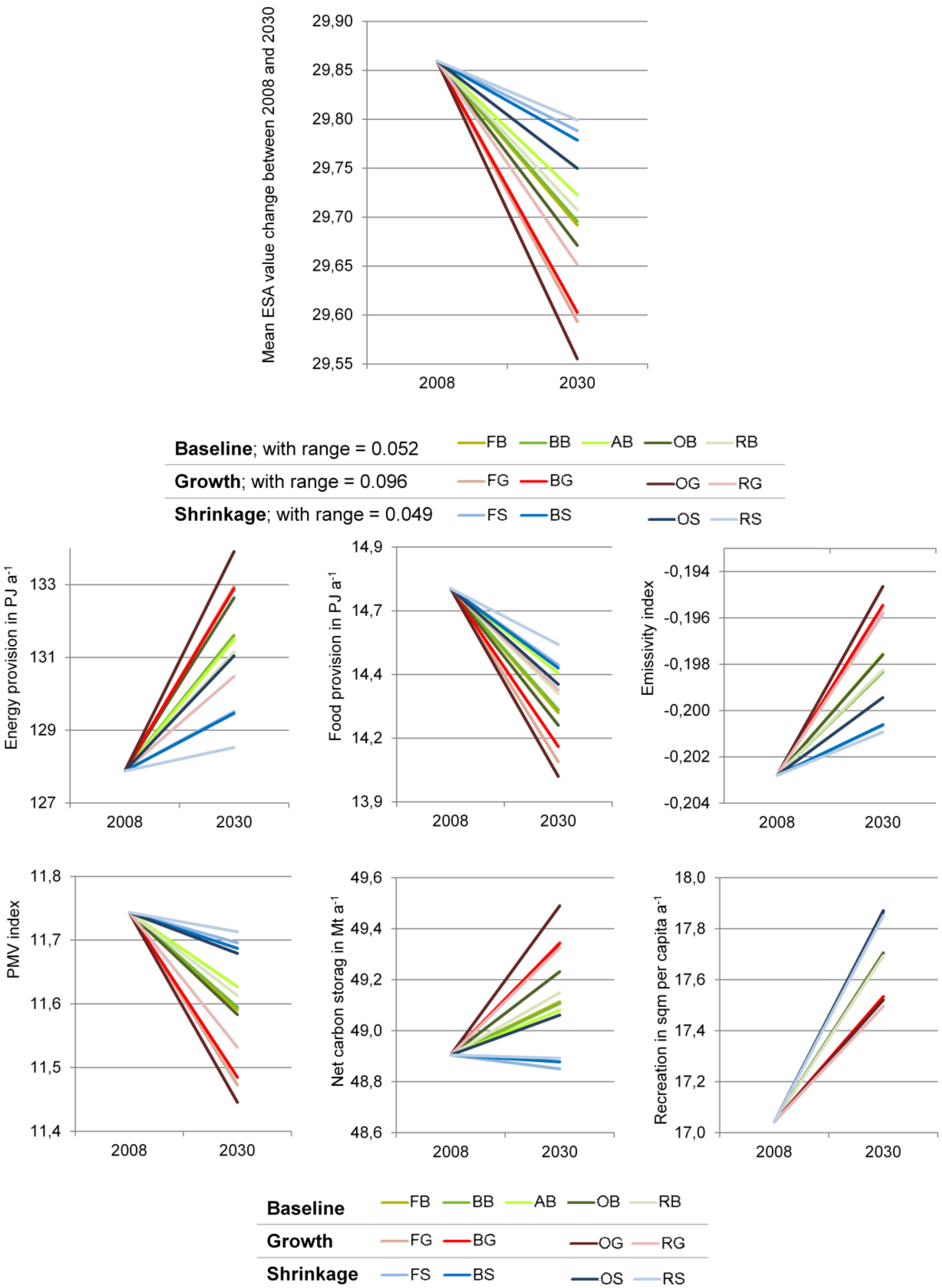


Figure A-V-4. Scenario results of the mean ESA value and all regional ES values between 2008 and 2030

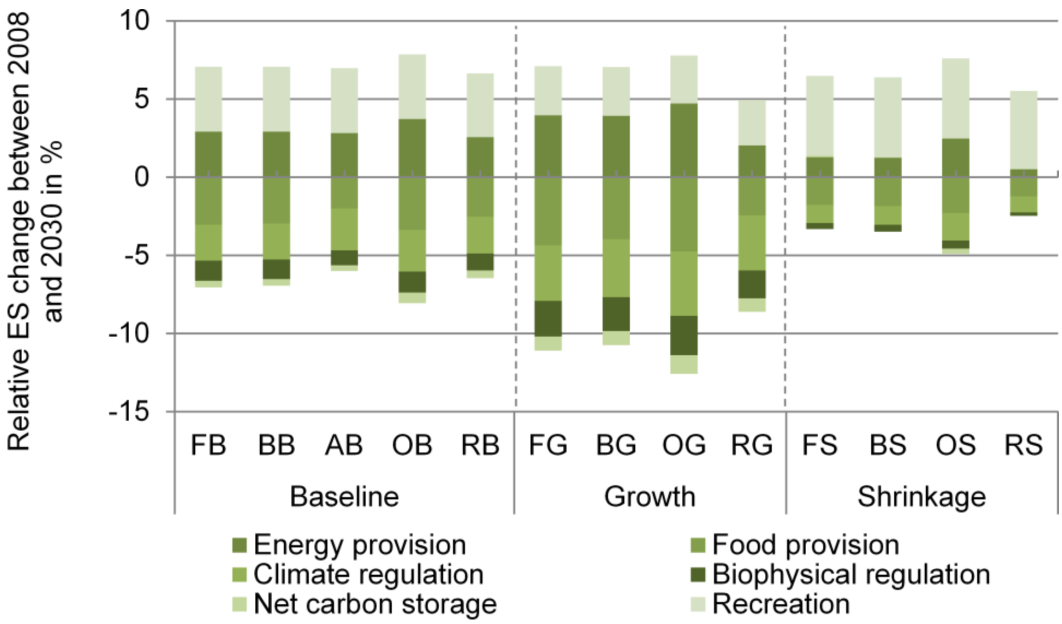


Figure A-V-4a. Scenario comparison of detailed ecosystem service changes

Table A-V-2. Relative amounts of all spreading land-use classes and their summarized ratio to the summarized transformation of open, green and agricultural land uses; ratio values >1 indicate an additional replacement of built-up uses by other built-up use (e.g. industrial to residential), whereas low ratio values indicate a replacement of non-built-up uses by other-built-up uses (e.g. arable land to urban green space)

	Baseline					Growth				Shrinkage			
	FB	BB	AB	OB	RB	FG	BG	OG	RG	FS	BS	OS	RS
Share residential area	0.49	0.49	0.49	0.64	0.38	0.51	0.51	0.61	0.33	0.30	0.30	0.52	0.21
Share other built-up areas	0.20	0.20	0.20	0.21	0.27	0.27	0.27	0.25	0.33	0.15	0.15	0.17	0.18
Share airport	0.13	0.13	0.13	0.14	0.19	0.11	0.11	0.10	0.14	0.13	0.13	0.15	0.15
Share green area	0.18	0.18	0.18	0.02	0.16	0.11	0.11	0.05	0.20	0.43	0.43	0.17	0.46
Ratio of changed open, green and agricultural area	0.85	0.85	0.85	0.97	1.07	1.01	1.01	1.10	1.00	0.56	0.56	0.72	0.53

Table A-V-3. Scenario comparison of percentage change rates (2008-2030) for relevant system parameters

		Baseline					Growth				Shrinkage			
		FB	BB	AB	OB	RB	FG	BG	OG	RG	FS	BS	OS	RS
Demography	Total population	2.2	2.2	2.2	2.2	2.2	6.8	6.8	6.8	6.8	-3.7	-3.7	-3.7	-3.7
	HH (?2persons)	8.8	8.8	8.8	37.5	8.8	12.7	12.7	49.1	12.7	3.9	3.9	35.5	3.9
	Child HH	-8.9	-8.9	-8.9	-49.4	-8.9	-3.3	-3.3	-54.6	-3.3	-16.1	-16.1	-60.7	-16.1
	Elderly HH (>45y)	17.0	17.0	17.0	98.3	17.0	19.5	19.5	117.9	19.5	13.8	13.8	99.8	13.8
Living space	Residential living space	3.3	3.3	3.3	8.9	2.8	7.6	7.6	13.2	6.2	0.0	0.0	8.0	0.3
	Capita living space	1.1	1.1	1.1	6.6	-0.3	0.7	0.7	6.0	-0.6	3.9	3.9	12.2	4.2
Land use	Built-up	3.9	3.9	3.9	5.4	2.5	6.9	6.9	8.8	4.8	0.0	0.0	2.2	-0.7
	Residential	4.1	4.1	4.1	6.3	2.3	5.9	5.9	8.6	3.0	1.7	1.7	4.8	0.8
	Central-located dense	1.0	1.0	1.0	1.8	1.6	2.0	2.0	2.7	2.8	0.6	0.6	1.7	0.7
	Intermediate	3.5	3.5	3.5	11.2	4.2	9.0	9.0	27.0	5.5	0.0	0.0	6.7	-0.4
	Decentralized low-density	4.7	4.7	4.7	6.0	1.9	5.7	5.7	5.5	2.3	2.3	2.3	4.9	1.1
	Non-built-up	-1.1	-1.1	-1.1	-1.4	-1.1	-1.8	-1.8	-2.2	-1.3	-0.2	-0.2	-0.7	-0.1
	Agricultural	-2.6	-2.6	-2.1	-2.8	-2.2	-3.7	-3.4	-4.1	-2.5	-1.9	-1.8	-1.9	-1.3
	Green and forest	0.6	0.6	0.1	0.3	0.3	0.5	0.2	0.2	0.1	1.5	1.3	0.7	1.1
Urban pattern	Sprawling index, SI	3.5	3.5	3.9	6.0	1.9	5.3	5.6	8.2	2.8	0.2	0.3	4.1	-0.3
	Compactness, ED·(-1)	-1.1	1.5	2.9	0.1	0.7	0.1	1.2	-0.2	2.6	-3.1	2.7	0.9	2.8
Ecosystem services	MEAN ESA	-0.4	-0.4	-0.2	-0.3	-0.3	-0.6	-0.6	-0.6	-0.5	-0.2	-0.2	-0.2	-0.2
	Energy provision	2.9	2.9	2.8	3.7	2.6	4.0	3.9	4.7	2.0	1.3	1.2	2.5	0.5
	Food provision	-3.3	-3.2	-2.3	-3.6	-2.8	-4.6	-4.2	-5.0	-2.7	-2.0	-2.1	-2.6	-1.5
	Emissivity index	-2.2	-2.2	-2.6	-2.6	-2.2	-3.5	-3.6	-4.0	-3.4	-1.1	-1.1	-1.7	-0.9
	PMV index	-1.3	-1.3	-1.0	-1.4	-1.1	-2.3	-2.2	-2.5	-1.8	-0.4	-0.5	-0.5	-0.3
	Net carbon storage·(-1)	-0.4	-0.4	-0.4	-0.7	-0.5	-0.9	-0.9	-1.2	-0.9	0.1	0.1	-0.3	0.0
	Recreation	3.9	3.9	3.9	3.9	3.8	2.9	2.9	2.8	2.7	4.8	4.8	4.9	4.8

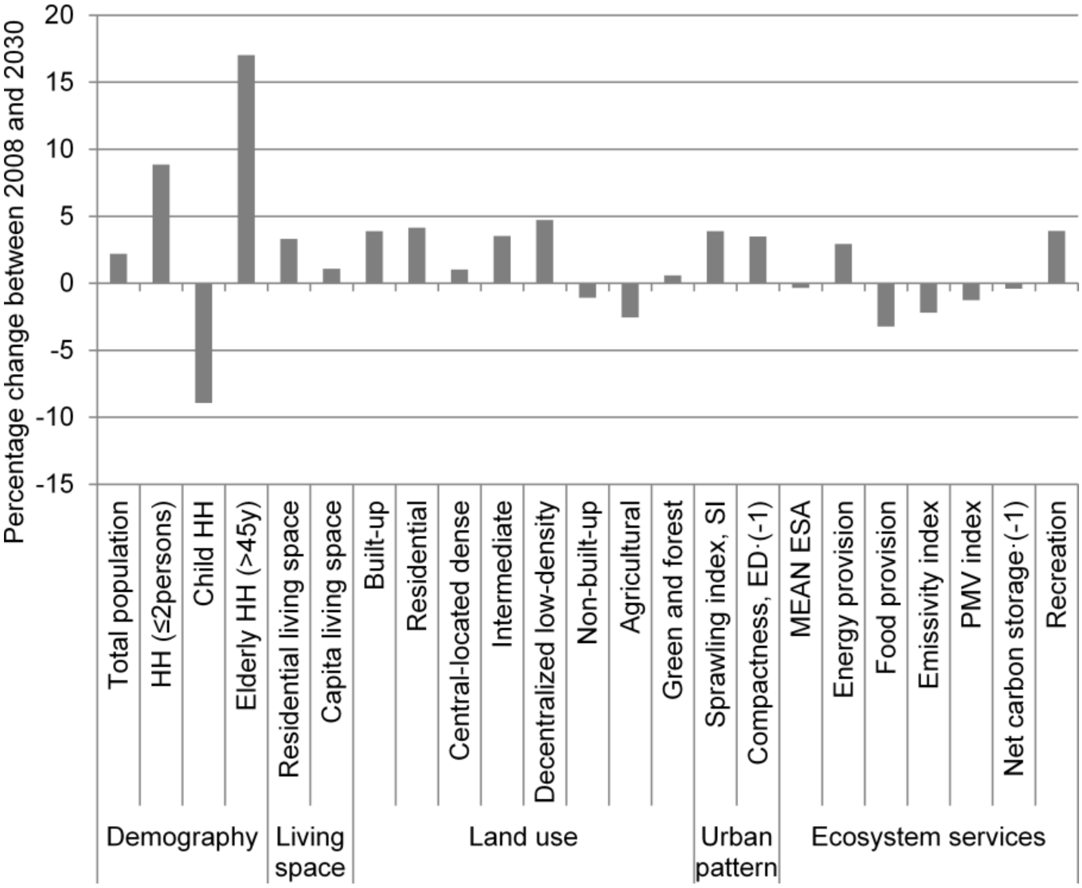


Figure A-V-5. Percentage changes of selected system parameters between 2008 and 2030 (BB)

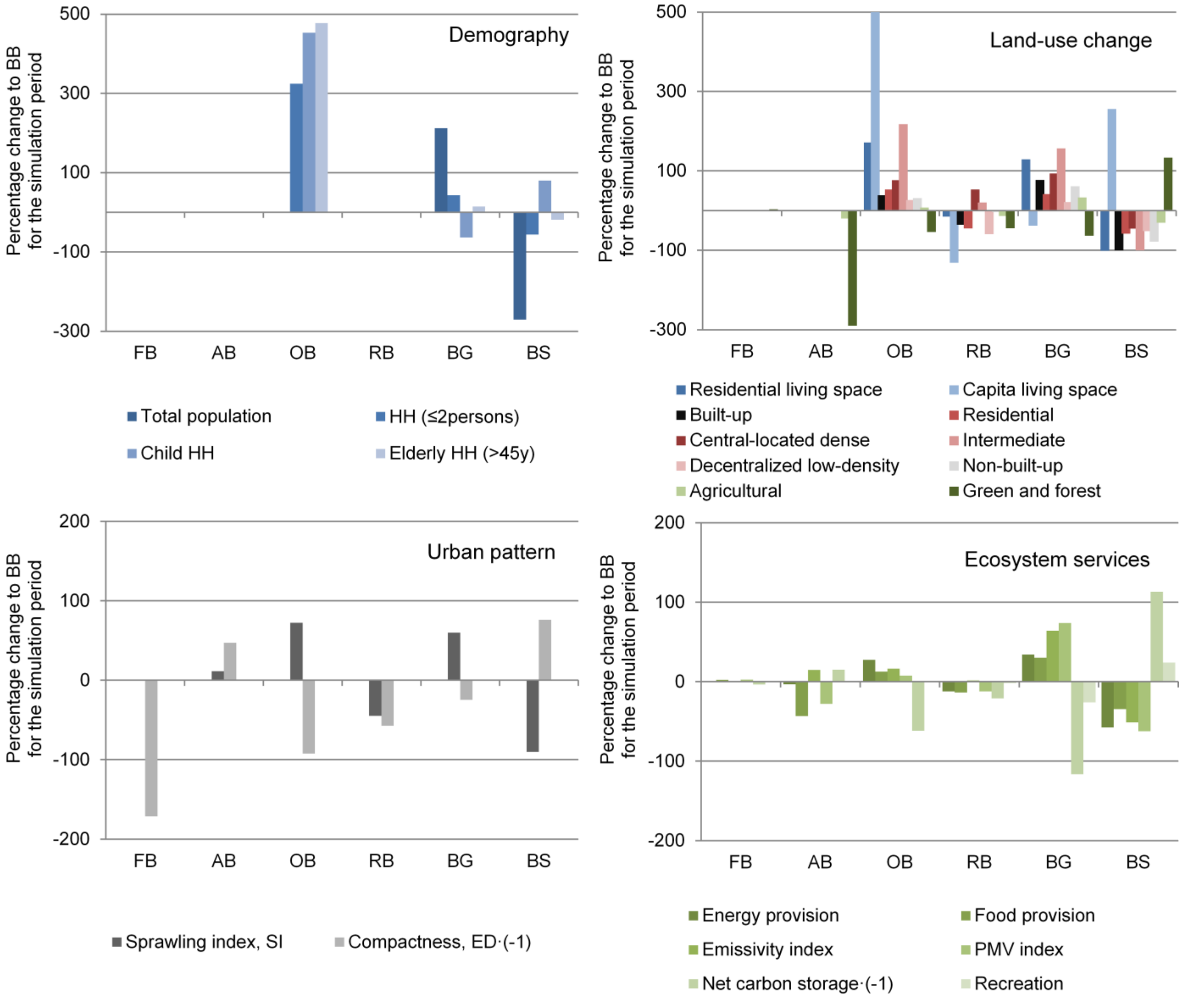


Figure A-V-6. Comparison of system parameter change between individual scenarios and BB between 2008 and 2030

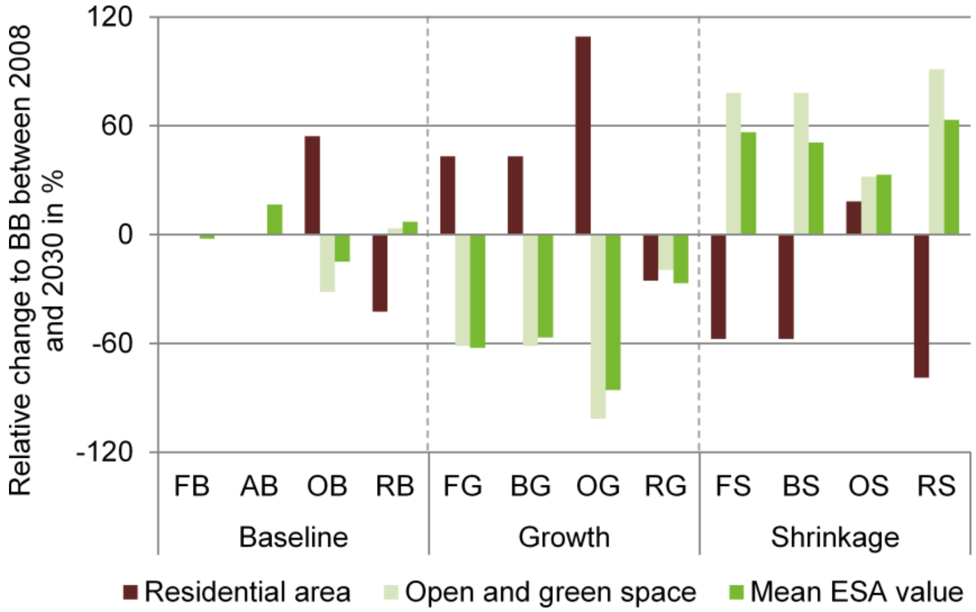


Figure A-V-7. Scenario deviation of summarized parameters to the Basic Baseline (BB) scenario

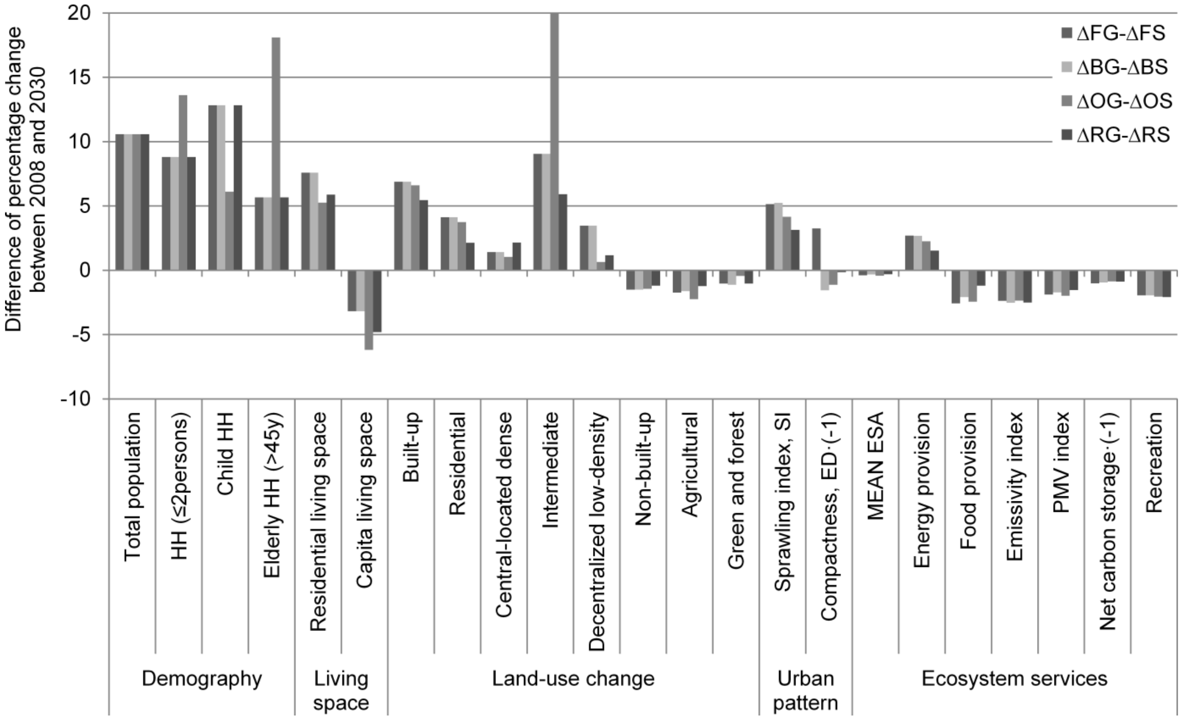


Figure A-V-8. Effectiveness of urban growth and shrinkage on different scenario combinations; the higher the bar, the higher the deviation of an urban parameter between growth and shrinkage, positive parameter values ~ growth>shrinkage, negative values ~ growth<shrinkage

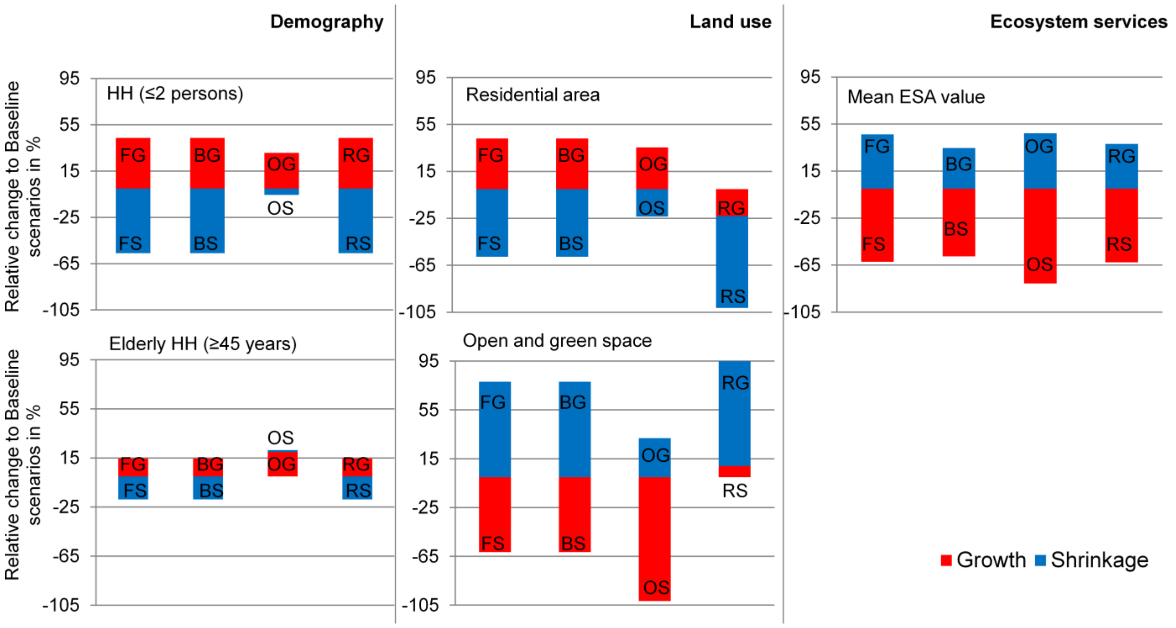


Figure A-V-9. The characteristics of selected parameters under growth and shrinkage conditions for varying scenarios; the longer the bar (red and blue) the higher the deviation and sensitivity of a respective parameter towards growth and shrinkage

Table A-V-4. Difference of percentage LUC (2008-2030) between growth and shrinkage

	$\Delta FG\text{-}\Delta FS$	$\Delta BG\text{-}\Delta BS$	$\Delta OG\text{-}\Delta OS$	$\Delta RG\text{-}\Delta RS$
Arable land	-2.7	-2.2	-2.5	-1.2
Pasture	0.0	-0.7	-1.8	-1.3
Shrubs and trees	-2.3	-2.2	-3.0	-2.4
Forest	-0.1	-0.2	-0.2	-0.4
Open spaces	-1.0	-3.4	-6.6	-3.9
Urban green space	-8.4	-8.4	-0.7	-5.8
Brownfields	-34.6	-34.6	-28.4	-20.0
Multi-story prefab	1.2	1.2	0.8	1.6
Inner-city blocks	1.7	1.7	1.2	3.2
Villas	6.7	6.7	32.9	6.9
Detached houses	3.4	3.4	0.7	0.9
Residential park	34.1	34.1	29.8	13.2
Multi-story rows	1.1	1.1	0.8	1.1
Suburban villages	3.9	3.9	0.1	2.8
Services	14.2	14.2	14.2	14.2
Commercial area	14.2	14.2	14.2	14.2
Industrial area	14.2	14.2	14.2	14.2

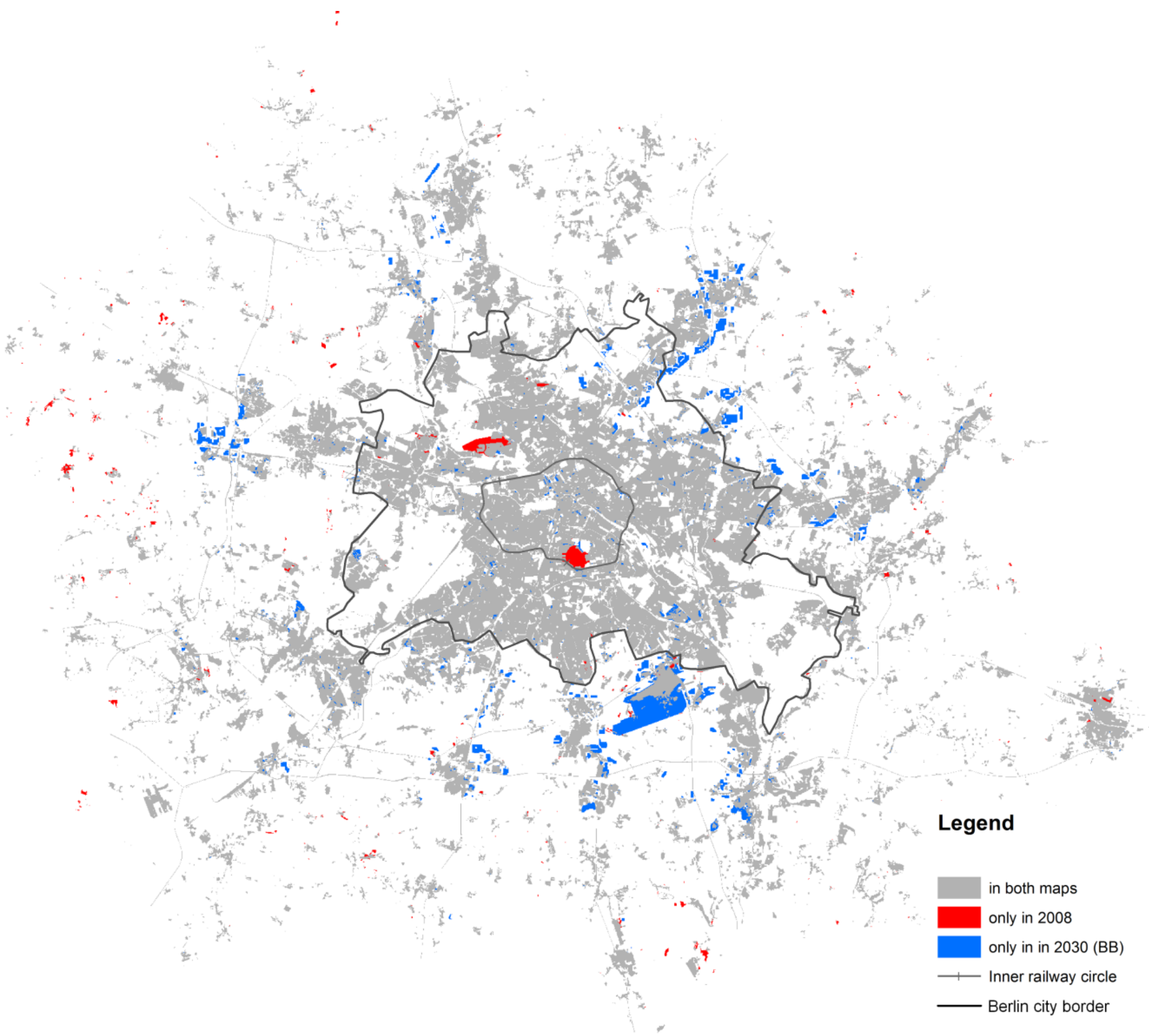


Figure A-V-10. Spatial comparison of the observed patterns of built-up area in 2008 and the simulated one in 2030 (BB scenario); blue patches represent spread built-up areas, red patches represent abandoned built-up areas

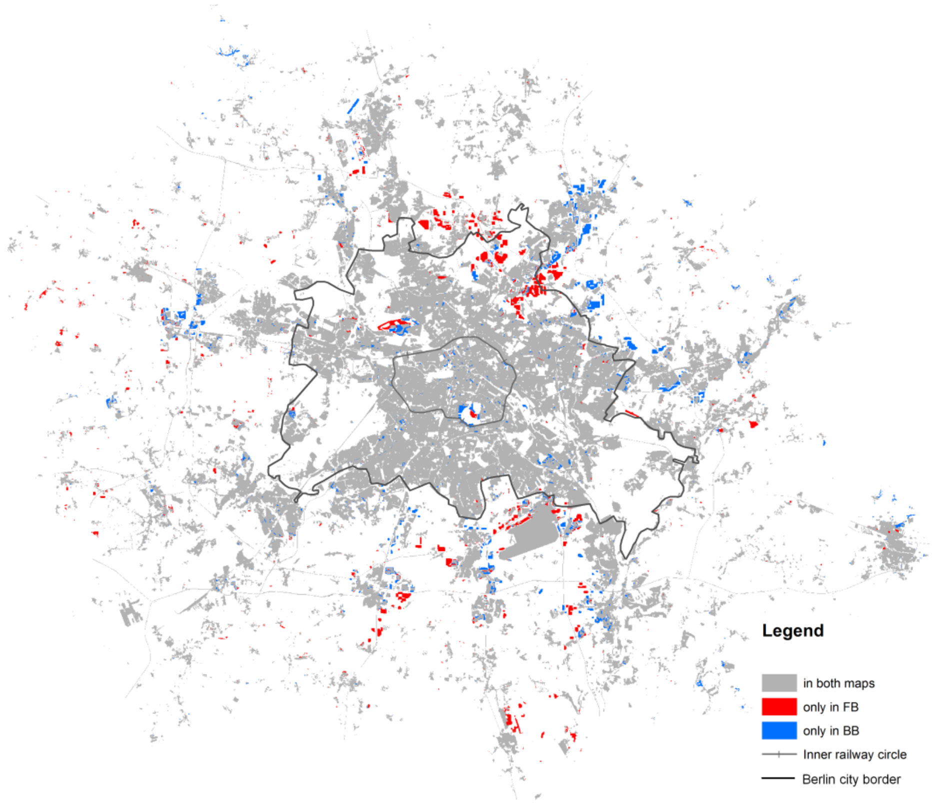


Figure A-V-11. Spatial comparison of the simulated patterns of built-up area in 2030, comparing the scenarios BB and FB

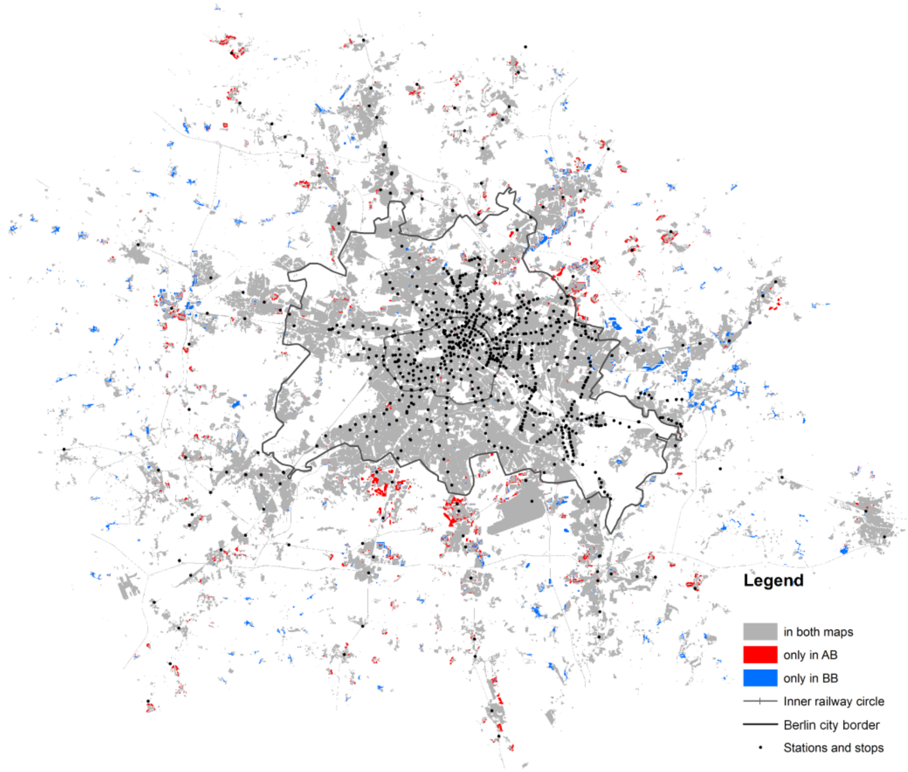


Figure A-V-12. Spatial comparison of the simulated patterns of built-up area in 2030, comparing the scenarios BB and AB

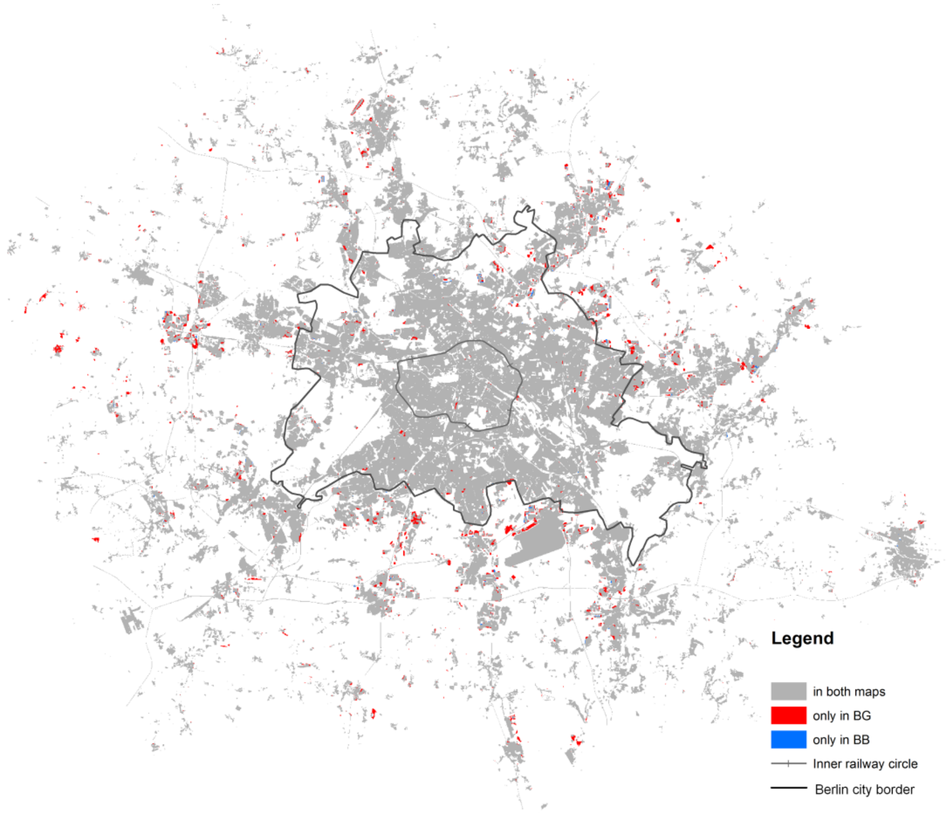


Figure A-V-13. Spatial comparison of the simulated patterns of built-up area in 2030, comparing the scenarios BB and BG

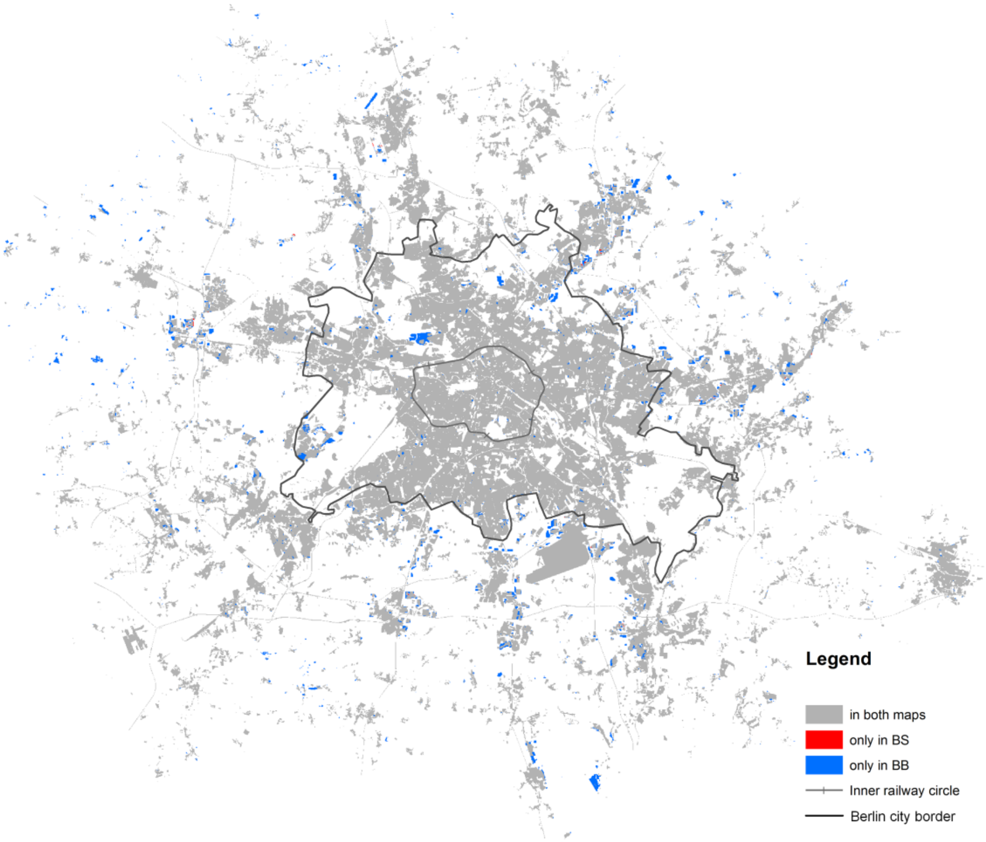


Figure A-V-14. Spatial comparison of the simulated patterns of built-up area in 2030, comparing the scenarios BB and BS

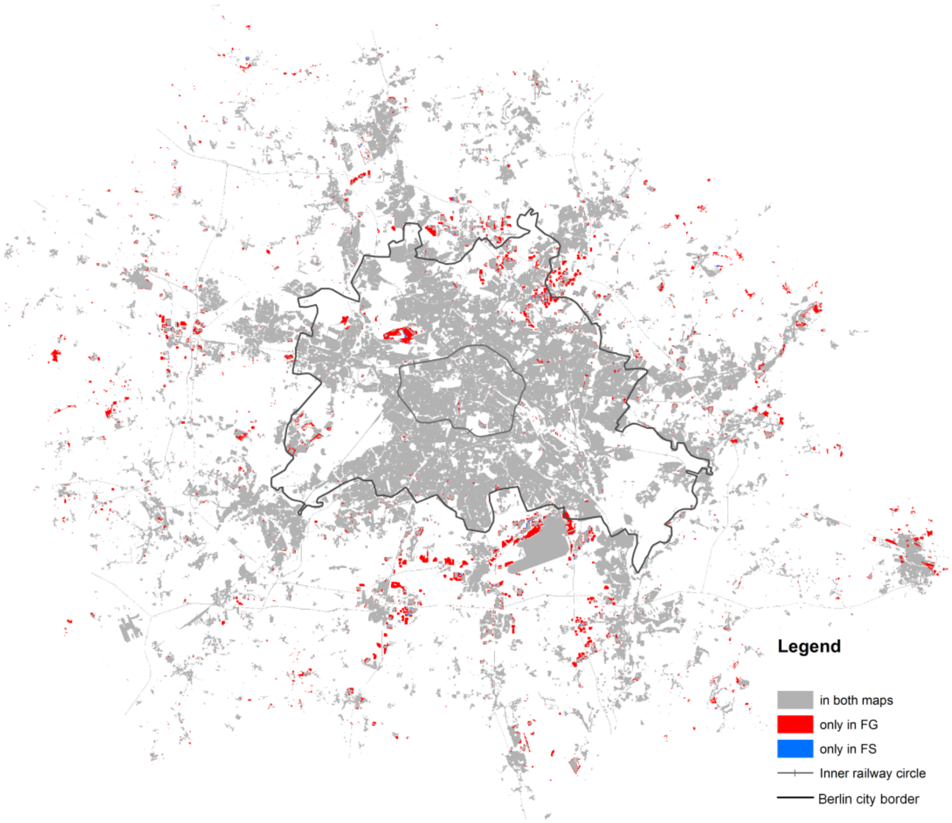


Figure A-V-15. Spatial comparison of the simulated patterns of built-up area in 2030, comparing growth and shrinkage, FG and FS

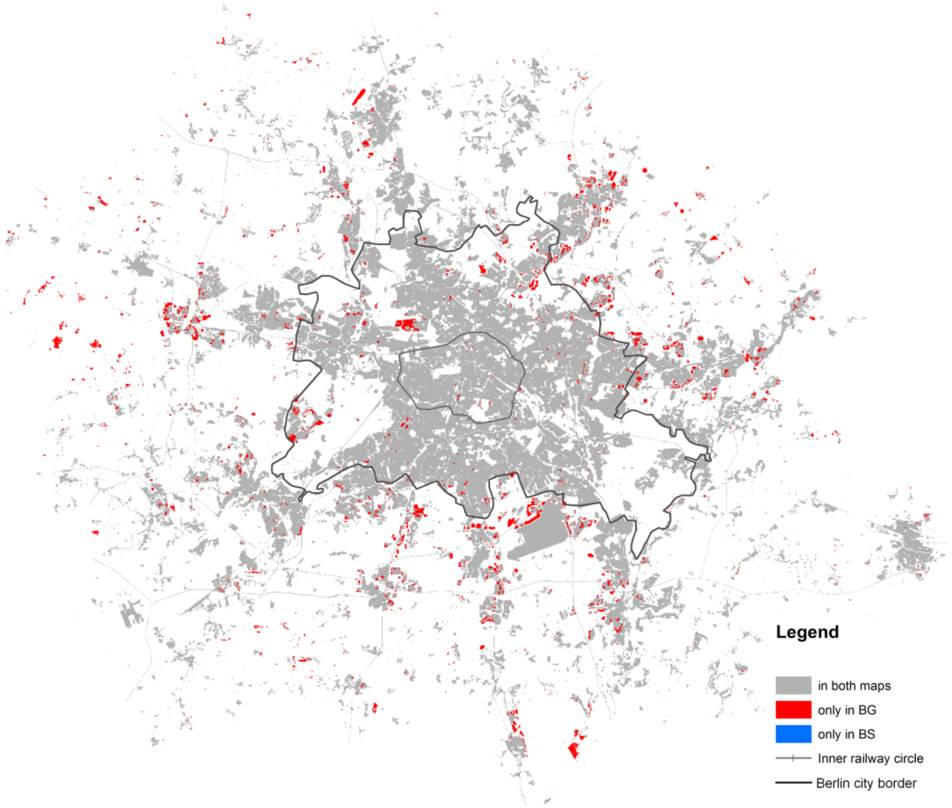


Figure A-V-16. Spatial comparison of the simulated patterns of built-up area in 2030, comparing growth and shrinkage, BG and BS

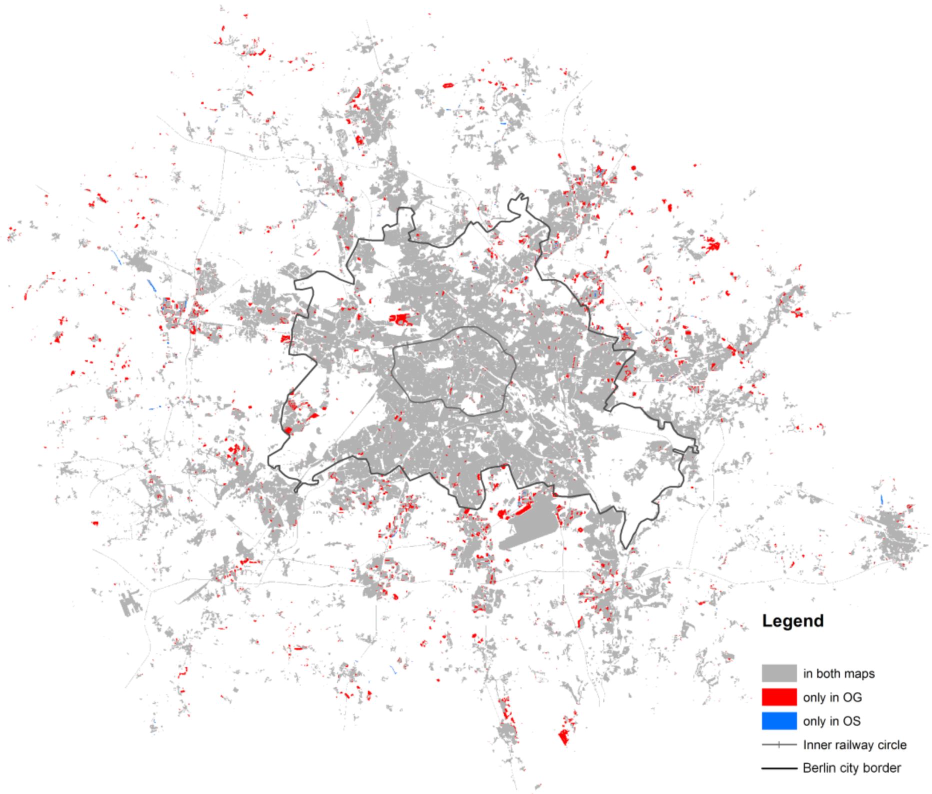


Figure A-V-17. Spatial comparison of the simulated patterns of built-up area in 2030, comparing growth and shrinkage, OG and OS

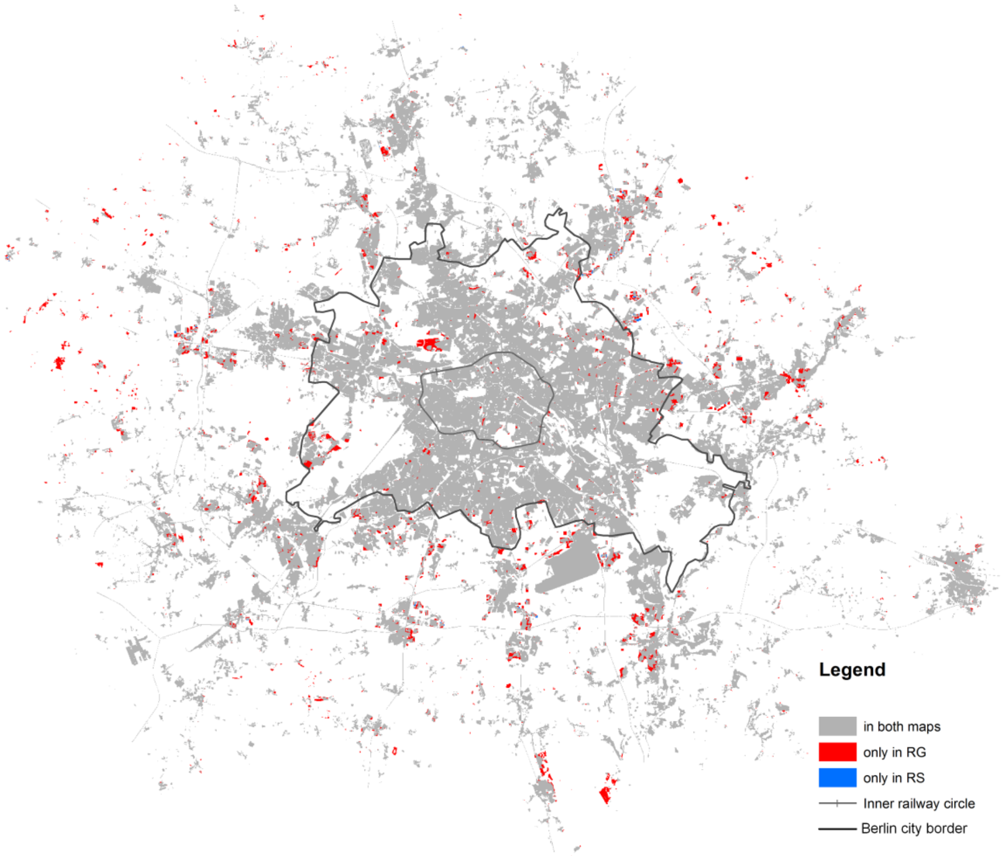


Figure A-V-18. Spatial comparison of the simulated patterns of built-up area in 2030, comparing growth and shrinkage, RG and RS

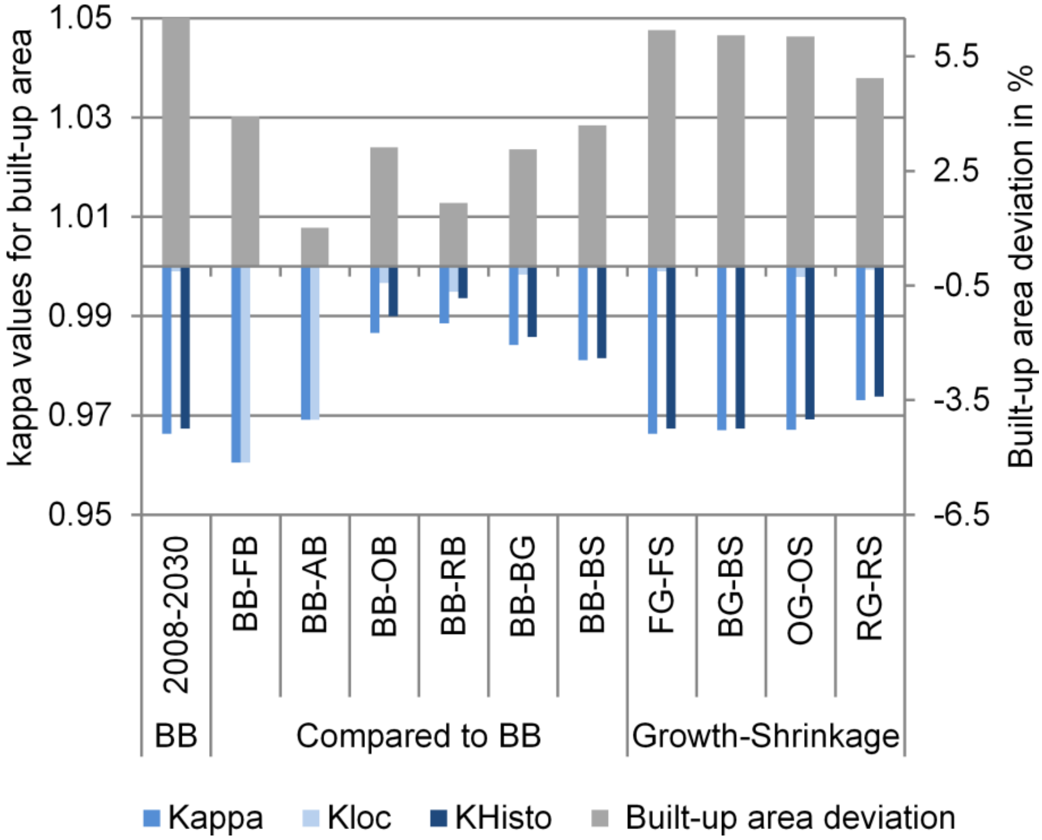


Figure A-V-19. Comparison of the spatial variations of built-up area after the simulation run for different scenarios using Cohen's kappa (high values indicate a high consistence) and the built-up area variation index (the quotient of non-agreeing built-up area to the agreeing built-up are, multiplied by one hundred, with high values indicating a high deviation)

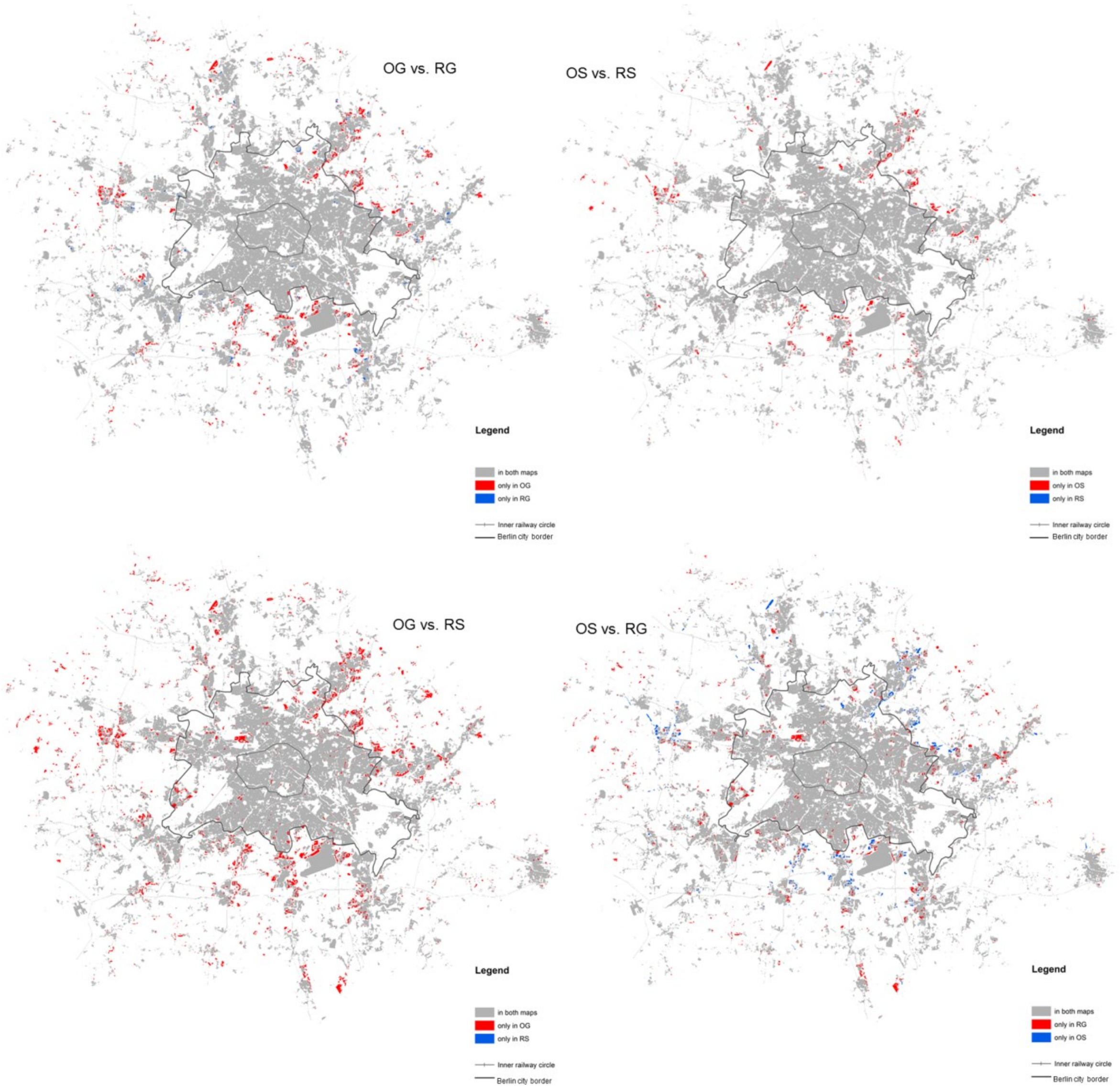
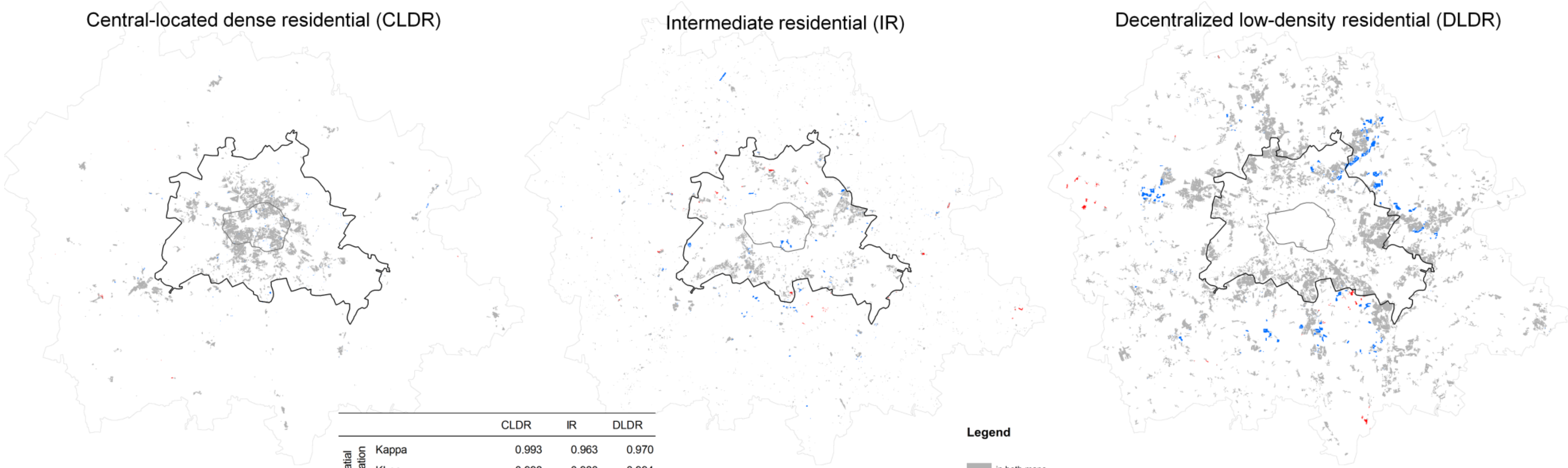


Figure A-V-20. Spatial comparison of the simulated patterns of built-up area in 2030, comparing overaging and reurbanization scenarios



		CLDR	IR	DLDR
Spatial variation	Kappa	0.993	0.963	0.970
	KLoc	0.998	0.980	0.994
	KHisto	0.995	0.982	0.976
Land-use transition [ha]	Agricultural	33	233	2485
	Urban green and forest	47	88	0
	Urban brownfields	61	108	0
	Other built-up	37	118	0

Figure A-V-21. Spatial comparison of the observed patterns of different residential categories in 2008 and the simulated one in 2030 (BB scenario); blue patches represent spread residential areas, red patches represent abandoned residential areas

Table A-V-5. Coefficients of determination between relevant urban parameters (signs shows the characteristic of the correlation; results are greyed out if R^2<0.24 or significance>0.05)

Stat. significance: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' (Student's t-test)

		Total population	HH (≤2persons)	Child HH	Elderly HH (>45y)	Residential living space	Capita living space	Built-up	Residential	Central-located dense	Inter-mediate	Decentralized low-density	Non-built-up	Agri-cultural	Green and forest	Sprawling index, SI	SI_ inner city	SI_ outer city	SI_ periphery	Compactness, ED·(-1)	(-)ED_ inner city	(-)ED_ outer city	(-)ED_ periphery	Fragmentation, PD	PD_inner city	PD_outer city	PD_periphery	MEAN ESA	Energy provision	Food provision	Emissivity index	PMV index	Net carbon storage
Demography	HH (≤2persons)	(+) 0.07 **																															
Demography	Child HH	(+) 0.05 **	(-) 0.77 ***																														
Demography	Elderly HH (>45y)	(+) 0.01 **	(+) 0.96 .	(-) 0.90 ***																													
Land use	Residential living space	(+) 0.43 .	(+) 0.78 *	(-) 0.31 ***	(+) 0.61 *																												
Land use	Capita living space	(-) 0.26	(+) 0.42 **	(-) 0.83 **	(+) 0.59 **	(+) 0.09																											
Land use	Built-up	(+) 0.83	(+) 0.34 *	(-) 0.02 **	(+) 0.18 **	(+) 0.76	(-) 0.03																										
Land use	Residential	(+) 0.43	(+) 0.64 *	(-) 0.23 **	(+) 0.49 *	(+) 0.86	(+) 0.05	(+) 0.83																									
Land use	Central-located	(+) 0.61	(+) 0.41 **	(-) 0.06 **	(+) 0.26 **	(+) 0.74 **	(-) 0.00	(+) 0.63 *	(+) 0.44 **																								
Land use	Intermediate	(+) 0.38 .	(+) 0.74 .	(-) 0.31 ***	(+) 0.58 *	(+) 0.84	(+) 0.06	(+) 0.69	(+) 0.80	(+) 0.57 *																							
Land use	Decentralized low-density	(+) 0.28	(+) 0.34 *	(-) 0.11 **	(+) 0.26 **	(+) 0.54	(+) 0.04	(+) 0.61	(+) 0.81	(+) 0.16 ***	(+) 0.38																						
Land use	Non-built-up	(-) 0.85 *	(-) 0.33 **	(+) 0.02 **	(-) 0.18 **	(-) 0.75 ***	(+) 0.03 **	(-) 0.99 ***	(-) 0.79 ***	(-) 0.65 ***	(-) 0.69 **	(-) 0.56 ***																					
Land use	Agricultural	(-) 0.74 **	(-) 0.27 ***	(+) 0.01 *	(-) 0.13 **	(-) 0.64 ***	(+) 0.03 ***	(-) 0.91 ***	(-) 0.76 ***	(-) 0.50 ***	(-) 0.69 ***	(-) 0.52 ***	(+) 0.90 ***																				
Land use	Green and forest	(-) 0.68	(-) 0.18 **	(-) 0.00 **	(-) 0.08 **	(-) 0.47 **	(+) 0.07 *	(-) 0.64 **	(-) 0.40 ***	(-) 0.58 **	(-) 0.31 *	(-) 0.29 ***	(+) 0.68 ***	(+) 0.36 ***																			
Urban pattern	Sprawling index, SI	(+) 0.51	(+) 0.70 *	(-) 0.22 **	(+) 0.52 **	(+) 0.95	(+) 0.02	(+) 0.88	(+) 0.98	(+) 0.61	(+) 0.86	(+) 0.81	(-) 0.89 *	(-) 0.85 **	(-) 0.59 .																		
Urban pattern	SI_inner city	(+) 0.80 ***	(+) 0.17	(+) 0.00 ***	(+) 0.06	(+) 0.56 ***	(-) 0.12 ***	(+) 0.79 ***	(+) 0.50 ***	(+) 0.76 ***	(+) 0.36 ***	(+) 0.44 ***	(-) 0.79 ***	(-) 0.68 ***	(-) 0.80 ***	(+) 0.59 ***																	
Urban pattern	SI_outer city	(+) 0.84	(+) 0.35 **	(-) 0.01 **	(+) 0.18 **	(+) 0.78 **	(-) 0.05 *	(+) 0.91 **	(+) 0.65 **	(+) 0.90	(+) 0.56 **	(+) 0.49 **	(-) 0.91	(-) 0.76 *	(-) 0.96	(+) 0.77 .	(+) 0.85 ***																
Urban pattern	SI_periphery	(+) 0.43	(+) 0.73 *	(-) 0.27 ***	(+) 0.57 *	(+) 0.93	(+) 0.04	(+) 0.83	(+) 1.00	(+) 0.53 .	(+) 0.88	(+) 0.83	(-) 0.83 *	(-) 0.82 **	(-) 0.50 .	(+) 0.99	(+) 0.52 **	(+) 0.69 *															
Urban pattern	Compactness, ED·(-1)	(-) 0.18	(-) 0.84 **	(+) 0.50 **	(-) 0.75 **	(-) 0.83 *	(-) 0.20	(-) 0.58 *	(-) 0.93 **	(-) 0.31	(-) 0.80 *	(-) 0.82 **	(+) 0.58 **	(+) 0.59 ***	(+) 0.27 .	(-) 0.87	(-) 0.26 ***	(-) 0.44	(-) 0.92														
Urban pattern	(-)ED_ inner city	(+) 0.99 .	(+) 0.12 *	(+) 0.03 **	(+) 0.02 *	(+) 0.51	(-) 0.28	(+) 0.84	(+) 0.43	(+) 0.79 ***	(+) 0.42	(+) 0.26	(-) 0.84 ***	(-) 0.74 ***	(-) 0.88 ***	(+) 0.54	(+) 0.81 ***	(+) 0.89 **	(+) 0.46	(-) 0.21 **													
Urban pattern	(-)ED_ outer city	(+) 0.91	(+) 0.03 **	(+) 0.12 **	(-) 0.00 **	(+) 0.29 *	(-) 0.45	(+) 0.60 .	(+) 0.19 *	(+) 0.73	(+) 0.24 .	(+) 0.06 *	(-) 0.60 **	(-) 0.50 ***	(-) 0.75 *	(+) 0.28	(+) 0.72 ***	(+) 0.70 .	(+) 0.22	(-) 0.04	(+) 0.90 **												
Urban pattern	(-)ED_ periphery	(-) 0.42	(-) 0.76 **	(+) 0.29 **	(-) 0.60 **	(-) 0.95 *	(-) 0.05	(-) 0.82 *	(-) 0.99 *	(-) 0.54	(-) 0.89 *	(-) 0.80 *	(+) 0.82 *	(+) 0.80 **	(+) 0.50	(-) 0.99	(-) 0.48 ***	(-) 0.69	(-) 1.00 .	(+) 0.93	(-) 0.45 *	(-) 0.21											
Urban pattern	Fragmentation, PD	(-) 0.08 ***	(-) 0.29 ***	(+) 0.16 *	(-) 0.25 **	(-) 0.18 ***	(-) 0.00 ***	(-) 0.21 ***	(-) 0.29 ***	(-) 0.05 ***	(-) 0.56 ***	(-) 0.07 ***	(+) 0.21 ***	(+) 0.35 **	(+) 0.00 ***	(-) 0.23 **	(-) 0.02 ***	(-) 0.05 **	(-) 0.28 **	(+) 0.27 ***	(-) 0.06 ***	(-) 0.04 ***	(+) 0.27 ***										
Urban pattern	PD_inner city	(+) 0.50 ***	(-) 0.00 ***	(+) 0.15	(-) 0.02 ***	(+) 0.09 ***	(-) 0.39 ***	(+) 0.27 ***	(+) 0.05 ***	(+) 0.24 ***	(+) 0.13 ***	(+) 0.00 ***	(-) 0.27 ***	(-) 0.23 ***	(-) 0.35 ***	(+) 0.09 ***	(+) 0.12 ***	(+) 0.29 ***	(+) 0.06 ***	(-) 0.01 ***	(+) 0.51 ***	(+) 0.48 ***	(-) 0.08 ***	(-) 0.04 ***									
Urban pattern	PD_outer city	(-) 0.99	(-) 0.09 **	(-) 0.05 **	(-) 0.01 **	(-) 0.44 .	(+) 0.34	(-) 0.80	(-) 0.38	(-) 0.75	(-) 0.40 .	(-) 0.19	(+) 0.80	(+) 0.73	(+) 0.80	(-) 0.48	(-) 0.80 ***	(-) 0.82	(-) 0.40 .	(+) 0.15	(-) 0.98	(-) 0.94	(+) 0.39	(+) 0.10 .	(-) 0.48 ***								
Urban pattern	PD_periphery	(+) 0.01 ***	(-) 0.19 ***	(+) 0.24 *	(-) 0.22 **	(-) 0.04 ***	(-) 0.08 ***	(-) 0.02 ***	(-) 0.11 ***	(+) 0.01 ***	(-) 0.29 ***	(-) 0.01 ***	(+) 0.02 ***	(+) 0.09 **	(-) 0.08 ***	(-) 0.06 ***	(+) 0.04 ***	(+) 0.01 **	(-) 0.09 **	(+) 0.15 ***	(+) 0.01 ***	(+) 0.03 ***	(+) 0.09 ***	(+) 0.87	(+) 0.00 ***	(-) 0.00 *							
Ecosystem service	MEAN ESA	(-) 0.88 .	(-) 0.09 **	(-) 0.03 **	(-) 0.02 **	(-) 0.46 ***	(+) 0.16 **	(-) 0.78 ***	(-) 0.45 ***	(-) 0.60 ***	(-) 0.46 **	(-) 0.24 ***	(+) 0.78 **	(+) 0.84 ***	(+) 0.39 ***	(-) 0.56 *	(-) 0.76 ***	(-) 0.79	(-) 0.50 *	(+) 0.23 **	(-) 0.95 ***	(-) 0.84 **	(+) 0.48 .	(+) 0.18 ***	(-) 0.47 ***	(+) 0.97	(+) 0.01 ***						
Ecosystem service	Energy provision	(+) 0.61	(+) 0.40 **	(-) 0.06 **	(+) 0.26 **	(+) 0.72 .	(+) 0.00	(+) 0.90	(+) 0.90 .	(+) 0.42 **	(+) 0.67 .	(+) 0.78 *	(-) 0.90 ***	(-) 0.84 ***	(-) 0.52 ***	(+) 0.97	(+) 0.63 ***	(+) 0.73 *	(+) 0.96	(-) 0.81	(+) 0.56 *	(+) 0.29	(-) 0.94	(-) 0.24 ***	(+) 0.09 ***	(-) 0.51	(-) 0.06 ***	(-) 0.55 ***					
Ecosystem service	Food provision	(-) 0.64 **	(-) 0.32 ***	(+) 0.03 *	(-) 0.19 **	(-) 0.67 ***	(+) 0.01 ***	(-) 0.87 ***	(-) 0.80 ***	(-) 0.45 ***	(-) 0.68 ***	(-) 0.61 ***	(+) 0.86 ***	(+) 0.96	(+) 0.33 ***	(-) 0.91 **	(-) 0.62 ***	(-) 0.71 *	(-) 0.91 **	(+) 0.72 ***	(-) 0.62 ***	(-) 0.36 ***	(+) 0.88 **	(+) 0.33 *	(-) 0.16 ***	(+) 0.59	(+) 0.10 *	(+) 0.76 ***	(-) 0.88 ***				
Ecosystem service	Emissivity index	(-) 0.94 **	(-) 0.21 ***	(-) 0.00 **	(-) 0.08 **	(-) 0.65 ***	(+) 0.09 ***	(-) 0.93 ***	(-) 0.61 ***	(-) 0.74 ***	(-) 0.57 ***	(-) 0.38 ***	(+) 0.93 ***	(+) 0.81	(+) 0.72 ***	(-) 0.72 **	(-) 0.86 ***	(-) 0.94 *	(-) 0.64 *	(+) 0.36 ***	(-) 0.96 ***	(-) 0.80 ***	(+) 0.63 **	(+) 0.12 **	(-) 0.37 ***	(+) 0.94	(-) 0.00 **	(+) 0.84 ***	(-) 0.72 ***	(+) 0.71			
Ecosystem service	PMV index	(-) 0.92 *	(-) 0.18 **	(-) 0.00 **	(-) 0.06 **	(-) 0.60 ***	(+) 0.11 ***	(-) 0.92 ***	(-) 0.62 ***	(-) 0.64 ***	(-) 0.58 **	(-) 0.39 ***	(+) 0.92	(+) 0.93 ***	(+) 0.52 ***	(-) 0.72 *	(-) 0.80 ***	(-) 0.87	(-) 0.66 *	(+) 0.38 **	(-) 0.93 ***	(-) 0.75 ***	(+) 0.64 *	(+) 0.20 ***	(-) 0.38 ***	(+) 0.92	(+) 0.01 ***	(+) 0.96 ***	(-) 0.74 ***	(+) 0.85 ***	(+) 0.94 **		
Ecosystem service	Net carbon storage	(+) 0.87	(+) 0.34 **	(-) 0.02 **	(+) 0.18 **	(+) 0.77 **	(-) 0.03 *	(+) 0.93 **	(+) 0.68 ***	(+) 0.83 ***	(+) 0.68 *	(+) 0.39 ***	(-) 0.95 ***	(-) 0.82 ***	(-) 0.70	(+) 0.80 .	(+) 0.81 ***	(+) 0.96	(+) 0.73 .	(-) 0.46 .	(+) 0.91 ***	(+) 0.73 *	(-) 0.73	(-) 0.15 ***	(+) 0.35 ***	(-) 0.87	(-) 0.00 ***	(-) 0.83 ***	(+) 0.75 ***	(-) 0.78 ***	(-) 0.95 ***	(-) 0.92 ***	
Ecosystem service	Recreation	(-) 0.98	(-) 0.07 *	(-) 0.05 **	(-) 0.01 **	(-) 0.43	(+) 0.25	(-) 0.79	(-) 0.38	(-) 0.67 ***	(-) 0.38	(-) 0.20	(+) 0.80 ***	(+) 0.71 ***	(+) 0.63 ***	(-) 0.46	(-) 0.77 ***	(-) 0.82 **	(-) 0.38	(+) 0.14 **	(-) 0.99	(-) 0.94 *	(+) 0.37 *	(+) 0.08 ***	(-) 0.53 ***	(+) 1.00	(-) 0.01 ***	(+) 0.90 ***	(-) 0.52 *	(+) 0.59 ***	(+) 0.93 ***	(+) 0.91 ***	(-) 0.86 ***
		Demography	*Demography*	*Demography*	*Demography*	*Land use*	*Land use*	*Land use*	*Land use*	*Land use*	*Land use*	*Land use*	*Land use*	*Land use*	*Land use*	*Urban pattern*	*Urban pattern*	*Urban pattern*	*Urban pattern*	*Urban pattern*	*Urban pattern*	*Urban pattern*	*Urban pattern*	*Urban pattern*	*Urban pattern*	*Urban pattern*	*Urban pattern*	*Ecosystem service*	*Ecosystem service*	*Ecosystem service*	*Ecosystem service*	*Ecosystem service*	*Ecosystem service*

Publications related to the doctoral thesis

Peer reviewed articles:

1 Lauf, S., Haase, D., Kleinschmit, B. (to be submitted): Contrasting interactions between urban development and demographic and residential preference shifts in the Berlin metropolitan region – a spatial scenario analysis. *Applied Geography.*
2 Lauf, S., Haase, D., Kleinschmit, B. (2014): Linkages between ecosystem services provisioning, urban growth and shrinkage – a modeling approach assessing ecosystem service trade-offs. *Ecological Indicators 42, 73-94.* doi: 10.1016/j.ecolind.2014.01.028
3 Lauf, S., Haase, D., Lakes, T., Hostert, P. and Kleinschmit, B. (2012): Uncovering land use dynamics driven by human decision-making - a combined model approach using cellular automata and system dynamics. *Environmental Modelling and Software 27-28,* 71-82. doi: 10.1016/j.envsoft.2011.09.005
4 Lauf, S., Haase, D., Seppelt, R., Schwarz, N. (2012): Simulating demography and housing demand in an urban region under scenarios of growth and shrinkage. *Environment and Planning B*, 39, 229-246. doi: 10.1068/b36046t
5 Lauf, S. (2011): Modelling of LUC and Ecologic Impacts (chapter 8.4), In: Lakes, T., Hostert, P., Kleinschmit, B., Lauf, S., Tigges, J. (2011): Remote Sensing and Spatial Modelling of the Urban Environment. In: W. Endlicher (Eds.): Perspectives in Urban Ecology - Ecosystems and Interactions between Humans and Nature in the Metropolis of Berlin. 1st Edition, Springer. p. 231-259. ISBN 978-3-642-17730-9
6 Lauf, S., Haase, D., Kleinschmit, B. (2012): Land-use scenario modelling based on human decisions – Combining system dynamics and cellular automata, In: R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.): International Environmental Modelling and Software Society (iEMSs), 6th International Congress on Environmental Modelling and Software, Leipzig, Germany, ISBN: 978-88-9035-742-8, http://www.iemss.org/society/index.php/iemss-2012-proceedings.
7 Heinsch, L., Lauf, S., Kleinschmit, B., 2012, Modeling urban growth and land use change with a cellular automaton in the Berlin metropolitan region *GIS-Zeitschrift für Geoinformatik 25(2)*, 56-68. ISSN: 1869-9391
8 Dugord, P.-A., Lauf, S., KLeinschmit, B., Schuster, C. (2014): How the urban structure affects the urban climate and the potential heat stress risk in Berlin. *Computers, Environment and Urban Systems 48, 86-98.* doi: 10.1016/j.compenvurbsys.2014.07.005

Conference presentations (oral, poster):

1 Lauf, S., Haase, D. and Kleinschmit, B. (2013): Modelling ecosystem service interactions for urban growth and shrinkage scenarios – the Berlin case. In: Qureshi, S. and Dagmar Haase, D. and Kabisch, N. (Eds.): International Congress of the Society for Urban Ecology (SURE) 2013, First congress, Berlin, Germany.
2 Lauf, S., Haase, D. and Kleinschmit, B. (2012): Land-use scenario modelling based on human decisions – Combining system dynamics and cellular automata. In: Seppelt, R. and Voinov, A. A. and Lange, S. and Bankamp, D. (Eds.): International Environmental Modelling and Software Society (iEMSs) 2012, Sixth Biennial Meeting, Leipzig, Germany. ISBN: 978-88-9035-742-8
3 Lauf, S., Haase, D., Hostert, P., Lakes, T. and Kleinschmit, B. (2011): Households, land uses and the environment in change. IALE-D Jahrestagung 2011, Berlin, Germany.

4 Lauf, S. and Schoenduwe, R. (2011): Improving life quality with land use modelling – A combined model approach. 51st European Congress of the Regional Science Association International (ERSA), Barcelona, Spain.
5 Lauf, S., Kleinschmit, B., Haase, D., Lakes, T. and Hostert, P. (2010): An integrated land use change and ecological impact model: the case of Berlin. 5th International Urban Ecology Congress, Cracks in the Concrete Jungle: New Perspectives on Urban Ecology, Berlin, Germany.
6 Lauf, S., Kleinschmit, B. and Hostert, P. (2009): An integrated model approach of land-use change involving an impact analysis on ecosystem services – the case of Berlin. Workshop „Urban Ecology in Mexico City and Berlin", Universidad national de México UNAM and Research Program Urban Ecology (GRK 780/III), Mexico City.
7 Lauf, S., Kleinschmit, B. and Hoster, P. (2008): Modellierung des urbanen Landnutzungswandels und Analyse seines Einflusses auf ausgewählte Landschaftsfunktionen. 4. Kongress des Graduiertenkollegs 780 der Deutschen Forschungsgemeinschaft, Stadtökologische Perspektiven in Wissenschaft und Praxis, Berlin.

Eidesstaatliche Versicherung

I prepared this dissertation without illegal assistance. This work is original except where indicated by special reference in the text and no part of the dissertation has been submitted for any other degree. This dissertation has not been presented to any other University for examination, neither in Germany nor in another country.

Berlin, April 2014 (Steffen Lauf)