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Opinion

Will a Transition to Timber Construction Cool the Climate?

Galina Churkina [1,*] and Alan Organschi [2,3,4]

[1] Institute of Ecology, Berlin University of Technology, 10587 Berlin, Germany
[2] Innovation Labs, Bauhaus Earth, 12161 Potsdam, Germany; alan@grayorganschi.com
[3] Yale School of Architecture, Yale University, New Haven, CT 06520, USA
[4] Gray Organschi Architecture, New Haven, CT 06510, USA
* Correspondence: galina@churkina.org

Abstract: Timber construction is on the rise and its contribution to climate change mitigation has been widely discussed by scientists and practitioners alike. As midrise building with wood in cities spreads, it will lead to fundamental and systemic change in forests, the manufacturing of construction materials, and the character and performance of the built environment. In this paper, we discuss the multifaceted implications of the transition to building with timber in cities for climate, which include greenhouse gas emissions but also go beyond those potential benefits. We demonstrate that while a transition to timber cities can have a balancing effect on the global carbon cycle, the other accompanying effects may enhance, reduce, or diminish that effect on climate. A collaboration of practitioners with scientists will be required to steer this transition in a climate-friendly direction.

Keywords: timber construction; climate change; forest management; heat island effect; waste heat emissions

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1. Background

From 1850 to 2018, the cumulative carbon emissions from burning fossil fuels and land use change released almost 645 GtC, increasing the amount of carbon in the atmosphere by 255 GtC, which is a 47% increase from its preindustrial value [1]. Land-based vegetation and the oceans persisted as strong carbon sinks, sequestering roughly half of the anthropogenically emitted carbon dioxide (CO_2) over the last century [1]. Global forests have been a net carbon sink because high atmospheric CO_2 concentrations, NOx deposition, as well as forest regrowth has stimulated their CO_2 uptake [2].

The global building sector is a prominent contributor to rising anthropogenic CO_2 emissions. Its escalating energy demand has been met mostly by the combustion of fossil fuels with high-associated CO_2 emissions. In 2019, building-related energy production was responsible for 38% of greenhouse gas (GHG) emissions [3]. The anticipated construction boom generated by the demands of urban population growth, as well as the trend of increasing floor area per capita, is likely to increase these emissions even more in the years to come.

The substitution of timber for steel and concrete in the construction sector at a significant scale offers a substantial potential to reduce the emissions from the construction industry and enhance carbon storage in cities, both of which are important prerequisites for mitigating climate change [4,5]. This potential can only be realized, however, if the entire life cycle of a biomass-based building is understood systemically, with working source forests and their growth cycles managed sustainably and the wooden components from dismantled timber buildings reused as well as recycled into durable second and third product lifecycles. The former condition is critical to securing the net carbon sink capacity of the forests for the future; the latter a fundamental necessity to reduce harvesting pressures on forests and extend the duration that carbon is stored in the built environment.

This transition to timber and other biomass-based construction assemblies will alter the systemic value chain of building production, from raw material extraction to manufacturing facilities and processes, and on to building construction and operation (Figure 1). It will shift raw material extraction from mining to timber harvest, which will have a notable effect on forest valuation and management, and, by extension, forest interactions with climate. Demand for cement and steel manufacturing will be reduced and accompanied by a decrease in the number of production facilities. The number of timber processing facilities will correspondingly increase. Timber cities may look different from their steel and concrete counterparts but, most importantly, they will definitely perform differently due in large part to the thermal properties of wood. In this paper, the multifaceted implications of a transition to timber cities and their corresponding forest effects for climate are discussed, including greenhouse gas emissions as well as heat exchange.

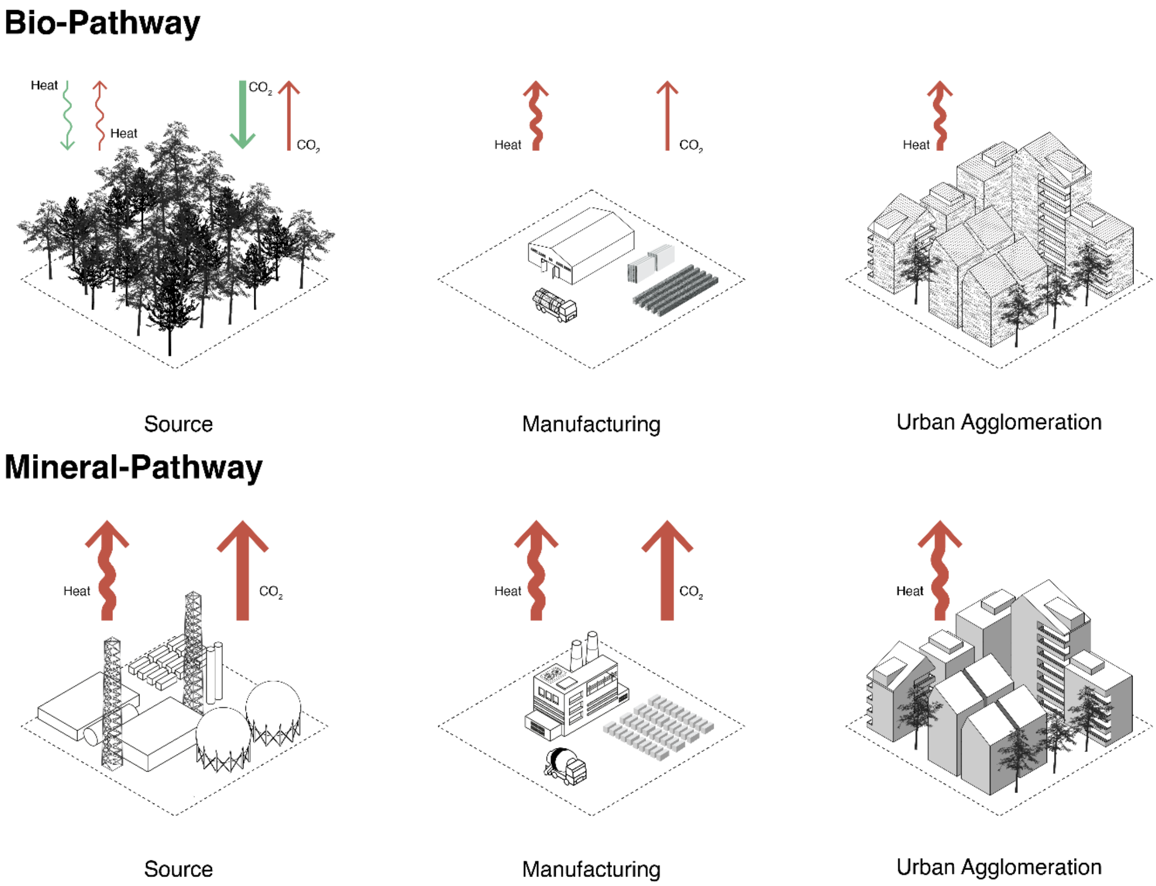

Figure 1. The comparative atmospheric effects of biomass-based and mineral-based materials in building production and urbanization. The thickness and size of arrows show relative differences in the magnitudes of heat and CO_2 fluxes between bio and mineral pathways. Heat emitted from building use, such as heating and cooling, is not included here.

2. Raw Material Extraction

A widespread transition to timber in construction will require an increase in forest harvests. This will likely increase pressure on forests for a limited period of time. Within a scenario of sustainable resource management, the rise in value of harvested wood products created by the new demand can serve to incentivize forest restoration and afforestation. Simultaneously, as regenerative practices and policies of urban timber construction as well as designs for disassembly and reuse proliferate, a substantial amount of wood from demolished buildings will become available for recycling and the pressure on forests will lessen.

The climatic implications of these changes in the management of forests and the built environment depend on the feedbacks that develop between forest and urban land and the atmosphere (Figure 1). These feedbacks can be divided broadly into two groups: as gas exchange (biogeochemical) and as modifications to land surfaces (biophysical).

2.1. Biochemical Feedbacks

Forests actively exchange a complex mix of gases with the atmosphere including CO_2 and methane (CH_4) [6,7], nitrous oxide (N_2O) [8], volatile organic compounds (VOCs) [9], water vapor (H_2O), etc. All tree species emit VOCs such as isoprenes or monoterpenes in varying quantities. If forests are located in and around the footprint of industrial plants or cities, VOCs mix with fossil fuel-based pollution from cars and industry to create harmful airborne cocktails such as NOx. Chemical reactions involving VOCs produce ozone and methane, two powerful greenhouse gases, and form airborne particles that can affect the condensation of water vapor in clouds. Changes in tree VOC emissions might affect the climate on a scale similar to changes in the Earth's carbon storage capacity and surface albedo [10].

Forests actively contribute to the greenhouse gas budget because they absorb and emit carbon dioxide, methane, and nitrous oxides. Among those greenhouse gas effects, their potential in balancing the global CO_2 budget is the most prominent. While methane oxidation in the atmosphere is the primary mechanism responsible for methane loss [11], the photosynthetic uptake of atmospheric CO_2 by land and aquatic ecosystems is one of the most dominant processes reducing atmospheric CO_2 concentrations. In recent decades, the world's forests took up more carbon than they emitted, creating a net CO_2 sink of 1.1 ± 0.8 GtC/year with tree living biomass accumulating most of it [12]. In 2001–2010, intact old-growth forests located primarily in the moist tropics and boreal Siberia absorbed ~0.85 (0.66–0.96) GtC/year because of the fertilizing effect of CO_2 [2]. Forest stands regrowing after past disturbances created an additional carbon sink of ~1.3 (1.03–1.96) PgC/year [2]. Net carbon uptake in forests therefore offset anthropogenic carbon emissions. It is important to note that the current terrestrial carbon sink is transient in nature. Forest fires, outbreaks of disease, and insect infestations, which have become more frequent with changes to climate, release carbon stored in forests into the atmosphere [13–15]. Among all terrestrial ecosystems forests store the largest amount of global carbon (~791 GtC) followed by peatlands (~220 GtC) [16]. Peatlands and mangroves, however, have the highest fraction of stored carbon that is irrecoverable [16]. Coniferous forests occupy ~13,110,000 km^2 (43% of the total forest area) and store 349 GtC (44% of the total forest carbon). Most coniferous forests are located in the temperate and boreal climate zones, while most broadleaf forests are located in the tropical climate zone.

Forests are also important in moderating climate because of their evapotranspiration and shading functions. Forests slowly release water extracted from soil and underground sources through evapotranspiration [17,18], a process that absorbs energy—energy that otherwise would have heated the area's surface—and thereby cools the air. In addition to the evapotranspiration process, forest tree cover effectively captures rainwater by preventing its quick evaporation from surface soils and reducing direct surface water runoff into streams and rivers. The combined local and non-local effects of a forestation scenario over 1900–1990 in Europe were estimated to increase summer precipitation by $7.6 \pm 6.7\%$ (0.13 ± 0.11 mm per day) on average, potentially offsetting a substantial part of the projected precipitation decrease from climate change [19].

2.2. Biophysical Feedbacks

Planting or harvesting trees modifies the physical properties of land surfaces, such as their reflectivity and roughness, and therefore modifies the heat exchange between land and the atmosphere. The reflectivity of the Earth's surface is measured in albedo (which differs for coniferous (0.09–0.15) and broadleaved (0.15–0.18) forests) and with seasonal changes as well as among different forest stand ages [20]. In comparison, the albedo of bare soil is higher and increases from 0.16 to 0.26 with rising soil moisture [21]. With an albedo lower than that of bare soil, forests absorb more shortwave solar radiation during daytime, which leads to a warming effect. Latent heat loss via evapotranspiration in forests can offset that heating effect and lead to an overall net cooling effect. Scientists have calculated the varied effects of increasing forest cover and of deforestation on land surface temperature at various latitudes. Their conclusion was that planting trees in the tropics would lead to strong cooling in temperate latitude and to modest cooling but in colder regions, it would cause warming [22]. The competing effects of albedo and evapotranspiration on surface temperature are the main cause of such a latitudinal pattern in the temperature impact. In tropical forests, high evapotranspiration offsets albedo warming and leads to the strongest cooling. In temperate forests, evapotranspiration is lower and albedo warming is higher; combined, they cause moderate cooling. Albedo warming surpasses the negligible cooling effect from evapotranspiration and leads to the pronounced warming in boreal forests [18,22].

To investigate the overall effects of changes in forest management on climate, both biochemical and biophysical effects must be considered and coupled to climate dynamics. A comprehensive study modeled all of the abovementioned feedbacks excluding VOC emissions and examined the effects of European reforestation and changing forest management on continental climate from 1750 to 2010 [23]. These changes included a shift in the dominant tree species from broadleaves to conifers, which have lower albedo, and partially offset the cooling effect of reforestation. The researchers found that these changes in forest cover did not cool the European climate and highlighted the importance of accounting for various processes in order to determine which effects on climate might offset or cancel one another.

While the understanding of the feedbacks between forest management and climate is continuously improving, very little is known about the feedbacks between mineral extraction facilities and climate. Here, mineral extraction sites are assumed to be net sources of heat, carbon dioxide, and other greenhouse gases (Figure 1, left panel of the mineral pathway), in contrast to forests which serve as sinks or sources of heat and carbon dioxide depending on the management, tree species, natural disturbances, and climate.

3. Manufacturing

Product manufacturing affects climate through emissions of greenhouse gases and heat (Figure 1, middle panels of both pathways). The main sources of greenhouse gas emissions are the processes of industrial production, which chemically or physically transform raw materials into commercial products. The emissions of greenhouse gases originate from chemical reactions associated with product manufacturing, such as calcination in cement production as well as the combustion of fossil fuels to generate energy for industrial processing, transport, use, and waste disposal. The existing estimates of these emissions have been recently reviewed for varying material classes used in construction and given current technologies and energy mixes [24]. Virgin steel has the highest emissions with a median value of 1.983 $kgCO_2e/kg_{mat}$, followed by cement (median value is 0.734 $kgCO_2e/kg_{mat}$), timber (median value is 0.41 $kgCO_2e/kg_{mat}$), and concrete (median value is 0.15 $kgCO_2e/kg_{mat}$). The relatively low CO_2 emissions of concrete per unit of mass are offset by its material intensity, which is an order of magnitude higher than that of metals and biomass-based materials [25]. It is critical that the comparative assessment of structural material is based on units of performance rather than by weight. For example, the mass of steel versus concrete needed to meet the same structural criteria in any given project represents a more meaningful measure of the impact of their actual application than their material weight.

The emission of heat accompanies all stages of material production. This form of heat is a result of energy losses at different production stages including extraction, refining, distribution, etc., and is often referred to as waste heat. Life cycle assessments track some of these energy losses, such as those emitted during fossil fuel extraction and distribution [26], but does not quantify their implications for the climate. A recent evaluation of global waste heat revealed that 51% of the global primary energy consumption by various industries is lost after conversion [27]. This industrial waste heat increases the temperature of air, water bodies, and soils. While the emission of heat into air can have an immediate effect on air temperatures, heat released into water or soils is accumulated and released slowly into the atmosphere. This accumulated heat can have a long-lasting effect on climate and can contribute to regional warming, with a substantial influence for regions with high densities of population and industries. The waste heat from industrialized regions located in Eurasia and North America emitted into the atmosphere was shown to be responsible for the northern hemisphere winter warming [28].

Emissions of waste heat from material manufacturing are most likely higher for the steel and cement industries than for the timber industry. Steel and cement industries dominate energy use worldwide [29] because they include thermally intensive processes needed for the chemical and physical transformation of raw material. In the steel industry, most of the energy is used for heating purposes, while in cement production, energy is needed for both heating and chemical reactions. Both manufacturing processes require very high temperatures (>1400 °C) [30,31] and a large share of heat associated with steel or cement production is discharged directly into the environment despite considerable efforts to recycle waste heat [31–33]. In mass timber production, the manufacturing temperatures are substantially lower (e.g., 80–140 °C during kiln drying of wood) [34] and therefore the potential of this industry to directly contribute to local or regional warming is lower. Estimates of waste heat emissions for the mass timber industry currently do not exist. A direct comparison of waste heat emissions from mass timber manufacturing to other construction material industries would offer evidence that is more conclusive.

In addition to the emissions of waste heat, there may be substantial differences in a local heat island effect related to the laydown and handling spaces of the facilities typical for different manufacturing industries. The materials used to produce the buildings, equipment, and infrastructures usually dominate steel and cement plants. Saw mills are typically less industrial and urban, e.g., as they have a lower share of area covered by impervious surfaces. The differences in the heat island effect between mineral-based materials and timber are likely to become more pronounced as we consider their application at the urban scale.

4. City

Many of us have observed that the budding and flowering of plants occur earlier in cities than in rural areas. We have enjoyed the cool shade of streets in cities on a hot summer day or noticed the contrast in temperature of snow-covered landscapes and snowless cities in winter. It is undeniable that temperatures within a dense cityscape are not the same as those of its surroundings. This phenomenon, which is referred to as an urban heat or cool island effect, was coined because of the similarity between the spatial patterns of the isotherms of the air temperature in the urban heat island effect and height contours of an oceanic island [35]. The urban heat island effect is one of the main reasons why urban agglomerations have an amplified effect on the weather and climate of densely populated regions such as Europe [36].

Cities have greater ability than rural areas to absorb and store sensible heat as well as to delay its release. The organizational density of urban structures, urban air pollution, and thermal properties of urban construction materials are responsible for the gradient of temperatures between cities and rural areas. A shift to timber in construction can influence two sets of factors responsible for the urban heat island effect, such as the thermal properties of buildings and city structure (Figure 1, right panels of both pathways).

Most building materials accumulate some of the incident solar radiation as heat during the day and release it during night. The material property that governs the heat exchange between a building and the ambient air is referred to as thermal admittance or thermal inertia. The difference in the average thermal admittances of different construction materials is quite substantial: it ranges from 200 to 535 $J/(m^2\sqrt{s}\,K)$ for wood (depending on its density), to 150–1785 $J/(m^2\sqrt{s}\,K)$ for concrete (depending on its density), to ~1110 $J/(m^2\sqrt{s}\,K)$ for glass, and to ~1065 $J/(m^2\sqrt{s}\,K)$ for brick, and reaches the maximum at 14,475 $J/(m^2\sqrt{s}\,K)$

for steel [35]. Materials with large thermal admittance sequester heat within the material and there is relatively small change in the surface temperature during the day. At night, they are mostly responsible for the heat island effect as they radiate the heat accumulated during the day. Materials with low thermal inertia store heat less readily. Their surface temperature changes quickly with changes in air temperatures and can have large amplitude during the day.

It is important to note that modern buildings are assemblies of different materials. The primary structural system of a building may be comprised largely of wood, steel, or concrete, but building assemblies/enclosures are not monolithic and the material heat admittance as well as inertia of those materials are complicated by the position of materials within the depth of the surface finishes, their density, and thermal conductivity. The position of insulation, if any, within the layers of a wall or roof assembly further challenge the equation. Glass, which comprises a fair amount of building surfaces, for example, would absorb or reflect solar radiation differently depending on its solar orientation, the angle of solar incidence, and the makeup of the glass panel itself, such as its layering of glass as well as ultraviolet reducing and low emissivity films. Building designers who seek the potential benefits of utilizing thermal mass to moderate diurnal temperature extremes within building interiors would be advised to consider the same thermodynamic effect on the exterior environments in which they build. The development of building assemblies with the goal of minimizing the heat island effect would represent a potentially fruitful collaboration between building designers and urban climate scientists.

The efficiency of a building's spatial organization, measured as a low surface area to floor area ratio, might also play a role in the mitigation of the heat island effect. A tall slender tower will have a greater active surface for energy exchange than a more cubic building volume, thus increased building density within moderate midrise building aggregations might offer further reductions. The circumstantial restrictions in the height of timber buildings, due to life safety considerations, may offer intrinsic benefits with respect to urban temperatures. Because the urban heat island effect is a complex phenomenon resulting from various interwoven factors, including local climate, convection currents, and the air turbulence created by varied building topographies, the hypotheses outlined above would have to be tested for cities in different climate zones using numerical urban climate models.

Lastly, although cities are some of the most durable artifacts of human civilization, if considered over the timescales of the building life span, they represent material formations in constant flux. The way in which we treat buildings at the end of their service lives will undoubtedly have an effect on the climate through, e.g., emissions of GHG's from landfills or waste energy combustion, thermal effects due to the changing of land surface albedo, or the heat island effect where material is stored for recycling or reuse. There will most likely be different climate impacts of various materials at the end of their first life as components of the building assembly. We know currently very little about the implications for the climate of abandoned city blocks or manufacturing plants, or the attempts to reclaim them for new uses. Nevertheless, it can be fairly assumed that the material that flows into the built environment will continue to imprint itself on the climate as it flows out again.

5. Conclusions

A large-scale transition to the timber construction of cities will lead to systemic changes in forest management, material manufacturing, and both the footprint and climate effects of urban settlement. The climate implications of these changes will be multifaceted and their overall effect is not yet well understood. With a high level of confidence, we can say that the substitution of timber for mineral-based construction materials has a significant potential to draw down atmospheric carbon and mitigate greenhouse gas emissions from the construction sector. This transition therefore has a high potential to rebalance the global carbon cycle. Accompanying changes in surface albedo, emissions of VOCs and the water cycle, however, may either enhance or diminish that effect on climate.

Substituting timber for steel and concrete will likely lead to a major shift in the industries that manufacture construction materials and their associated impacts on climate. The implications of that substitution for greenhouse gas emissions have been scrutinized at scales from the molecular to global level. By contrast, we know very little about the impacts of this transition with respect to industrial waste heat.

A large-scale transition to timber in urban construction might contribute to a change in the morphology of buildings and, by extension, their thermal performance vis a vis their admission and release of ambient heat. Whether such a material change (or at least the reorganization of the constituent layers of the urban building assembly that it might entail) could prove instrumental in the mitigation of the urban heat island effect for various climate regions remains unclear.

The putative benefits to forest health and the reductions in atmospheric carbon that might result from the substitution of biomass-based materials in urban construction are subjects of ongoing research and debate. Little attention has been paid, however, to the thermal effects of such a transition or the degree to which climate benefits might be either exaggerated or offset by the thermodynamics of changing forest landscapes as well as urban building morphology and materiality. This area of research, as well as the forest management strategies and building design criteria that might arise from it, represent a significant challenge for a generation of architects, engineers, and climate scientists focused on the restoration of our climate and the rebalancing of global ecosystems.

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References

1. Friedlingstein, P.; Jones, M.W.; O'Sullivan, M.; Andrew, R.M.; Hauck, J.; Peters, G.P.; Peters, W.; Pongratz, J.; Sitch, S.; Le Quéré, C.; et al. Global Carbon Budget 2019. *Earth Syst. Sci. Data* **2019**, *11*, 1783–1838. [CrossRef]
2. Pugh, T.A.M.; Lindeskog, M.; Smith, B.; Poulter, B.; Arneth, A.; Haverd, V.; Calle, L. Role of forest regrowth in global carbon sink dynamics. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 4382–4387. [CrossRef] [PubMed]
3. GlobalABC. *2020 Global Status Report for Buildings and Construction: Towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme: Nairobi, Kenya, 2020; p. 7.
4. Churkina, G.; Organschi, A.; Reyer, C.P.O.; Ruff, A.; Vinke, K.; Liu, Z.; Reck, B.K.; Graedel, T.E.; Schellnhuber, H.J. Buildings as a global carbon sink. *Nat. Sustain.* **2020**, *3*, 269–276. [CrossRef]
5. Oliver, C.D.; Nassar, N.T.; Lippke, B.R.; McCarter, J.B. Carbon, fossil fuel, and biodiversity mitigation with wood and forests. *J. Sustain. For.* **2014**, *33*, 248–275. [CrossRef]
6. Pangala, S.R.; Enrich-Prast, A.; Basso, L.S.; Peixoto, R.B.; Bastviken, D.; Hornibrook, E.R.C.; Gatti, L.V.; Marotta, H.; Calazans, L.S.B.; Sakuragui, C.M.; et al. Large emissions from floodplain trees close the Amazon methane budget. *Nature* **2017**, *552*, 230–234. [CrossRef]
7. Ito, A.; Inatomi, M. Use of a process-based model for assessing the methane budgets of global terrestrial ecosystems and evaluation of uncertainty. *Biogeosciences* **2012**, *9*, 759–773. [CrossRef]
8. Machacova, K.; Bäck, J.; Vanhatalo, A.; Halmeenmäki, E.; Kolari, P.; Mammarella, I.; Pumpanen, J.; Acosta, M.; Urban, O.; Pihlatie, M. Pinus sylvestris as a missing source of nitrous oxide and methane in boreal forest. *Sci. Rep.* **2016**, *6*, 23410. [CrossRef]
9. Laothawornkitkul, J.; Taylor, J.E.; Paul, N.D.; Hewitt, C.N. Biogenic volatile organic compounds in the Earth system. *New Phytol.* **2009**, *183*, 27–51. [CrossRef]
10. Unger, N. Human land-use-driven reduction of forest volatiles cools global climate. *Nat. Clim. Chang.* **2014**, *4*, 907–910. [CrossRef]
11. Turner, A.J.; Frankenberg, C.; Kort, E.A. Interpreting co\ntemporary trends in atmospheric methane. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 2805–2813. [CrossRef]
12. Pan, Y.; Birdsey, R.A.; Fang, J.; Houghton, R.; Kauppi, P.E.; Kurz, W.A.; Phillips, O.L.; Shvidenko, A.; Lewis, S.L.; Canadell, J.G.; et al. A large and persistent carbon sink in the world's forests. *Science* **2011**, *333*, 988–993. [CrossRef]

13. Reyer, C.P.O.; Bathgate, S.; Blennow, K.; Borges, J.G.; Bugmann, H.; Delzon, S.; Faias, S.P.; Garcia-Gonzalo, J.; Gardiner, B.; Gonzalez-Olabarria, J.R.; et al. Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? *Environ. Res. Lett.* **2017**, *12*, 034027. [CrossRef]
14. Seidl, R.; Thom, D.; Kautz, M.; Martin-Benito, D.; Peltoniemi, M.; Vacchiano, G.; Wild, J.; Ascoli, D.; Petr, M.; Honkaniemi, J.; et al. Forest disturbances under climate change. *Nat. Clim. Chang.* **2017**, *7*, 395–402. [CrossRef]
15. Seidl, R.; Schelhaas, M.-J.; Rammer, W.; Verkerk, P.J. Increasing forest disturbances in Europe and their impact on carbon storage. *Nat. Clim. Chang.* **2014**, *4*, 806. [CrossRef]
16. Goldstein, A.; Turner, W.R.; Spawn, S.A.; Anderson-Teixeira, K.J.; Cook-Patton, S.; Fargione, J.; Gibbs, H.K.; Griscom, B.; Hewson, J.H.; Howard, J.F.; et al. Protecting irrecoverable carbon in Earth's ecosystems. *Nat. Clim. Change* **2020**, *10*, 287–295. [CrossRef]
17. Ellison, D.; Morris, C.E.; Locatelli, B.; Sheil, D.; Cohen, J.; Murdiyarso, D.; Gutierrez, V.; Noordwijk, M.V.; Creed, I.F.; Pokorny, J.; et al. Trees, forests and water: Cool insights for a hot world. *Glob. Environ. Chang.* **2017**, *43*, 51–61. [CrossRef]
18. Li, Y.; Zhao, M.; Motesharrei, S.; Mu, Q.; Kalnay, E.; Li, S. Local cooling and warming effects of forests based on satellite observations. *Nat. Commun.* **2015**, *6*, 6603. [CrossRef]
19. Meier, R.; Schwaab, J.; Seneviratne, S.I.; Sprenger, M.; Lewis, E.; Davin, E.L. Empirical estimate of forestation-induced precipitation changes in Europe. *Nat. Geosci.* **2021**, *14*, 473–478. [CrossRef]
20. Halim, M.A.; Chen, H.Y.H.; Thomas, S.C. Stand age and species composition effects on surface albedo in a mixedwood boreal forest. *Biogeosciences* **2019**, *16*, 4357–4375. [CrossRef]
21. Gascoin, S.; Ducharne, A.; Ribstein, P.; Perroy, E.; Wagnon, P. Sensitivity of bare soil albedo to surface soil moisture on the moraine of the *Zongo glacier* (Bolivia). *Geophys. Res. Lett.* **2009**, 36. [CrossRef]
22. Li, Y.; Zhao, M.; Mildrexler, D.J.; Motesharrei, S.; Mu, Q.; Kalnay, E.; Zhao, F.; Li, S.; Wang, K. Potential and actual impacts of deforestation and afforestation on land surface temperature. *J. Geophys. Res. Atmos.* **2016**, *121*, 14372–14386. [CrossRef]
23. Naudts, K.; Chen, Y.; McGrath, M.J.; Ryder, J.; Valade, A.; Otto, J.; Luyssaert, S. Europe's forest management did not mitigate climate warming. *Science* **2016**, *351*, 597–600. [CrossRef] [PubMed]
24. Pomponi, F.; Moncaster, A. Scrutinising embodied carbon in buildings: The next performance gap made manifest. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2431–2442. [CrossRef]
25. Heeren, N.; Fishman, T. A database seed for a community-driven material intensity research platform. *Sci. Data* **2019**, *6*, 23. [CrossRef]
26. Moncaster, A.M.; Symons, K.E. A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. *Energy Build.* **2013**, *66*, 514–523. [CrossRef]
27. Forman, C.; Muritala, I.K.; Pardemann, R.; Meyer, B. Estimating the global waste heat potential. *Renew. Sustain. Energy Rev.* **2016**, *57*, 1568–1579. [CrossRef]
28. Zhang, G.J.; Cai, M.; Hu, A. Energy consumption and the unexplained winter warming over northern Asia and North America. *Nature Clim. Chang.* **2013**, *3*, 466–470. [CrossRef]
29. Gutowski, T.G.; Sahni, S.; Allwood, J.M.; Ashby, M.F.; Worrell, E. The energy required to produce materials: Constraints on energy-intensity improvements, parameters of demand. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2013**, *371*, 20120003. [CrossRef]
30. Zhang, H.; Wang, H.; Zhu, X.; Qiu, Y.-J.; Li, K.; Chen, R.; Liao, Q. A review of waste heat recovery technologies towards molten slag in steel industry. *Appl. Energy* **2013**, *112*, 956–966. [CrossRef]
31. Fierro, J.J.; Escudero-Atehortua, A.; Nieto-Londoño, C.; Giraldo, M.; Jouhara, H.; Wrobel, L.C. Evaluation of waste heat recovery technologies for the cement industry. *Int. J. Thermofluids* **2020**, *7–8*, 100040. [CrossRef]
32. Wang, R.Q.; Jiang, L.; Wang, Y.D.; Roskilly, A.P. Energy saving technologies and mass-thermal network optimization for decarbonized iron and steel industry: A review. *J. Clean. Prod.* **2020**, *274*, 122997. [CrossRef]
33. Jouhara, H.; Almahmoud, S.; Chauhan, A.; Delpech, B.; Bianchi, G.; Tassou, S.A.; Llera, R.; Lago, F.; Arribas, J.J. Experimental and theoretical investigation of a flat heat pipe heat exchanger for waste heat recovery in the steel industry. *Energy* **2017**, *141*, 1928–1939. [CrossRef]
34. McDonald, A.G.; Gifford, J.S.; Steward, D.; Dare, P.H.; Riley, S.; Simpson, I. Air emission from timber drying: High temperature drying and re-drying of CCA treated timber. *Holz Als Roh-Und Werkst.* **2004**, *62*, 291–302. [CrossRef]
35. Oke, T.R.; Mills, G.; Christen, A.; Voogt, J.A. *Urban Climates*; Cambridge University Press: Cambridge, UK, 2017.
36. Trusilova, K.; Jung, M.; Churkina, G.; Karstens, U.; Heimann, M.; Claussen, M. Urbanization impacts on the climate of Europe: Numerical experiments with the PSU/NCAR Mesoscale Model (MM5). *J. Appl. Meteorol. Climatol.* **2008**, *47*, 1442–1455. [CrossRef]