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The ties that bind: how trees can enhance agroecological transitions

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Abstract Agricultural systems have a long history of responding to various economic and sociopolitical forces, including supply and demand, political preferences and power inequalities. Our current food system continues to respond to contemporary forces with a call for sustainable transformations in the face of increased pressure and competition over resources, severe consequences of climatic change, widespread degradation of land and water resources, and the accelerating loss of biodiversity. Both agroforestry and agroecology have evolved as approaches to agricultural management that focus on the application of ecological principles to achieve sustainable agriculture. Agroecological principles are designed to engage with the entire agrifood system, for instance identifying broad participation and involving a diversity of actors and knowledge systems. Agroecological approaches to production have significant historical and contemporary links to agroforestry approaches, but not all agroecology involves trees and not all agroforestry is in line with agroecological principles. Drawing on (1) a literature review, (2) case studies on the agroforestry and agroecology nexus presented at the 5th World Congress on Agroforestry (WCA), and (3) audience responses to statements presented at the Congress, we explore the two main ways that agroforestry and agroecology come together: agroforestry that encompasses agroecological principles and agroecological transitions that involve trees. We review the status of agroecology, the functions specific to agroforestry that can enhance the achievement of agroecological outcomes, the tensions between simple agroforestry systems and agroecology, and the larger potential of multidimensional sustainability of agroforestry with the inclusion of agroecological principles. We also present the level of agreement on four key statements about the agroforestry-agroecology nexus enumerated at the WCA. It is clear that some features of agroforestry operationalize agroecological principles that aim to transition away from monocultures and the use of environmentally disruptive agrochemicals, and toward strengthening biodiversity and resilience. Yet, much remains to be done to enhance agroecological principles more fully in framing agroforestry practices and to incorporate trees within agroecological practices. Pathways to strengthen the nexus of agroforestry and agroecology are proposed, which focus on the role of trees in multifunctionality and resilience and using agroecological principles related to knowledge sharing and equity to enrich agroforestry practices.

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Introduction

The management of agricultural systems has a long history of responding to various economic, political and social forces, including supply and demand, political preferences and power inequalities, and to increasing environmental change, which continue to shape calls for transformation of agricultural and food systems today (Archer et al. 2008; Ingram 2011; Caron et al. 2018). Currently, agricultural systems face amplified pressure and competition over renewable resources, as well as contribute to, and face increasingly severe consequences from, climatic changes and the loss of biodiversity (IPBES 2019; IPCC 2019). Agroecological principles have emerged as explicit statements that can guide agricultural change to achieve sustainable agriculture, as highlighted in the Committee on World Food Security, High Level Panel of Experts report (HLPE 2019). These principles incorporate the 10 elements of agroecology approved by the 194 Member Nations of the Food and Agriculture Organizations of the United Nations to guide its vision on agroecology (FAO 2019a, b; Wezel et al. 2020). Agroecology was recently proposed as a critical management approach adopted by the Kunming-Montreal Global Biodiversity Framework to restore biodiversity in agriculture fields (CBD 2022), and agroecological principles and practices were endorsed as key contributors to adapting agrifood systems to climate change in the Sixth Assessment of the IPCC (IPCC 2022). It was also recognized that tackling such transformations in agriculture requires a long-term perspective and holistic approach, hence a coalition for food systems transformation with agroecology was a prominent outcome of the UN Food Systems Summit (Sinclair 2020). The agroecology coalition declaration highlights the implementation of policy recommendations of the Committee on World Food Security on agroecological and other innovative approaches, guided by the 13 principles set out by the high level panel of experts (CFS 2021).

Cumulatively, these documents and deliberations reinforce that agroecology involves the application of ecological principles to agricultural research and practice, as well as an approach that engages the entire agrifood system, meeting wellbeing needs while remaining within planetary boundaries (O'Neill et al. 2018; DeClerck et al. 2023), and that includes participation of a range of actors and knowledge systems (Isaac et al. 2018; Blesh et al. 2023). Importantly, civil society organizations and grassroot movements such as La Via Campesina, are actively engaging with agroecological practices on multiple scales in response to deficiencies with the currently dominant industrial agrifood paradigm (Rosset and Martínez-Torres 2012; Méndez et al. 2013; Montenegro de Wit and Iles 2016). La Via Campesina has successfully advocated for and influenced policies supportive of agroecological transitions across Asia, the Americas and Europe. For instance, in Cuba, efforts to foster farmer-to-farmer exchanges have successfully promoted agroecological practices through innovative networks and education systems, led by the National Association of Small Farmers (Rosset et al. 2011). In India, the Andhra Pradesh Community Natural Farming (APCNF) movement has spread agroecological practices to multiple Indian states as a grassroots response to the perceived negative impacts of high input agriculture (Duddigan et al. 2022).

The evolution of farmer-led agroecological practices and the science-policy landscape around agroecology are evidenced in the central role of agroecology in global agreements and resolutions referred to above as well as the operationalization of agroecology principles that guide agroecological transitions. This evolution of agroecology has direct implications for evaluating the relationships between an agroecological approach to agriculture and other forms of diversifying agricultural systems, including agroforestry. In particular, agroforestry, or the addition of trees to annual crop and livestock systems, can offer various beneficial long term outcomes, but not all agroforestry practices are agroecological. While some agroforestry practices, especially in the tropics, center on achieving socioecological sustainability and equity (Rasmussen et al. 2024; Leakey 2020), others, often in temperate contexts, generate environmentally negative outcomes from capital intensive agribusiness (Ollinaho and Kröger 2021). In this paper we explore the relationships between agroecological principles and agroforestry practices, indicating how trees can enhance agroecological transitions and

how the application of agroecological principles to agroforestry can enhance environmental and social outcomes.

Ecological functions of agroforestry practices that contribute to agroecological outcomes

Agroforestry in tropical contexts has been defined in agroecological terms for over a quarter of a century (Leakey 1996) and was generalised as an 'interdisciplinary approach to land use, involving woody perennials, herbaceous plants, livestock and people, and their interactions with one another in farming and forest systems, that embraces an ecosystem focus including stability, sustainability and equitability, in addition to productivity, with social as well as ecological and economic aspects implied' (Sinclair 1999). This approach, that is agroecological, was distinguished from a set of agroforestry practices that may be more or less agroecological depending on how they are managed, and manifest at a range of scales, from the field to the landscape (Sinclair 2004). Agroforestry has been characterised as evolving through a series of paradigms, starting with a largely agronomic focus in the 1980s and increasingly embracing landscape scales and overall land use governance and policy (Van Noordwijk et al. 2019a, b). This mirrors the expansion of the scope of agroecological science over the past half century, from a focus on agroecosystem management to embracing whole food system transformation (Wezel et al. 2020).

The addition of trees to annual cropping and livestock systems can offer various beneficial long term effects, whether they are agroecological or not, a fact that has underpinned agroforestry research agendas (Anderson and Sinclair 1993). The integration of trees into cropping systems addresses many short and long term ecological constraints associated with nutrient cycling (Ilstedt et al. 2016; Isaac and Borden 2019; Barrios et al. 2023;), microclimate modification (Van Noordwijk et al. 2021; Gagliardi et al. 2020); a seasonal fodder availability (Cajas-Giron and Sinclair 2001) and management of pests, diseases and weeds (Pumariño et al. 2015; Avelino et al. 2023; Harrison et al. 2019). Distinctive structural and functional characteristics of trees, relative to crops, remains a cornerstone of ecological functions in agroforestry practices. The optimization of such characteristics between tree and crop for balanced and non-competitive interactions has been the basis of innumerable studies, with recent meta-analysis and systematic syntheses clearly depicting benefits from agroforestry in comparison to monoculture (Europe: Torralba et al. 2016; Tropics: Muchane et al. 2020; Global: Kim and Isaac 2022).

Agroforestry practices contribute to operationalising many of the HLPE (2019) agroecological principles (Wezel et al. 2020), including: biodiversity, soil health, animal health and welfare, input reduction, recycling, and synergy. The addition of trees to annual crops amplifies how each of these principles can be achieved beyond what could be expected with mixtures of annual crops. Enhancing biodiversity in agricultural systems is a well-articulated objective of agroecological practices and includes diversity of species, of ecological functions and of knowledge held by different actors (Barrios et al. 2020). "Associated biodiversity" (sensu Kremen et al. 2012; FAO 2019b) in agricultural landscapes can be, and often is associated with trees (e.g. hedgerows, shelterbelts, small woodlots, riparian systems). Also common is "targeted" tree-based biodiversity. In some of the most prominent agroforestry practices worldwide, perennial tree crops such as coffee and cocoa are combined with companion trees as a diversification strategy (Cerdan et al. 2012; Smith Dumont et al. 2014; Isaac et al. 2024), while trees are also integrated with staple food crops (Rodenburg et al. 2022) and in silvopastoral systems (Harvey et al. 2011). The domestication and commercialisation of indigenous tree species has been the cornerstone of widespread initiatives to develop more productive and climate resilient food production systems across Africa over the last three decades (Leakey et al 2022). Intentional integration of specific tree species may augment the agroecological outcomes from these agroforestry practices, for instance, recent research on farmer managed natural regeneration of trees in crop fields in West Africa, showed how tree functional diversity, and hence economic value, could be enhanced through enrichment planting where valuable species did not regenerate naturally (Lohbeck et al. 2020). Intercropping of annuals, in particular cereals and legumes, has been a tried and trusted method to derive benefits of increasing diversity on key facilitative interactions (Jensen et al. 2020). Recent metanalyses of long-term trials across Africa and Europe show higher yields

with greater crop diversity, with legumes substituting for inorganic nitrogen additions where they are included in the crop mix (Maclaren et al. 2022) and the substitution effect of legume rotations for inorganic nitrogen applications to a range of staple crops was confirmed in a global metanalysis (Zhao et al. 2022). Woody perennials in agricultural landscapes can also offer a suite of ecosystem services beyond those related to overyielding and nitrogen provision in intercropping, such as pollination, biological control of pests and diseases, and soil health (Barrios et al. 2023).

Trees in agricultural fields provide three distinct functions not found in annual cropping systems that contribute to achieving soil health; animal health and welfare; input reduction, recycling and synergy: (1) trees contribute to litter diversity, and via decomposition, to soil organic matter fluxes (Barrios and Cobo 2004; Buchanan et al. 2024), (2) trees create microclimates that influence herbaceous communities (Archibald et al. 2022) and soil communities and subsequent functions (Munroe et al. 2015; Kamau et al. 2017; Dierks et al. 2021; Schmidt et al. 2022), and (3) trees have deeper roots that augment nutrient cycling, synchronous nutrient uptake and a secondary source of root exudate inputs (Borden et al. 2019; Van Noordwijk et al. 2019a, b). These functions provide substantial opportunities to replace or complement chemical fertilizer inputs with biological processes, offering direct or indirect sources of nutrients for crop uptake, reducing the reliance on external inputs and enhancing efficiency and recycling (Barrios et al. 2012a). These distinct properties and functions of trees can also enhance soil water availability, soil organic matter accumulation, shading and deep soil water resources (Link et al. 2015), reducing the reliance on irrigation and contributing to resilience. In many contexts smallholder farmers have been found to have detailed knowledge about how tree attributes of different species affect these functions (Smith et al. 2019). The structural complexity of trees in agricultural landscapes can also contribute to integrated weed, pest and disease management, either directly (barriers; Gagliardi et al. 2021) or indirectly (microclimate modifications that disrupt life cycles; Avelino et al. 2023), creating synergies. Importantly, these synergies are not small in scale as trees are often larger than annuals, thus contributing a larger scope of change over a longer timescale, consequently enabling more efficient use of resources and the creation of niches and habitats that will benefit the agroecosystem as a whole and contribute to the conservation of biodiversity (Harvey et al. 2006; Barrios et al. 2018).

Novel agroecological outcomes from agroforestry practices

Three other agroecological outcomes are achieved by using trees to diversify farms: enhanced crop portfolios especially through the integration of fruit trees; land tenure arrangements that are conducive to tree planting, and land restoration. Many trees used in agroforestry practices produce fruit, medicine, timber and other non-timber forest products (Sears et al. 2014) as documented in the use of trees to diversify cocoa (Sauvadet et al. 2020) and coffee (Rigal et al. 2022) production systems. By simultaneously expanding the crop and product portfolio with the addition of ecological function, this supplemental source of nutrition, materials, energy and income in agroforestry practices can contribute to achieving key agroecological principles of economic diversification, as well as contributing to social values and diets (McMullin et al. 2019; Kerr et al. 2022). A diverse product base, coupled with putting a value on ecosystem services generated from agroforestry, has been put forward as the foundation of a multifunctional agricultural approach to food system transformation in Africa (Leakey et al. 2021). Trees also enhance the scope for synergy (managing interactions amongst components) because their structural and functional complementarity with other components enable more diverse sources of production and income often including high value products. By-products from trees may serve as an energy source, or as a substrate for production of associated high value products such as mushrooms (Bandara et al. 2021). Agroforestry thus helps connect farmers to new value-chains and other sectors through, for example, forestry and NTFPs, bringing not only new products, but also new ideas, patterns and processes from these sectors that can inspire farmers. Where farmers have been involved in deciding about trees to incorporate on their farms they have often opted for a far greater diversity of species, in a wider range of planting niches, than previously recognised by research and extension services

(Derero et al. 2021). This illustrates the central agroecological principle of co-creation and sharing of knowledge. Agroforestry may also revitalize landscapes, even when implemented at the plot level, to create new opportunities for recreation and tourism.

The longer lifespan of trees than annual crops may encourage longer-term commitment to a parcel of land with some positive benefits, notably, security of land tenure. While the relationship between land tenure, tree tenure and adopting agroforestry differs with context, there is evidence that trees may enhance a farmer's tenure on land (Rao et al. 2016) although they may also attract competing claims on the trees themselves and the land they are on from forest authorities (Chomba et al. 2020). While land and tree tenure issues and the secure access to land and rights has long been a deterrent for the adoption of agroforestry, opportunities to enhance land tenure claims through the integration of such perennialization remain, particularly if customary and statutory tenure systems are aligned (Borelli et al. 2019; FAO 2023). Seeking such tenure rights and coordination involves participation of multiple stakeholders, opening the door for women and landless people to engage with agroforestry. These actions directly relate to the agroecological principles of participation, fairness and land and natural resource governance.

With the integration of trees, the accumulation of soil nutrients and the belowground processes of root stratification and nutrient capture are realized over time. Trees are long-term; while tree management requires a high level of commitment, they also provide a level of beneficial consequences over the long-term. Multiple studies show that agroforestry systems can be effective in restoring degraded lands (van Noordwijk et al. 2020; Biswas et al. 2022). For instance, agroforestry can enhance soil erosion control, soil fertility, water availability and water quality (Sharma et al. 2007; Muchane et al. 2020). There is a large potential in how agroforestry practices can achieve agricultural land restoration to enhance the transition to successful agroecological practices and rebuilding landscapes. This is a crucial point where agroecological and agroforestry practices meet and become complementary: while agroecological practices often have often short-term impacts that stabilize after a few years, the addition of trees may add long-term effects, enhancing overall resilience and transformational capacity (Sinclair et al. 2019).

Knowledge production and dissemination pathways

A foundational principle of agroecology is the co-creation of knowledge (Wezel et al. 2020) and local knowledge has had a critical influence on how agroforestry has developed, being a relatively young science but an ancient practice (Sinclair and Walker 1999). Through this process, equitable and blended knowledges, including those from often under-represented groups in decision making processes, is possible (Méndez et al. 2013; Kuria et al. 2019); further, it creates a valuable space for south-south knowledge-sharing and learning (Barrios et al. 2006). Specifically, these co-creation processes give farmers (and especially women, youth and indigenous people) more freedom and decision-making power over what and how knowledge is produced and shared (Eastwood et al. 2022). This place-based approach within a translocal context, encourages locally adapted, co-created practices (Barrios et al. 2012b). The adoption of agroforestry is shaped by influential macro- and micro-forces, from institutions and the State, to agricultural cooperatives, markets, and farmer-to-farmer networks (Bacon et al. 2012; Isakson 2014; Isaac et al. 2021; Blesh et al. 2023). Although the relationships between different stakeholders in agroforestry policy, finance, research, advice, and practice are often characterised by economic, moral, or political inequities, both agroforestry and agroecology science and practice have been associated with widening 'to whom' and 'from whom' knowledge is created and shared. Agroecology as a science, a set of practices and a series of social movements has been more consistently explicit about the political economy of food systems than has been evident in the agroforestry literature (Anderson et al. 2021).

Opportunities for agroecological transitions to draw on agroforestry's decades-long engagement with agricultural extension are not fully realized. While agricultural extension remains largely focussed on industrial models of production, agroforestry has been at the core of extension training programs, particularly in the Global South (Kiptot et al. 2016) including development of the 'rural resource centre' concept in West Africa that combines knowledge exchange with training and market linkages, through a community-based approach (Degrande et al 2015). Co-creation and sharing of knowledge is a key

principle of agroecology, emphasising a more bottom up approach than classic, transfer of technology methods, familiar from agricultural extension (Cook et al. 2021). Developing practical ways to implement co-creation by supporting local innovation at scale, through farmer to farmer spread and recent developments in citizen science could draw on the years of experience in knowledge-intensive extension methods that have been used to promote agroforestry (Sinclair 2017).

Agroecological transitions to sustainable food systems: the role of agroforestry

Agroforestry can contribute substantially to a biodiversity-nutrition-climate change nexus (Barrios et al. 2020; FAO 2023). Agroforestry has well established mechanisms to mitigate climate change impacts at the plant, field and landscape scale (Rosenstock et al. 2019; Van Noordwijk et al 2021). Simultaneously, agroforestry can contribute to nutrition through rural food security (Jemal et al. 2018) and to the five pillars of food and nutrition security through food availability (Mbow et al. 2014). This is achieved through direct pathways (food production from integrated perennial components; Sarvade et al. 2014) or indirect pathways (production enhancement with perennialization; Toensmeier et al. 2020). However, it is also well documented that agroforestry can weaken local food sources if a move to more commodity-oriented agroforestry is prominent (Khoury et al. 2014). Smallholder subsistence farming may be reduced or eliminated completely when commodity crop markets, materials and extension are active in the agricultural landscape. Agroforestry may have lessons to learn from agroecological initiatives that attempt to embrace the entire food system, in a holistic way, by focusing more on the governance of this food system, the power dynamics between its different actors—farmers, traders, institutions, governments—and the sharing of risks and benefits between them (Anderson and Maughan 2021).

Reconciling scale along agroforestry gradients

The scales at which agroforestry outcomes are realized can vary substantially. There are multiple types of agroforestry with disparate desired outcomes; while some agroforestry systems have high densities of diversified trees, others are identified only through basic additions of shade trees at low density and low diversity (Ollinaho and Kroger 2021). The origins of an agroforestry system can have substantial effects on the level of complexity (Nijmeijer et al. 2019). Agroforests derived from forests, while contributing to forest degradation, also offer more complex structure and function and higher probability of offering agroecological outcomes. In contrast, trees added to monocultures are simple in form and function and may contribute minimally to sustainability and equity. Many agroforestry systems are indeed nominal, falling short on achieving agroecological outcomes. For instance, the reason why shelterbelts and some intercropping agroforestry systems have rows of trees spaced widely apart is often to allow the passage of large farm machinery for the purpose of maintaining intensive field crops with little change in farm equipment or crop management. The deployment of agroforestry systems in these contexts is generally capital intensive and they can even be presented as new "technical packages" to be integrated into the agro-industrial production model in order to ensure its sustainability (Kolinjivadi et al. 2019), or even to launch a new trend of ecological diversification without challenging this model. However, while introducing trees in rows into a monoculture system may seem like a very small change, it can still be the first step in integrating agroecology principles (Rue 2020). However, Mupepele et al. (2021) suggest that landscape context and land-use history are fundamental to achieving beneficial outcomes of agroforestry, even more so than the agroforestry practice itself, indicating the clear need to go beyond classification and consider historical and contemporary context.

The future of the agroforestry and agroecology nexus

In July 2022, the 5th World Congress on Agroforestry was held in Quebec City, Quebec, Canada. Throughout the presentations in a session "Agroforestry as a pillar in agroecology" and a panel on "Agroforestry-agroecology nexus", there was an evident call for a transformation at all scales in the face of increased pressure over resources, increasingly

severe consequences of climatic changes and the loss of biodiversity, but also in the face of reduced farmer autonomy and consolidation of power. Across the talks on agroecology and agroforestry, clear examples of where agroforestry and agroecological principles align were evident, for instance, in urban agroecology, in forest farms, in tree diversification in perennial cropping systems, all with multi-dimensional outcomes as a common signature. This opportunity to discuss the implicit yet undefined relationship between agroforestry and agroecology was a continuation of the 4th World Congress on Agroforestry, where a session on "Agroforestry and agroecology: opportunities and challenges" also explored this important nexus (Barrios et al. 2020).

In the 2022 Congress, two axes of the agroforestry and agroecology nexus emerged: agroforestry farms that draw on agroecological principles and agroecological farms that transition toward tree integration. Arguably, agroforestry may or may not align with or embrace principles of agroecology versus a productionist model. As argued by Ollinaho and Kroger (2021), there are multiple types of agroforestry with disparate desired outcomes. Some agroforestry practices aim for basic additions of shade trees at low density and low diversity. While these systems may function optimally with regard to shade levels, inputs and outputs, they do not produce other agroecological outcomes (e.g. social values and diets, fairness, participation). Would the layering of agroecological principles on these agroforestry practices enhance their multi-dimensional outcomes and their sustainability? Can these agri-business-oriented, simplistic agroforestry practices draw on agroecology, in particular, principles that align with more transformational approaches to production, moving these practices beyond farm level techniques towards playing a more substantial role in the transformation of global food systems?

Emerging from talks throughout the Congress is the clear momentum to reframe this tenet of agroforestry to understand how trees increase the opportunity to operationalise agroecological principles and achieve agroecological outcomes. This led to four summary statements posed to the audience of the closing plenary of the Congress: (S1) Not all agroforestry is agroecology and not all agroecology is agroforestry; (S2) Trees increase opportunities to realize agroecological outcomes; (S3) Co-creation and sharing of knowledge is necessary and requires fundamental change in how research, education and advisory services are organized; (S4) There is limited evidence about what options work where and for whom, and we lack metrics that capture holistic impacts of agroecology with trees. Among our respondents (~170 individuals ranging from agroforestry experts to farmers to government to industry to students; Fig. 1), agreement was high with the first three statements, with the majority of the audience in strong support with the statements (S1: 78%, S2: 90%, S3: 93%). The audience response to the final statement in regards to the metrics and availability of evidence showed less agreement although still a majority of respondents, perhaps because two issues were conflated (S4: 62%).

What emerged from this audience engagement exercise is that there was critical mass for agroforestry to transition from largely focusing on yield to more fully encompass the multi-dimensionality of outcomes from integrating trees with agriculture, aiming to support local economies while strengthening biodiversity, resilience, and social justice (Méndez et al. 2013; Isaac et al. 2018; Wezel et al. 2020). Yet, the expansion of the agroecology movement faces heterogeneous perspectives and ideologies, combined with social, cultural, political, and economic challenges (Khadse et al. 2017). For instance, in the Netherlands, the government policies aimed at reducing nitrogen emissions which impact the expansion of the dairy, pig, and poultry farms (Stokstad 2019) have been met with protests from farmers who feel that these policies do not take into consideration the economic viability and the sustainability initiatives that they have already undertaken (Stokstad 2019; Aarts and Leeuwis 2023). Similarly, adopting agroecology is contentious due to the large-scale industrial agriculture systems which are deeply integrated with agribusiness interests, and skepticism towards adopting agroecological practices loom large (Giraldo and Rosset 2018). In sub-Saharan Africa, the implementation of agroforestry practices is highlighted as a path forward to address pressing challenges such as food insecurity and climate change impacts (Leakey 2020). Yet, adopting these practices may impose greater labour demands causing exploitation of small-scale farmers who may work longer hours for lesser payment (Bottazzi and Boillat 2021).

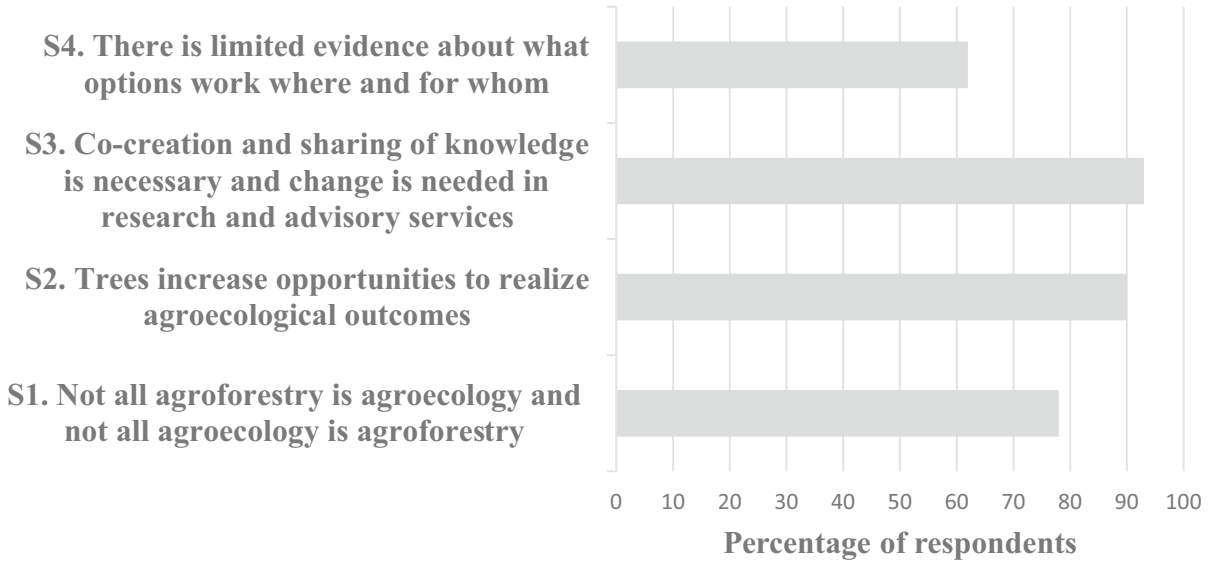

Fig. 1 Summary statements and responses from the World Congress on Agroforestry, July 2022, Quebec City, Canada ($n = 170$)

Even with these documented social, political and economic barriers to adopting agroecological principles in agroforestry practices, the grassroots, bottom up approaches and social movements are, and remain, critical components of effective transition pathways (Rosset and Martínez-Torres 2012). Multiple examples exist of effect transitions to agroforestry systems with agroecological principles. The CGIAR Forests, Trees, and Agroforestry programme, engaged with policy-driven initiatives through national workshops and actively engaging with communities to identify needs and address barriers, employing agroforestry practices to enhance socio-economic conditions and foster economic development in sub-Saharan Africa (Bernard et al. 2019). Similarly, in Madhya Pradesh, India, the integration of trees into agroecosystems is being advanced by local farmer initiatives and government schemes that encourage tree management on private lands to maintain beneficial trees for both livelihood and biodiversity. These schemes and practices are further enhanced by strong support from educational and research institutions who help in actively imparting training and knowledge to promote sustainable agroforestry models across the region (Bijalwan et al. 2019). In all, these examples help shape the future nexus of agroecological and agroforestry approaches to sustainable agriculture.

Pathways forward

It is well-established that trees in agricultural fields have a functional, as well as socio-political, role. How can agroecological farms draw on agroforestry functions to meet key principles beyond those which can be provided by annual crops or intensive livestock rearing alone? And how can agroecology facilitate multiple outcomes (nutrition and healthy diets, inclusion and social engagement) within agroforestry practices? We propose pathways to enhance the role of trees in agroecological farms to achieve a suite of agroecological principles and pathways to move from simplistic agroforestry practices toward ecologically diverse and socially just agroecosystems guided by key agroecological principles (Fig. 2).

As described above, trees offer multifunctionality to agroforestry practices that underpin ecosystem dynamics that are essential to replace external inputs with biological processes. While encouragement of biological processes to enhance nutrient and water availability for crop uptake can be accomplished via intercropping of annuals and organic amendments, appropriate trees can accelerate agroecological outcomes because of their size, longevity and ecological combining ability with annual crops. Key drivers include organic input diversity, structural complexity, microclimate creation and deep soil exploration.

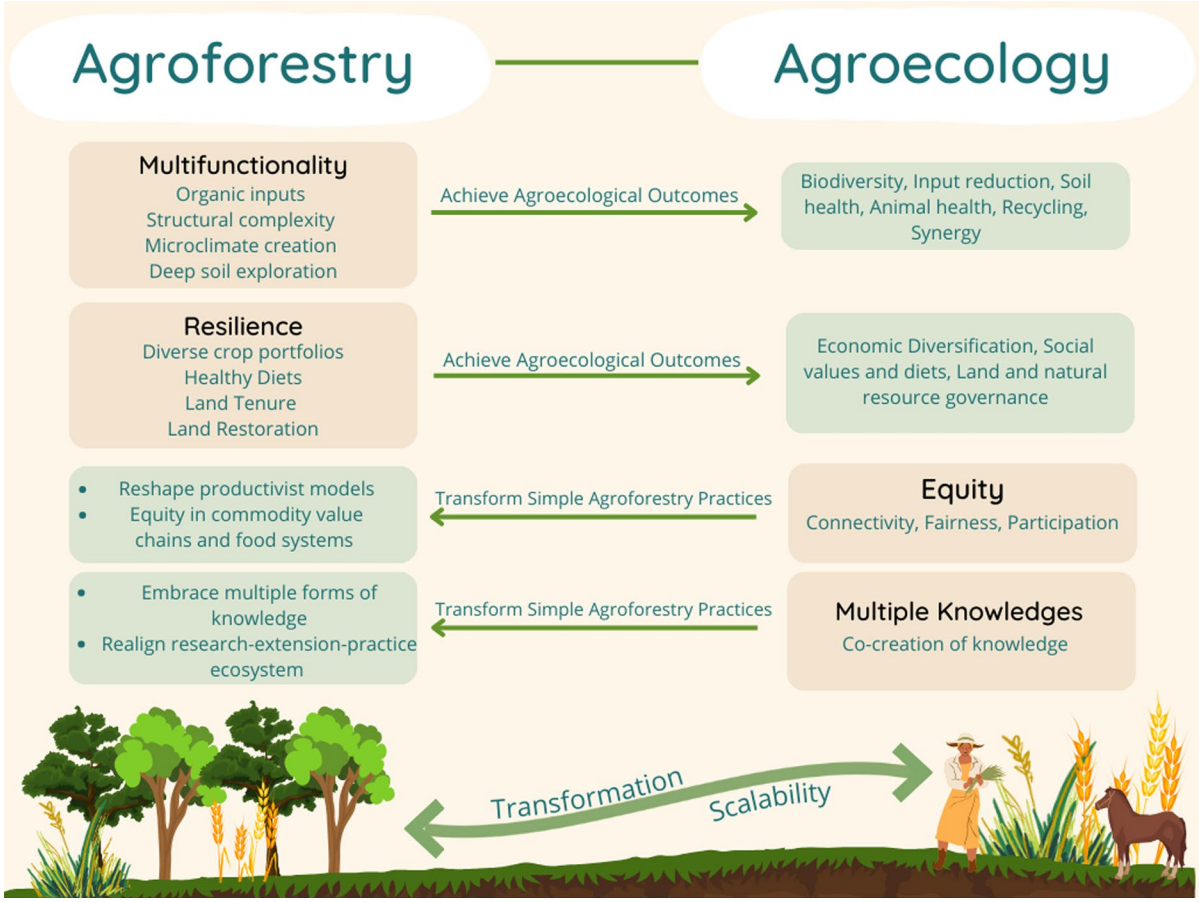

Fig. 2 Pathways between agroforestry and agroecology. Agroforestry provides enhanced multifunctionality and resilience to agroecological farms, achieving a suite of agroecological outcomes and agroecological principles contribute to reshaping knowledge sharing and centering equity in agroforestry practices. Agroforestry contributes methods of scalability to agroecological systems and agroecological principles enhance transformational capacity of agroforestry

While competition between species occurs, decades of advancement in optimal plant-plant interactions has provided the basis for facilitative, or, at least, non-competitive interactions, as well as shade and fodder for livestock. This can provide the basis to enhance multiple agroecological principles including biodiversity, soil and animal health, nutrient cycles, input reduction and synergy.

The integration of trees can enhance resilience. Crop portfolios are diversified with the integration of trees contributing to healthy diets, and also providing long-term production benefits such as timber. Trees can enhance land tenure by delineating ownership in regions with less secure land tenure arrangements. Trees may also offer considerable restoration potential, contributing to soil aggregation and stability to avoid land degradation. These attributes of trees contribute to achieving agroecological principles of economic diversification, social and culturally appropriate diets and responsible natural resource governance.

Some agroforestry developments, on the other hand, have focused on trying to meet the goals of productionist agriculture without carving out a socially-just path (see "agrobizforestry", Ollinaho and Kroger 2021), leading to large scale simple agroforestry practices. The implementation of agroforestry practices, and the push for agroforestry policy, can be served by drawing on decades of social movements formed around agroecology and the potential of agroecology to create equity in commodity value chains and food systems, enhancing agroecological principles of connectivity (especially amongst producers and

consumers), fairness and participation, to reshape productionist models. Agroforestry has long drawn on the history of multiple forms of knowledge, embodied in the agroecological principle of co-creation and sharing of knowledge. While agroforestry systems often combine local knowledge and scientific knowledge, particularly in the global South there can be a top down approach in many agroforestry contexts, given ties to export and commodity markets that may dictate production models. The agroforestry research-extension-practice ecosystem could be usefully realigned in light of agroecological principles, shifting agroforestry outreach from extension to advisory services, fostering co-creation and knowledge sharing and embracing multiple forms of knowledge. This is particularly important because there are many different agroforestry options, in terms of tree species and how they might be managed with what other crop and livestock components, suitable for the heterogenous contexts of smallholder farmers (Sinclair and Coe 2019). This is most efficiently addressed through participatory approaches but it is necessary for them to operate at scale; that is, with millions of farmers (Coe et al. 2014).

The nexus of agroecology and agroforestry can address the long standing issue of scalability of agroecology and agroforestry (Sachet et al. 2021). Not all agroforestry systems are equal, yet these systems hold a large potential given the land cover under agroforestry (Zomer et al. 2016), including perennial tree-crops, annual cropping systems, and pastoral systems. Integrating an agroforestry canon into agroecology futures can shape the scalability of agroecology. Many agroforestry practices operate at a large scale, and some are commodity-based and export-oriented but still embrace incremental diversification. Agroecological transitions can incorporate advances made in agroforestry that re-organize large production systems from simplistic models to more complex systems.

The nexus of agroecology and agroforestry can stimulate transformation particularly when supported by tools facilitating integrated policy design (Place et al. 2022; FAO 2023). Trees offer various beneficial long-term effects not found in annual cropping systems, even if agroecological, a fact that has underpinned agroforestry research agendas to provide the evidence of successful agroforestry practices. Some features of agroforestry operationalise agroecological principles that aim to transition away from a focus on yield maximization with synthetic inputs, to ones that support local economies while strengthening biodiversity. These pathways include the role of trees in multifunctionality and resilience in agroecological systems. Agroecological principles relating to knowledge sharing and equity, if applied to agroforestry practices, may offer new pathways to reshape simpler agroforestry practices so that they contribute more deeply to developing sustainable agricultural and food systems.

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Declarations

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