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CLIMATE CHANGE AND CARBON SEQUESTRATION (O CAMPOE, SECTION EDITOR)

Seeing the Trees Without the Forest: What and How can Agroforestry and Urban Forestry Learn from Each Other?

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Abstract

Purpose of Review Agroforestry and urban forestry have evolved mainly as separate disciplines, although they share a long history of tree cultivation in man-made environments. Here, we review their common threads, exploring how trees in both systems interact with and shape their environments. We examine common themes and methodologies – ranging from tree growth dynamics to environmental stressors, ecosystem services provision, and questions of governance – and identify opportunities for synergies between these fields.

Recent Findings We emphasize the potential of agroforestry and urban forestry for enhancing multifunctional landscapes. Geographical divides in research are evident, with agroforestry predominantly studied in the Global South and urban forestry receiving more attention in the Global North. However, significant research gaps provide avenues for collaboration, for instance, addressing challenges in capturing the monetary and socio-cultural value of ecosystem services and environmental justice considerations.

Summary In light of the growing need for integrated approaches in addressing contemporary challenges, from climate change mitigation and adaptation to community well-being, our review explores what these research fields can learn from each other and provides recommendations for fostering greater interdisciplinary dialogue and new avenues for collaborations in a meaningful and synergistic manner, aiming to advance policy, research, and practice in agroforestry and urban forestry.

Keywords Ecosystem services · Interdisciplinary research · Social – ecological systems · Sustainability · Trees outside forests · Urban–rural green infrastructure

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Introduction

In an era where environmental and social crises loom large, nature-based solutions can play a major role in addressing climate change and other societal challenges through the protection, sustainable management and restoration of both natural and modified ecosystems, benefiting biodiversity and human well-being [1]. Nature-based solutions, underpinned by the benefits that flow from healthy ecosystems, can contribute to climate mitigation, food and water security, biodiversity goals, sustainable livelihoods and economic development [1, 2]. In this sense, agroforestry and urban forestry systems can be regarded as nature-based solutions that are centred on trees and shrubs outside conventional forest ecosystems (see Box 1 for definitions). While there are distinct differences between both systems, they share a long history of tree cultivation, typically in highly managed environments, and provide multiple ecosystem services [3•, 4••, 5, 6]. This provision is reliant on a range of different structures, from single, isolated trees to linear tree structures (e.g., alleys, avenues, shelter strips, windbreaks) and forest patches of varied size (e.g., parks, woodlots, remnant forests) (Fig. 1), and related management practices to maintain them. Moreover, while the societal importance of the various ecosystem services differs between urban and rural settings, the mechanisms by which they are generated are principally the same. Agroforestry and urban forestry also share similarities in ownership and management responsibilities. For instance, in the Global North, most agricultural land is privately owned, akin to a significant part of the green infrastructure in cities. Hence, questions of governance and issues of environmental and climate (in)justice regarding ecosystem services beneficiaries show parallels between agroforestry and urban forestry [7, 8, 9••].

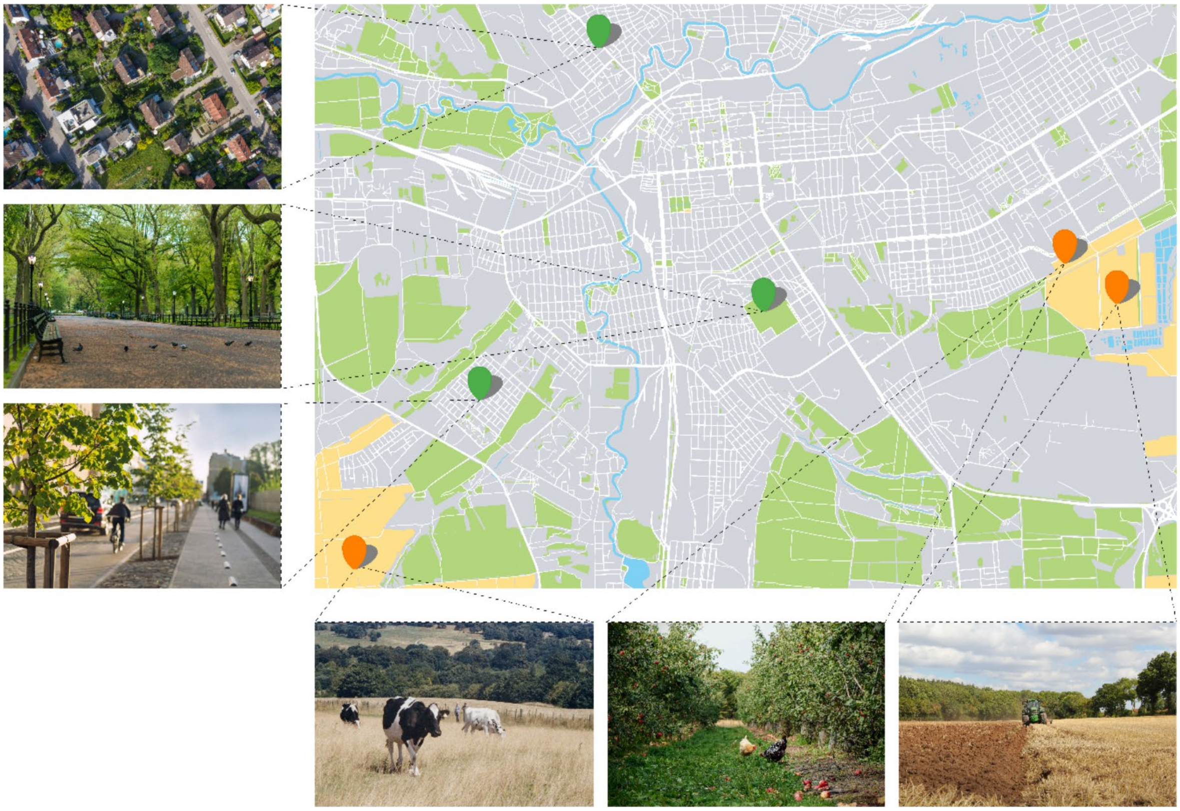

Fig. 1 Comparative elements of agroforestry and urban forestry across different land uses. The map shows built-up areas (shaded grey), urban and peri-urban green areas (shaded green), and agroforestry systems (shaded yellow). Urban forestry elements under study in this paper are represented by trees planted on private property (left top photo), in city parks (left middle), and street trees (left bottom). For agroforestry, illustrated examples include agrosilvopastoral systems integrating trees, animals, and crops (bottom left), silvopastoral systems combining trees with animals (bottom center), and agrisilvicultural systems where trees are combined with crops (bottom right)

Box 1. Definitions

Agroforestry: Land-use systems and practices where trees and shrubs are deliberately integrated with crops and/or animals on the same land management unit without the intention to establish a forest stand [126]. The trees may be arranged as single stems, in rows or in groups, while grazing may also take place inside parcels or on the limits between parcels [126]. Agroforestry can also be defined as a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels [127]

Urban forestry: The art, science and technology of managing trees and forest resources in and around urban community ecosystems for the physiological, sociological, economic and aesthetic benefits trees provide society [128]

Ecosystem services: The benefits humans derive, directly or indirectly, from ecosystems [129]. These include provisioning services such as food and water; regulating services such as climate regulation and flood and disease control; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, and other non-material benefits

Green infrastructure: Strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings [130]

Owing to the abovementioned similarities, many studies on agroforestry and urban forestry ask related questions and use related methodologies [5, 10–14]. Yet, few studies tackle questions associated with both, and there are very few examples of how research in agroforestry informs research in urban forestry or vice versa (Box 2). Given the obvious similarities, it is quite surprising that agroforestry and urban forestry studies seem to be largely undertaken by separate communities with little interaction [15]. However, both communities of researchers and practitioners might benefit from sharing their research paradigms and knowledge base. For instance, understanding the growth mechanisms of tree species under the broad range of environmental conditions that both agricultural and urban landscapes offer would enable us to investigate and select the best management approaches for increasing tree benefits in both systems. Furthermore, agroforestry and urban forestry operate and overlap in expanding urban regions comprising urban and rural subsystems. Therefore, synergies in agroforestry and urban forestry research should be sought to effectively contribute to functional urban–rural green infrastructure for sustainable and climate-resilient development.

Box 2. Bibliographic analysis of publications in agroforestry and urban forestry

We conducted a bibliometric analysis to compare the number of studies published in the fields of agroforestry and urban forestry (Fig. 2), using the Dimensions scholarly database. Dimensions is free accessible and includes both journal articles and citation counts [131]. To find relevant literature, we restricted our keyword search to titles and abstracts and further narrowed the results to publications indexed in the ERA 2023 journal list, covering the period from 1990 to 2022

For urban forestry, our search terms were: ("urban" OR "cit*") AND ("forest*" OR "tree"). For agroforestry, we used: ("agroforest*" OR "silvopastoral" OR "silvopasture"). To pinpoint studies addressing both domains, we employed a composite search: ("urban" OR "cit*") AND ("forest*" OR "tree") AND ("agroforest*" OR "silvopastoral" OR "silvopasture")

The solid lines in Fig. 2 present the publication trend for agroforestry, urban forestry, and the articles that included both search strings in the title or abstract. It is, however, important to note that the analysis is not a systematic review and should not be interpreted as one. This analysis aims to provide insights into the volume of research in each field and potential intersections in their literature

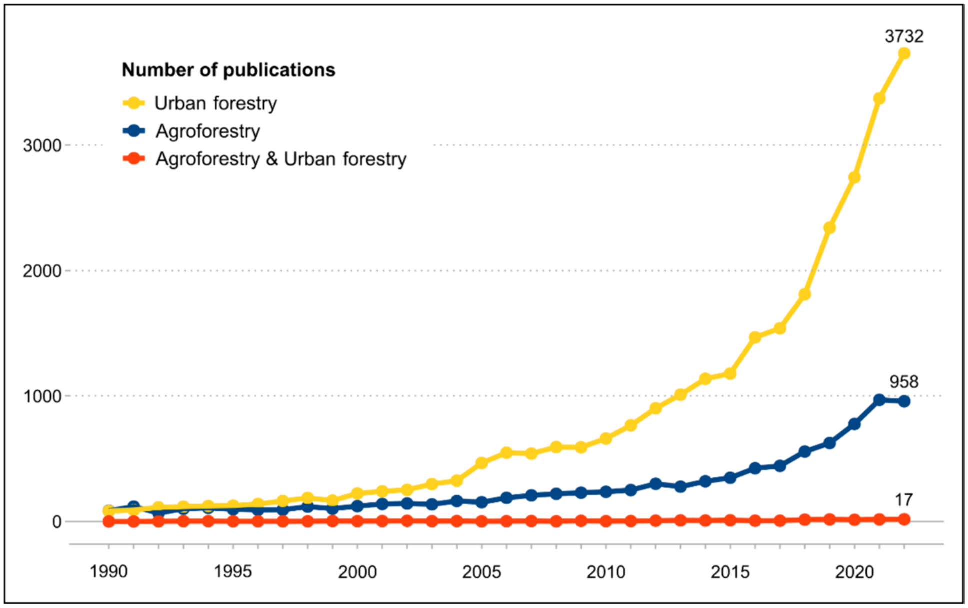

Fig. 2 Number of published studies that included our search strings for agroforestry (blue), urban forestry (yellow), or both (red) in the title or abstract

Considering this, within this review, we aim to (i) highlight themes and methods common in agroforestry and urban forestry research; (ii) identify potential synergies between agroforestry and urban forestry where collaborative efforts can be pursued; and (iii) propose recommendations for fostering improved collaboration and integration between the two research communities. This article is the product of a workshop held at the University of Freiburg, Germany, in 2023 to discuss synergies between agroforestry and urban forestry and involved academics from both fields. The objective of our study did not lend itself to a systematic review; more appropriately, we applied a structured approach. We aimed to include as many relevant studies as possible, considering factors such as relevance to the review's objectives, the quality and strength of the evidence and the diversity of perspectives presented. For this review, we did not distinguish between agroforestry and urban forestry in different geographic regions. We do acknowledge, however, that based on the research experience of the authors of this paper, there is a focus on agroforestry and urban forestry in temperate regions of the Global North.

Overlapping Research Themes and Methods

Trees outside forests are the common thread linking research in agroforestry and urban forestry [16]. Central to both fields is the study of how trees simultaneously influence, and are influenced, by their surrounding environment. For instance, urban trees face more challenging conditions in the city than trees in a natural environment, including higher temperatures and reduced access to water, which can significantly impact their survival and growth [17, 18]. At the same time, as urban trees adapt to these stresses, their expanding canopy plays an essential role in shaping the environment: the larger their canopy grows, the more they affect the surrounding environment via shading, evapotranspiration, and increased albedo [19–21]. Similarly, agroforestry also makes use of the capacity of trees to modify their environment, both above and below ground [4••]. For instance, the presence of trees in agricultural landscapes helps mitigate temperature extremes and reduce wind speeds, providing a more favourable environment for crop growth and yields [22]. The following sections further probe questions from tree growth dynamics to interactions with environmental stressors, provision of ecosystem services, and governance within both fields.

Tree Growth and Allometric Equations

Studying the growth of trees in agroforestry systems and within the urban environment is an expanding field of research, mainly driven by the range of tree species utilised and the environmental heterogeneity in rural and urban landscapes. Within agroforestry, much of the research has focused on the influence of trees on crops, soils, or livestock, and often, allometric equations from dedicated repositories, such as the GlobAllomeTree database, are used to estimate tree dimensions that drive the effects on the environment. These equations, however, are most commonly derived from forest-grown trees, which differ in growth rates, management history, and canopy architecture from those grown in less-dense growth conditions, which can result in significant over-, or underestimation of crown extent and density, biomass increment and carbon sequestration potential when applied to trees outside forests. In response, there has been an increased effort to develop generic as well as species- and site-specific allometric equations for trees used in agroforestry systems [23].

In urban forestry, there is also a growing emphasis on understanding the growth dynamics of urban trees across a range of conditions, from inner urban to suburban areas and with varying degrees of green cover and climates. For instance, Pretzsch et al. [24] studied the growth of urban trees in ten cities around the globe and across climate zones (boreal, temperate, Mediterranean, and subtropical). Based on tree ring analyses, the authors concluded that urban trees tend to grow more quickly than trees in rural surroundings and that urban trees have responded with accelerated growth to climate change since the 1960s, but to a lesser extent than rural trees. Other studies have investigated the growth response of tree species in terms of their growth characteristics and species features, for instance, looking at the growth response of eco-physiologically contrasting tree species under water stress [25] and by comparing commonly planted urban tree species under identical growth conditions within a city [26, 27] as well as across different cities [28, 29]. This expanding body of knowledge supports the development of tree growth models, allowing the estimation of structural attributes of common species under different environmental conditions [11].

Stress Factors

Environmental stressors, including extreme weather and climate events compounded by climate change, affect trees regardless of location. But compared to the conditions found in closed-canopy forests, trees in agroforestry and urban systems with their exposed crowns and often restricted rooting space face significantly more challenging conditions both above- and below ground [17]. Limited rooting space directly affects the roots' ability to reach nutrient and water resources, while soil compaction effects can also indirectly restrict root extension. The extent to which site conditions contribute to tree stress is unclear, but previous studies have suggested that as much as 90% of all urban trees experience vitality problems that can be mainly attributed to local physical and chemical soil conditions [30]. Furthermore, in urban settings, management practices to which trees had been exposed, for example, by trenching or construction or from mowing practices which repeatedly damaged the roots anchoring the tree, could leave them more vulnerable to windthrow than typical forest trees [31]. Root damage may also result from ploughing or tillage in agroforestry systems, especially in late conversion of alley cropping systems or areas where infrequent sub-soil management activities are carried out. Such damage may affect tree growth and development, as cut roots may serve as an entry point for decay while also potentially destabilising the tree. Nevertheless, agroforestry trees may demonstrate sufficient root plasticity by adapting to repeated ploughing and tillage by utilising rooting zones in deeper soil horizons [32].

Trees in urban and rural areas can also be particularly vulnerable to pests and pathogens as the ubiquity of monoculture plantings, combined with limited genetic diversity, allows the rapid spread of fungi and beetles due to the availability of suitable host trees for beetle breeding [33]. Prominent examples are the Dutch elm disease, a fungal pathogen (*Ophiostoma* spp.) that has decimated elm (*Ulmus* spp.) populations across Europe and North America [34], as well as the spread of the emerald ash borer (*Agrilus planipennis*), one of the most destructive insects in urban forest history [35]. At the same time, climate change is allowing pests to breed more frequently, while international trade and human movement are spreading native and non-native insects and pathogens more widely, increasing the risk of infections or further spread in both urban and rural environments [36, 37•]. For example, a recent study assessing potential tree losses in Nordic cities caused by the spread of new pests and pathogens estimated that, in the worst-case scenario, up to 90% of the cities' trees could be lost in a combined outbreak of Asian long-horned beetles [38]. This points to the urgent need to increase awareness of such threats and develop tree management strategies that increase the resilience of urban forests to multiple risks, including the promotion of a diversity of tree species and genera, as we discuss in the following section.

Operational Management of Trees

Tree management is crucial in both agroforestry and urban forestry, albeit for different objectives and under different sets of rules. In agroforestry, trees might be planted in rows or according to specific patterns; they might also be managed in specific ways, such as being pruned to increase the yield of fruit-tree canopy crops or of the intercropped plants, enhance wood quality, or ensure clearance for agricultural machinery [39–41]. In cities, pruning is often applied for vehicle, pedestrian, and utility lines clearance and to reduce the risk of personal injury and property damage [42]. Furthermore, pruning is also frequently advocated as a necessary management practice to maintain tree health and structure [43]. Moreover, while trees on private properties might reflect owners' individual preferences, public urban trees are managed under standardised practices. These range from strategic planning rules, with some aiming at specific tree densities along streets and others like the "3–30-300 rule" promoting equitable access to trees and green spaces [44], to technical rules regarding the tree and its planting site. For example, large trees in public spaces must have a minimum volume of structural soil, and street trees must be pruned to a specified height to prevent interference with power lines and to ensure road accessibility.

Historically, the choice of tree species, especially in urban settings, has been informed by decades of accumulated knowledge on the suitability of a large range of native and introduced tree species, particularly in European and North American contexts [45–47]. Tree species selection is also often highly dependent on the design and existing character of a street or a park as well as the positioning of underground and belowground utilities, but it is only more recently that tree species selection has been studied more systematically and that scientific studies began to establish the suitability of tree species for urban plantings [48]. Climate change has boosted the interest in this topic as increased temperatures and prolonged periods of drought during the growing season require adaptation of traditional species selection towards, for example, more heat- and drought-tolerant species [49]. In a few studies, matching site conditions with the origins of the trees or emphasising particular tree traits have been suggested to select suitable tree species for harsh urban environments [50–52]. Such studies help to improve understanding of the different responses of urban trees to prevailing environmental conditions, which may not only advance the scientific state of the art but also have practical implications for tree planting strategies and their management in different environmental contexts. Concurrently, as tree species' responses to changing environmental conditions become increasingly unpredictable, rigorous monitoring of tree growth and health becomes paramount, both to validate previous species selections and inform future tree management strategies [42, 53]. Future research on the extent to which different tree species and genera are susceptible/resistant to new pathogens and pests, as well as on effective treatments, will become increasingly important. Until such information becomes available, planning for greater diversity of tree species and genera is of primary importance [38, 45].

Beyond pruning, tree choice and placement, as well as other management practices such as artificial irrigation, targeted fertilizer applications, and even indirect benefits from potential herbicide overspray, play important roles. For instance, in agroforestry systems, irrigation can supplement water for trees to support tree growth. Farmers also often apply fertilizers, manure, or compost to supply nutrients to crops, which is indirectly benefitting trees through overspray or runoff. While in cities, residents may be encouraged to water street trees in front of their homes, compensating for potential water stress during drought. Increasingly, options to retain and infiltrate stormwater runoff in tree trenches, thereby enhancing water supply for the trees, are explored [54]. Hence, trees in agroforestry and urban settings are exposed to highly variable water and nutrient regimes, making it difficult to apply a common management of these resources and calls for monitoring approaches focussing on individual trees.

Monitoring Tree Performance

Within urban forestry, agroforestry and also conventional forestry practices, a range of methods and measures have been employed to monitor tree conditions, including measures of establishment success, relative recent growth rate (based on diameter at breast height), canopy size and vigour, tree mortality, and even public perception [55]. While tree health and condition are important in explaining tree performance, the subjective nature of such assessments makes quantitative measures, such as growth metrics, potentially better indicators to predict future growth and mortality [55].

Technological advancements are increasingly used to bridge some of these knowledge gaps. LiDAR, in the form of terrestrial laser scanning or drone-based technology, has emerged as a game-changer in assessing tree structure in both urban and agroforestry settings. This technology offers a non-destructive analysis of living trees, producing point clouds that allow three-dimensional modelling of trees and the automated extraction of structural parameters to derive the volume and spatial arrangement of tree structures in single trees and groups of trees. With high accuracy and agreement with traditional methods, the possibility of inferring secondary attributes, such as changes in the structure and form of trees [56, 57] or tree-shade effects [58, 59], is also highly relevant for agroforestry and urban forestry. Such developments emphasise the potential of leveraging technology to inform agroforestry and urban tree management strategies where local occlusion, scale, and access are often problematic.

Ecosystem Services, Disservices and Human Wellbeing

Per definition, ecosystem functions provide services only where there is also a demand and direct or indirect use by people. As agroforestry and urban forestry are generally placed in more densely populated areas such as urban, peri-urban or intensively managed agricultural areas, ecosystem services and disservices are felt more directly and more consistently by the population than forest ecosystem services. This means that trees are foremost perceived as ecosystem services providers.

In urban studies, the cooling potential of trees has received particular attention as a strategic measure to mitigate heat stress – a growing concern for human health and well-being. For instance, a recent study has found that increasing tree cover within European cities to 30% would lower air temperatures by a mean of 0.4 °C and prevent premature deaths from urban heat islands in these cities by 40% [60]. Trees can reduce local temperatures via shade, reducing direct sunlight exposure, and transpirational cooling, by which moisture is released back into the atmosphere. Similarly, smallholders in the tropics have been found to favour agroforestry systems compared to other agricultural land uses due to improved microclimate and, thus, better daily labour conditions and overall health [61]. Extensive work has been conducted on the thermal effects of urban vegetation using both modelling approaches and small-scale field experiments [20, 62]. Results show significant differences between species (e.g., due to morphological characteristics such as tree crown shape and leaf characteristics), and environmental conditions of planting sites also influence the cooling potential of urban trees [21, 62]. In agroforestry systems, trees provide shade and protection from extreme rainfall while still allowing sufficient light to pass through, and they can make cropping systems more resilient by moderating the microclimate by buffering extreme temperatures [63–65]. More secure and diversified income is, therefore, a key benefit of agroforestry systems. However, increasing crown cover may favour diseases and increase competition for light, water and nutrients, which may reduce crop yield if not well managed [66, 67].

Urban trees provide benefits in relation to the interception and infiltration of rainwater and are essential for urban stormwater management strategies by reducing the peak and magnitude of storm runoff, mitigating flood risks, decreasing erosion, filtering pollutants from base runoff, and lowering the overall costs of stormwater management [68, 69, 70••]. Stormwater management in agroforestry systems is also of importance; for example, the presence of trees can prevent erosion and, thus, the loss of nutrients and soil structure at times of low crop coverage.

In agroforestry systems, the ability of trees to sequester carbon is of increased interest due to global efforts to combat climate change. Incorporating trees or shrubs can significantly increase the amount of carbon sequestered compared to annual crops or pastures [4••, 71]. Recent estimates suggest that the shift from agriculture to agroforestry could significantly increase soil carbon sequestration by 34% [72], highlighting the immense potential of agroforestry to contribute to climate change mitigation efforts [72–74]. The carbon sequestration and storage potential of urban trees and forests is more modest compared to agroforestry. For instance, the total tree carbon storage in U.S. cities (c. 2005) was estimated at 643.2 million tonnes, about 3.2% of the estimated carbon stored in all forestland across the United States, and annual sequestration at 25.6 million tonnes [75], but these values are not negligible considering that these estimates do not include the carbon stored in the urban soils, which are estimated to store approximately 1.9 billion tonnes of carbon [76], three times more than urban trees.

Trees also provide critical habitat and landscape-scale connectivity for a wide range of fauna and flora, counteracting the homogenizing effects of agricultural expansion and urbanization. Street trees, for example, provide important foraging habitat for birds, serving as a critical resource for urban avifauna [77]. While native trees are most likely to support larger numbers of native species, non-native trees also play a valuable role in supporting biodiversity in cities [77, 78]. Researchers have found that urban forests can harbour high levels of biodiversity, including endangered species and those of high conservation value, which not only contributes to preserving biodiversity but also delivers social benefits through greater aesthetic appreciation [79]. Agroforestry systems, similarly, create and improve habitats, especially for pollinators, as the tree understoreys can provide floral and nesting resources and overwintering habitat, increasing pollinator abundance diversity and pollination services, thereby improving crop quality and yields [80, 81].

In recent years, there has been increasing research on the linkage between ecosystem services and human well-being, which is highly relevant to both agroforestry and urban forestry and is likely to garner even more attention in the future. In terms of well-being, there is evidence, particularly from the Global South, that agroforestry does not only improve income but also has the potential to enhance food security, nutrition and health, as well as provide improved access to other basic materials such as wood for home construction or fuelwood for cooking [82–84]. Good social relations have been associated with specific agroforestry interventions and particular systems, as is the case in shifting cultivation landscapes [85]. For example, family farms that practice agroforestry have been linked to higher recreational services for household members as well as society at large [86]. In urban forestry, a growing body of research is examining the contributions of urban trees to human health and well-being, from improved cardiovascular function and related health outcomes to stress reduction and cognitive restoration, but also by supporting good social relations [87–89]. The question of equity in accessing ecosystem services has also gained prominence. The number of studies on environmental injustice (i.e., the disproportionate distribution of environmental burdens and benefits among different socioeconomic groups) and green gentrification (i.e., “the displacement, exclusion, or marginalisation of residents in areas surrounding green urban (re)developments as they attract wealthier in-movers” [8]) has grown in recent years underscoring this concern. Particularly in the Global North context, studies have shown that socially vulnerable groups of class and racial/ethnic minorities often have reduced tree canopy cover compared to wealthier neighbourhoods [7], which, in turn, may have resulted in making them disproportionately exposed to environmental harms and risks [90, 91].

Finally, while agroforestry and urban forestry are commonly seen as win–win solutions for environmental and social outcomes, trees in these systems can also entail disservices, such as human-wildlife conflicts, the emergence of new pests, or allergies, that can reduce people’s well-being [61, 92, 93]. Similarly, while urban trees may provide numerous health benefits, they are also the source of various types of harm, nuisance and costs, including trees concealing traffic signs and roots lifting pavement, leaves making surfaces slippery or blocking stormwater drainage, and pollen causing allergic reactions [93, 94]. Appropriate species selection and timely maintenance practices can mitigate many of the nuisances associated with urban trees. Yet, few studies have attempted to quantify the synergies and trade-offs among different types of ecosystem services, and more of this work is required to improve the planning of ecosystem service provision [61, 93, 95]. As part of the workshop, an assessment of ecosystem services and their relevance within agroforestry and urban forestry systems was carried out. Table A1 shows the results of an expert opinion assessment indicating the importance of ecosystem service provision in either agroforestry or urban forestry systems.

Planning and Governance

From the perspective of linking concepts of agroforestry and urban forestry research, green infrastructure forms a common basis. Given that agroforestry typically refers to a rural or peri-urban setting and urban forestry obviously pertains to urban environments, the definition of green infrastructure (see Box 1) bridges these two concepts by highlighting how strategically planned areas with vegetation like trees and shrubs can be present and beneficial in both settings. Importantly, green infrastructure is expected to deliver multifunctional social, economic and environmental benefits. In this respect, the development of synergies between agroforestry and urban forestry research themes sits comfortably with increasing emphasis on multifunctionality and integration into policy and practice [96].

Whilst the delivery and planning of urban green infrastructure on the ground has received considerable attention within the literature, greenspace governance mechanisms and methodologies have been less scrutinised. Within Europe, there has been a growing shift from top-down approaches to more participatory models involving diverse stakeholders working together in partnership [97]. This shift has been described as a movement from "government" to "governance", in which different actors (citizens, NGOs, and other non-governmental actors) make decisions about and manage urban green spaces at different levels, with or without the active involvement of government authorities and public agencies. Less consideration has been paid to processes, interactions, organisations and decisions, which lead to the establishment and maintenance of such spaces and the ecosystem services they provide [98]. Although far less research has been generated in Latin America, recent studies also pointed to a gradual inclination towards participatory and bottom-up management practices [96]. However, significant challenges related to weak local governance, marked socioeconomic inequalities, and conflicts with traditional indigenous practices are a considerable obstacle in the shift from "government-led" practice to other types of management in the region [96]. A contrasting example comes from China: The governance of the "One Million-Mu Plain Afforestation Project" in Beijing is a prominent example of government-dominated large-scale urban greening projects, where this top-down approach may have improved the efficiency and effectiveness of the project but did not give farmers and nearby residents opportunities for decision-making [99].

In agroforestry, the complexity of systems and combinations and farmers' needs also benefit from participatory approaches, as shown in several studies worldwide [100, 101]. In contrast to many technology-driven interventions, the testing and implementation of different agroforestry systems has started at the farm level and evolved from traditional land management practices and has only recently received increasing attention in research and politics.

While research agrees on the importance of political and legal frameworks for agroforestry and urban forestry (as any other land use), aspects of governance and legal frameworks are usually dealt with at the case study level and commonalities have barely been determined at larger scales. A recurring subject – although more elaborated for agroforestry, but not less relevant for urban forestry – is the genuine cross-sectoral nature of both integrated approaches (in the case of agroforestry, combining crops, animals and/or trees; in the case of urban forestry, combining urban housing/business, infrastructure, and trees) which makes them subject to more than just one policy and legal domain, for example, such as in forestry. This integration is hardly reflected in political or legal practice. In several European countries, where farmers strongly rely on subsidies, for instance, there is limited recognition of, or policy support for tree planting in agricultural landscapes [102].

Uncertainty of land and tree tenure rights are often described as insufficient to accommodate the integrative nature of agroforestry systems. In many countries in Africa or Asia, trees are the constitutional property of the state, adding to the land rights challenges faced by smallholders with often limited or only customary land rights [103]. In some cases, secondary rights holders are even forbidden to plant trees because tree planting is considered a privileged act of primary rights holders [104]. Establishment of trees in cities, on the other hand, besides restricting factors of the planting site, must cope with a multitude of regulations concerning, e.g., tree preservation regulations, their invasive potential, distances from power lines, existing and proposed buildings, and property boundaries, interference with underground utilities, and safety standards, to name just a few [47]. Furthermore, for urban forestry, the division between public ownership and many private landowners poses particular challenges for holistic planning and management [105]. Even though legal constraints to adopting agroforestry and urban forestry are widespread globally, research on policy and institutional dimensions remains limited, with a lack of coherent theoretical frameworks [99, 106, 107]. This presents a common research gap where synergies could be further investigated.

A better understanding of the economic value generated by trees and respective ecosystem services can facilitate the adoption of efficient policies and measures to preserve and enhance them. Yet, in many cases, the information needed to monetise the services does not exist [108]. For instance, capturing the non-use value component of cultural services, a category of ecosystem services that is of key importance in urban environments, can be cumbersome, as it is usually measured based on the preferences of individuals [109]. This is similar within the agroforestry sector, where most research and practice tend to focus on provisioning services with tangible outputs such as crop yields [110]. Non-marketable ecosystem services, such as erosion control, pollination services, or cultural and heritage values, are typically not monetarised and hence are not included in the market value of the most profitable production system [111•].

Key Differences and Emphases

As elaborated upon in the earlier sections, the comparison of agroforestry and urban forestry also presents obvious differences. In this section, we will succinctly address them.

Agroforestry, encompassing a wide array of land-use systems, is predominantly production-orientated. Thus, the trees that grow within such systems are established for defined purposes which are largely production-related and ensure compatibility between individual components, whether directly (producing a product) or by delivering a service (improve soil fertility, moderate microclimate) that positively influences crop yield. Beyond this, trees in agroforestry might also be valued for other regulating and cultural services, which is sometimes even associated with incentives to landowners [112]. While agroforestry systems within a particular region may have similar designs and composition, they may vary more strongly between regions, where production foci shift with site and climatic conditions. In contrast, urban forestry, which might encompass green spaces such as allotments or vegetable gardens in the widest sense, is less production-driven than agroforestry. This leads to different priorities and different management strategies for each domain.

Further differences relate to risk assessment and safety aspects. These considerations are more prominent in urban forestry than in agroforestry, in part because many urban trees are on public or publicly accessible land frequented by people, while many agroforestry sites have limited public access. The perception of risk may further vary among user groups; for instance, a house owner might be more concerned regarding risk to property, whereas public authorities prioritise reductions of personal risk. This difference in risk perception is crucial given that liability, with its potential cost implications, steers management towards minimising risks. As safety and risk aversion are paramount in both public and private property, trees or large branches perceived as dangerous are often quickly removed. This erring on the side of caution is largely due to the challenges in evaluating tree safety. Technological innovations to aid tree safety inspectors may provide more reliable risk assessments but are costly and require training and skills. Such equipment is more affordable for larger companies and local governments (again reflecting a greater uptake in urban forestry situations) and is also more prevalent where risks are high.

A distinct geographical divide is evident in the research focus between agroforestry and urban forestry. While tropical agroforestry systems, which are more widespread, have garnered significant attention, temperate regions, particularly in Europe and North America, remain much less studied. In contrast, urban forestry research is predominantly carried out in the Global North, especially in Europe, North America, China, and Australia. The nature of research also varies with the setting. In urban forestry, collaborative methods such as co-creation approaches are common, often seen in urban labs involving public–private partnerships. However, as stakeholders, local communities might be incorporated later in the process. In agroforestry, a relatively new research field in countries of the Global North, there is a great potential to learn from these joint research processes and co-development of knowledge instead of leaning towards basic research and top-down approaches, as have been common in research on conventional agricultural production systems.

Research Gaps and Synergy Opportunities

A significant research gap persists in how we estimate the economic value of agroforestry and urban forest systems in terms of direct and indirect benefits (i.e., ecosystem services). Although the importance of specific services might be distinct, as we pointed out above, the underlying principle of providing multifunctional benefits remains consistent across both fields. Yet, existing tools and methodologies used to quantify and value these services and their integration into policy and market systems can differ and might not always capture their full significance. For example, the economic literature on the valuation of urban ecosystem services is still scarce compared to the extensive economic literature on forest ecosystem services. This may be in part because the ecosystem services of single or groups of trees were deemed less significant than that of large tracts of forests or because the ecosystem services are more difficult to quantify for individual trees when compared to well-defined contiguous forest areas. In addition, the trade-offs between different ecosystem services and disservices from trees may be more pronounced in urban settings [95]. Moreover, while tools such as payments for ecosystem services have been around for some time, valuation techniques specifically tailored to bridge the nuances of agricultural and urban contexts remain largely underexplored. For example, Alam et al. noted that economic analyses of non-market services of agroforestry and potential trade-offs between bundles of services were almost non-existent [113]. At the same time, Van Oijstaeijen et al. reported that economic valuation studies are rare among the many studies that consider the environmental and social benefits of urban green infrastructure [114]. Nonetheless, the increasing number of studies emerging, particularly focusing on human well-being and urban resilience, suggests that benefits that may currently be unquantified or under-quantified in the literature are expected to be identified and quantified. Methods and tools to translate the value of agroforestry and urban forestry services into monetary metrics include hedonic pricing, stated preferences, replacement costs, or avoided damage costs [113, 115]. For social and cultural values, more holistic approaches and methods may be required, including qualitative measures, constructed scales, and narration [115].

Central to this discussion is the theme of environmental justice, which raises essential questions about the beneficiaries of the services rendered by agroforestry and urban trees and those who might bear the brunt of any disservices [7, 9••]. Furthermore, there is an underexplored area concerning who gets to make decisions about these landscapes and whose perceptions and values are recognised or marginalised in these processes. This ties into broader questions of access, representation, and equity in the management and benefits of both agroforestry and urban systems. With agroforestry and urban forestry proximity to society, they offer a unique platform to investigate these questions of justice in tangible, lived-in environments. This can be achieved using transdisciplinary approaches and involving a plurality of actors and institutions who can co-create target knowledge jointly envisioning future systems and actionable knowledge on how to get there [116, 117].

At the same time, to estimate or predict ecosystem services accurately, site- and management-specific models based on widely spaced, single trees are required. As a first step, allometric equations for different tree species growing in different environments need to be developed to enable better quantification of biomass increment, carbon accumulation, transpiration, or shading effects. In urban forestry, the number of studies on the growth of urban trees is well-expanding rapidly and contributes to a mechanistic understanding of tree–environment interactions. The number of tree species incorporated in process-based tree models is also limited, and statistical models provide less reliable estimates for urban settings [11]. This is due to the complexity and heterogeneity of urban environments, which can result in a mismatch between model assumptions and the realities of urban landscapes. For instance, urban trees can be found at very contrasting growing sites across a city and depend greatly on the often changing conditions at a very small scale (e.g., shaded conditions in the vicinity of high buildings or management practices such as pruning and irrigation). Such variations make generalizations very difficult and can make models' estimates and predictions less accurate [11]. Here, intersections with forestry and agroforestry may be of particular interest. For example, the integration of joint information hubs and databases, accessible and developed by both agroforestry and urban forestry, such as GlobAllomeTree, TRY (global database of plant functional traits), or the Forestry Compendium (global compilation of knowledge on tree species and their attributes), could greatly foster more integration of research in these fields. This synergy would also promote the joint development and enhancement of models, for example, of interactions of single trees with their environment.

Another promising opportunity for synergies between agroforestry and urban forestry revolves around governance and participation, as the boundaries of the socio-ecological systems where ecosystem services provided by trees are used or demanded by society blur the traditional disciplinary boundaries. For example, the importance of community participation, knowledge co-production, and partnership development is evident and provides an opportunity to expand participatory-based research. Key areas of emphasis include enhancing community-driven decision-making, fostering co-production processes and knowledge exchange (e.g., among farmers and/or urban forestry practitioners). At the base are strong partnership frameworks that engage community members and other multisector stakeholders to ensure diverse perspectives and sustain their efforts. Providing residents and local stakeholders with meaningful opportunities for input in the identification and prioritisation of ecosystem services and disservices associated with urban–rural green infrastructure within their communities is of vital importance. Provision of these opportunities align with a broader trend towards democratising the development, management, and governance of public spaces [118, 119]. Social and environmental justice issues should be at the forefront of such research. Evaluating governance models that enhance sustainability and maximise biodiversity gains through effective co-production procedures in agroforestry and urban forestry practices is just as important and remains understudied [96, 120]. In addition, providing comprehensive economic models and frameworks to support the decision-making processes of local authorities and rural development agencies implementing agroforestry and urban forestry projects is another area where further research and development effort is needed.

Expanding on these synergies, the combined potential of agroforestry and urban forestry as contributors to local food supply through providing opportunities for local product sourcing, improving local food security and cultivating community connections through initiatives such as urban food forests and community orchards is a nascent research domain. At the interface of agroforestry and urban forestry, food forests, with their dense and biodiverse multi-strata setup, provide a substantial untapped potential to contribute to urban sustainability by increasing food security and landscape multifunctionality, from food to shade, education, and community building [121, 122]. Yet, for food forests to become sustainable and potentially be more widely adopted, comprehensive entrepreneurial ecosystems are needed with supporting structures. These structures include, amongst others, provide training opportunities to develop relevant farming and entrepreneurial know-how, financing and legal support to ease sufficient start-up funds and secure long-term access to suitable land, as well as favourable land use regulations [123].

Finally, the combined role of agroforestry and urban forestry as contributors to mosaic cultural landscapes, fostering economic, social, environmental and cultural well-being benefits across different land use configurations, from mitigating urban development impacts to reinforcing ecological connectivity, is yet another area demanding further research [124, 125].

Recommendations and Conclusions

How to Bring the Agroforestry and Urban Forestry Research Communities Together?

A first and important step to bring the different communities together is to create platforms and events that facilitate exchange. This paper is the outcome of a workshop held at the University of Freiburg, Germany, where research groups in agroforestry and urban forestry met to discuss synergies between the two fields. Such future joint events may be best organised by research and teaching institutions and organisations with agroforestry and urban forestry in their portfolio. For example, within the International Union of Forest Research Organizations (IUFRO), the working group on Agroforestry resides in the Division of Silviculture, whereas the working group on Urban Forestry sits under the Division of Social Aspects of Forests and Forestry, highlighting the current separation and potential to bring together distinctly different research communities on the above-mentioned issues of common interest. Another approach to facilitate exchange and collaboration is through networking the networks, which could also be in the form of joint events (conferences, workshops, excursions) or the creation of joint knowledge hubs or information platforms. Effective collaboration can be incentivised through targeted research project calls that address questions and approaches common to agroforestry and urban forestry. Several interdisciplinary inquiries involving both natural and social sciences have been previously highlighted. Non-academic stakeholders, including practitioners and policymakers, play an important role in both research communities and can serve as connectors in transdisciplinary processes. In addition to addressing disciplinary representation, it is important to recognise the need to foster collaboration among research groups around the world. While this review is based on a workshop involving German-based researchers, which shaped its primary focus on the Global North, we emphasise the importance of actively involving researchers and stakeholders from underrepresented regions in joint initiatives. This can help ensure a more inclusive and equitable exchange of knowledge and expertise. In the medium to long term, fostering collaboration can be further advanced by establishing joint research groups within interdisciplinary research centres and developing integrated curricula. Such curricula would offer students courses spanning across both fields, for example, on the inventory of trees outside forests, the provision and valuation of ecosystem services, biodiversity conservation in agro- and urban forests, the role of trees for human well-being, or the management and governance of green infrastructure.

How can we Achieve Greater Synergies between the Agroforestry and Urban Forestry Research Communities?

One common aspect that may be regarded as a hurdle in both agroforestry and urban forestry is the preponderance of case studies. To facilitate generalisation beyond particular case study settings, unifying methods, protocols, research designs, concepts, and theories becomes increasingly important and necessary. By examining urban–rural gradients, we can spearhead collaborative research spanning urban, peri-urban, and rural landscapes and across distinct climate regions, from continental to global scales. This broader perspective would not only greatly improve our understanding of socio-ecological systems where both fields are embedded but also help develop and implement research approaches that are both comprehensive and integrative, cutting across domains and disciplines such as ecology, forestry, social sciences, governance, or economics. We do not intend to suggest that theoretical and methodological approaches should blindly and wholly converge across disciplines, which would undermine the value of bringing them together, but that such research should be inherently inter- and transdisciplinary to frame agroforestry and urban forestry as two interrelated fields of science and practice in urban–rural landscapes.

Next Steps and Future Perspectives

Drawing from our review, we outline five research themes that could guide future research efforts to bridge cross-disciplinary gaps across agroforestry and urban forestry:

1. Valuation of ecosystem services: *How might assessment approaches and methods go beyond monetary valuation and cover a broader suite of ecosystem services, in particular cultural services, and incorporating these in easy-to-use, easy-to-understand, but rigorous tools for valuing ecosystem services?*

2. Landscapes, cultural values, and biodiversity: *How can we design agroforestry and urban forestry systems that foster biodiversity conservation while meeting human needs in increasingly anthropogenic landscapes? How do agroforestry and urban forestry practices interactively shape, retain, or transform local cultural landscapes, and what implications might these shifts have for societal values and sense of place?*

3. Tree resilience and suitability*: How can insights from agroforestry and urban forestry optimise the selection of climate-resilient species and planting techniques? How can pest and disease management strategies be collaboratively developed by drawing from the successes, mistakes and failures from both fields while continuously integrating new knowledge in decision–making as it becomes available?*

4. Governance and community engagement: *What are best practices for fostering genuine community participation, co-production, and partnerships, especially in contexts with diverse stakeholder interests and regions undergoing rapid urbanisation or agricultural intensification? Which governance models are suited to reward provision of non-marketable ecosystem services and enhance effective co-production procedures in agroforestry and urban forestry practices?*

5. ***Environmental justice and equity:*** *How can we effectively integrate environmental justice principles into agroforestry and urban forestry practices, ensuring equitable distribution of benefits and burdens? How can we design studies that rigorously examine the environmental justice implications of new green infrastructure networks in urban and rural landscapes?*

Addressing these questions will bridge existing research gaps while promoting interdisciplinary collaborations between agroforestry and urban forestry research foci.

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Declarations

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- • Of importance
- •• Of major importance

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