Land Use Policy 156 (2025) 107620

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Polycultural food production in temperate woodlands: Multifactorial benefits and political-economic barriers

Steffen Hirth [a,b,*], Ivan Drlička [a], Matthew Paterson [a], Paul W. Thomas [c,d]

[a] Sustainable Consumption Institute, Alliance Manchester Business School, University of Manchester, UK
[b] Sustainability Research Institute, School of Earth and Environment, University of Leeds, UK
[c] Faculty of Natural Sciences, University of Stirling, UK
[d] Mycorrhizal Systems Ltd., Lancashire PR25 2SD, UK

ARTICLE INFO

Keywords:
Agroforestry
Forest gardening
Carbon sequestration
Biodiversity conservation
Food production
Food security
Ecosystem services
Political economy

ABSTRACT

Given the need to produce sufficient food while meeting net zero targets and protecting biodiversity, there is renewed impetus to expand woodland-based food systems in the Global North, including agroforestry and forest gardening. Typically, however, agriculture, forestry, and conservation are separated spatially, as well as conceptually, and afforestation policies insufficiently consider the integration of edibles into forest management, or woody species into agriculture. We review the scientific evidence on the benefits of woodland-based food systems in temperate climates in relation to four aspects: climate change mitigation and adaptation, biodiversity restoration, food production, and social benefits. Findings suggest high potential of enhancing ecological and cultural ecosystem services through woody polyculture. However, an analysis of barriers and enablers of woodland-based food systems also shows that the productivist and monocultural approaches dominating agriculture in and for the Global North are a barrier to transforming the agri-food system towards more complex polycultural systems with woody species. Therefore, we discuss the conditions for making woody polyculture viable, upscaling these systems, and yielding multifactorial benefits at large-scale in relation to the wider political economy. We conclude that significant transformational rather than incremental shifts are needed, most notably regarding the practical and financial valuation of ecosystem services.

1. Introduction

This paper focuses on woodland-based food systems – the organisation and development of food production systems within forest settings. Agroforestry, a subvariant of these systems, that integrates woody species and cultivated crops or livestock has long had attention among agricultural specialists as a particular sort of agricultural system suitable in specific social and ecological contexts. But it has come to the fore more broadly in recent years for several intertwined reasons. These include the shift to net zero in climate change strategies, the centrality of forests and food systems to strategies focused on biodiversity enhancement, the ongoing crises of agricultural livelihoods (e.g. linked to price dumping by retailers), and questions concerning food security and production.

Perhaps the biggest recent driver of the renewed impetus to consider agroforestry more seriously comes from the shift in the focus of climate mitigation strategies towards 'net zero' as a goal. This has sharpened focus not only on the ambition and speed of greenhouse gas (GHG) emission reduction strategies, but also heightened attention on the means to take carbon out of the atmosphere. While there is considerable attention to novel technologies that might do this at scale, land-based sequestration through afforestation, peatlands management, and mangrove restoration, remains key to carbon removal. But this raises important questions about the multiple social and ecological interests in, and uses of, land. In the UK for example, the Committee on Climate Change estimates approximately 22 % of current land would need to be afforested in order to meet net zero goals by 2050 (Committee on Climate Change, 2020). The principal potential tension here is between these goals and those of food production, security, and sustainability, given that the UK is already a significant net food importer. This sort of tension is general for many countries.

Agroforestry has come back to the fore precisely because it holds out the promise of afforestation without losses in food production and security. However, more dense and diverse land use forms such as forest

---

* Corresponding author at: Sustainable Consumption Institute, Alliance Manchester Business School, University of Manchester, UK.
E-mail addresses: steffen.hirth@manchester.ac.uk, s.hirth@leeds.ac.uk (S. Hirth).

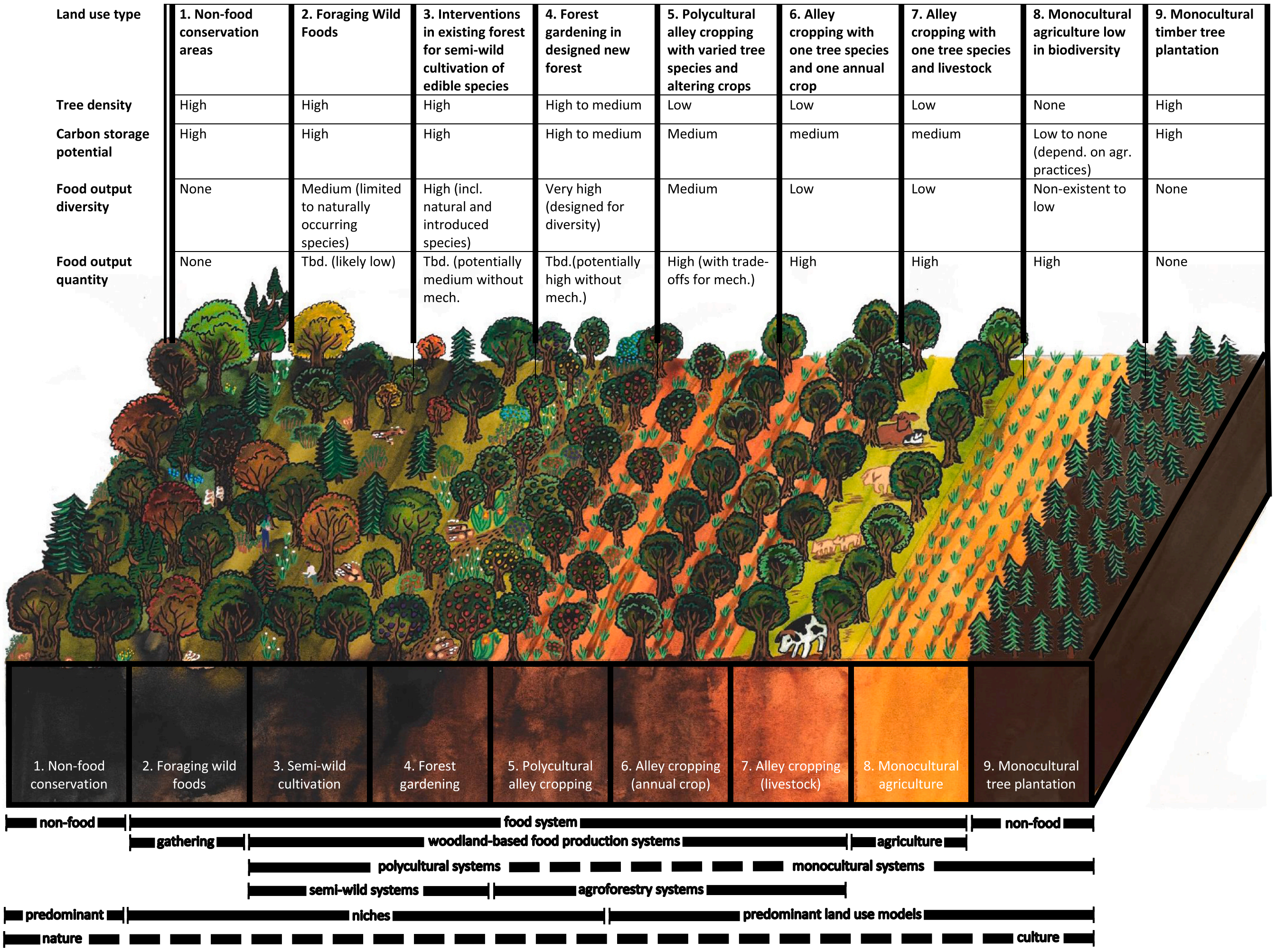
https://doi.org/10.1016/j.landusepol.2025.107620
Received 22 August 2023; Received in revised form 6 February 2024; Accepted 18 May 2025

gardening (Crawford, 2010), though less common, also deserve consideration. In this context, the objective of this article is to critically review the scientific evidence on optimising woodland-based food production systems by maximising key ecosystem services. We examine how agroforestry and other forms of food production in forests help to reduce trade-offs and divisions between the social-ecological needs of climate change mitigation and adaptation, biodiversity conservation, and food production. This article thus provides a systematic review of recent research on food production in woodland to achieve multiple benefits captured by the Sustainable Development Goals – with major contributions it could make to at least SDGs 1, 2, 3, 5, 6, 8, 10, 12, and 13. Drawing on a wide range of literature from multiple disciplines, the article has three aims. First, we develop a typology of woodland-based food systems as discussed in existing literature, to identify their key similarities and differences. Second, we identify and discuss four principal benefits for woodland-based food systems: climate change mitigation and adaptation; biodiversity conservation and restoration; food production and security; and other social benefits. Third, we identify key challenges and obstacles which arise ultimately from the political economy of land use – the property systems, investment regimes, business models, and regulatory arrangements that shape and limit the possibilities for woodland-based food systems to be developed at scale. We conclude by outlining a research agenda to build a more systematic evidence base for how such obstacles may be overcome and the full potential of woodland-based food systems to be achieved.

2. Towards woodland-based food systems: establishing a conceptual framework

In public debates at least, agroforestry and forest foods are more often associated with the Global South – as a contribution to livelihoods and food security – while that is rarely the focus in the Global North, as if there was no need to improve food systems in industrialised countries. Our premise for this article is that there is value in exploring the literature on woodland-based food systems, how to ecologically and socially improve agri-food chains, and achieve sustainability and resilience in the Global North in order to lessen the burden on ecosystems globally and tackle post-colonial resource extraction from South to North. Correspondingly, we excluded tropical climates from our search, and confined the research to temperate ones. This means taking a critical stance towards the notion that “development” is necessary exclusively in the South (Ziai, 2015) and account for the disproportionate resource use as part of what Brand and Wissen (2021) call “imperial modes of living” to denote the unsustainable practices of production and consumption in the North. Even though agroforestry features prominently in our scope of research due to its considerable base of literature, our focus and our search terms were explicitly wider, incorporating any form of food production in woodlands that falls in the spectrum between foraging “wild” food and agriculture. Fig. 1 provides a schematic overview of land uses relevant in this context, while Table 1 provides a simplified typology of key concepts used in the article.

Both foraging and agriculture represent the ends of the spectrum of food-related land uses we included, but while foraging does not involve



Land use type	1. Non-food conservation areas	2. Foraging Wild Foods	3. Interventions in existing forest for semi-wild cultivation of edible species	4. Forest gardening in designed new forest	5. Polycultural alley cropping with varied tree species and altering crops	6. Alley cropping with one tree species and one annual crop	7. Alley cropping with one tree species and livestock	8. Monocultural agriculture low in biodiversity	9. Monocultural timber tree plantation
Tree density	High	High	High	High to medium	Low	Low	Low	None	High
Carbon storage potential	High	High	High	High to medium	Medium	medium	medium	Low to none (depend. on agr. practices)	High
Food output diversity	None	Medium (limited to naturally occurring species)	High (incl. natural and introduced species)	Very high (designed for diversity)	Medium	Low	Low	Non-existent to low	None
Food output quantity	None	Tbd. (likely low)	Tbd. (potentially medium without mech.	Tbd.(potentially high without mech.)	High (with trade-offs for mech.)	High	High	High	None

Fig. 1. Schematic overview of different types of land use and their environmental and nutritional qualities (Designed by lead author, drawn by Clara Gooding).

Table 1
Key terms to contextualise the foci of the paper.

Key term	Description	Dominant form and key issues
Contextual terms		
Agriculture	Cultivation of plants and animals to provide useful products	Typically treeless; Industrial agriculture based on large-scale monocultures dominates global agricultural output
Monoculture	Growing only one species in an area at a time, e.g. crop species, farm animals in large-scale concentrated feeding operations, or monocultural tree plantations	Dominant approach since 20th century; Treeless in agriculture and livestock production; lack of biodiversity in tree plantations
Polyculture	Growing more than one crop species together, (e.g. "three sisters": maize, beans, and squash); forms of polyculture include, intercropping, the use of cover crops, agroforestry, and integrated aquaculture	Growing multiple crops is still typically treeless; only polycultural agroforestry significantly integrates woody species
Foraging or gathering	Collecting foods in natural systems without proactive production (cultivation)	Marginalised, with traditional knowledge and practical skills endangered
Core focus of the paper		
Woodland-based food production	Any form of proactive food production (cultivation) that relies on crops from woody species; includes agroforestry, forest gardening	Marginal at the scale of global agricultural output
Variants of woodland-based food production		
Agroforestry	Trees or shrubs are integrated in agricultural crop- or pastureland	Typically monocultural tendencies with agroforestry forms that include only one timber tree species integrated with one species of crop or livestock; no additional crop in many cases of timber trees
Polycultural agroforestry	Multiple woody species integrated in agricultural crop- or pastureland	Typically in the form of alley cropping (Wolz et al., 2018) which includes a treeless agricultural part, but avoidance of monoculture through both within-row and between-row diversification and additional understory shrub layer
Forest gardening or food forestry	Creating young woodland maximising density of edible species while mimicking natural succession and processes (Crawford, 2010)	Marginalised, only a few initiatives and typically (not necessarily) very small-scale
Semi-wild food systems	Authors' notion for a woodland-based food system designed through minimally intrusive human interventions; includes forest gardening (forest grown from scratch) or increasing the proliferation of edible species (in existing forests)	Marginalised in the case of forest gardens; initiatives to take proliferation approach in existing forests unknown to the authors

active production (i.e. no cultivation element), agriculture is *typically* treeless and focused on annual crops (i.e. pure cultivation). Moreover, conventional land use typically separates both conceptually and spatially between agriculture, forestry, and conservation. That is, food production is confined to agriculture only, food and timber are grown in monoculture, and conservation areas are monofunctional (as opposed to "convivial"; Büscher and Fletcher, 2019). By contrast, this paper explores benefits of multifunctional, polycultural approaches that include trees and shrubs into food production and host a diversity of different species. Next to agroforestry systems, which typically involve relatively ordered alley cropping, this also includes "semi-wild" systems, which involve human interventions in ecosystems which nevertheless attempt to draw closely on wild food systems. The following subsection expand on agroforestry and semi-wild systems.

2.1. Towards Polycultural Agroforestry

Agroforestry is a land use practice that intentionally integrates woody perennials (trees or shrubs) into crop and animal farming systems (Muschler, 2016), and encompasses a range of systems varying in density, complexity, and scale. Trees combined with crops are referred to as *silvoarable* or *agrisilvicultural* agroforestry systems (Fig. 1 [6.]), whereas trees with domesticated animals are *silvopastoral* (Fig. 1 [7.]), and a mix of all three components is known as *agrosilvopastoral,* but there are also systems with non-pastoral animal species such as fish or bees (Muschler, 2016; Smith et al., 2013). Another classifier is agricultural land having a tree cover of at least 10 %, which corresponds to the FAO definition of a forest (Zomer et al., 2016).

Another characteristic that recurs frequently in the literature is that agroforestry is supposed to create environmental, economic, and social benefits that are not granted by growing crops and trees separately. Agroforestry systems yield a considerable variety of products such as fuelwood, foods, fodder, construction materials, medicines, shade and shelter, thereby decreasing pressure on natural forests (Hall and House, 1994). Next to the diversity of products, the benefits lie in enhanced ecosystem services such as carbon sequestration below and above ground (in vegetation, soil, and fungal biomass), reduced soil erosion, improved water quality, infiltration, holding capacity, and thus reduced water loss (Ellison et al., 2017; Muschler, 2016). Benefits also have a temporal dimension, with many studies reporting possible negative short-term impacts on yields in transitions to agroforestry, whereas yield benefits emerge over time (Branca et al., 2013).

Finally, it is important to elucidate degrees of diversity in land management systems. As opposed to monocropping, intercropping is a term to describe growing two or more crops in proximity, with the aim to have yield benefits; as such the term applies to both agroforestry, in the form of tree-based intercropping, and agriculture. Overall, however, not only is agriculture dominated by monoculture crops (i.e. row crop landscapes where annual crops are distinctly separated from natural areas), agroforestry systems such as traditional alley cropping also have monocultural tendencies. This is the case for example where one species of timber tree monoculture is combined with alley crops of one species of grains or livestock (Wolz et al., 2018; see Fig. 1 [6. and 7.]). Thus, standard alley cropping agroforestry can be distinguished from more diverse systems referred to as woody polyculture, where within-row diversification, between-row diversification, and an additional understory shrub layer can contribute to more diverse and productive outputs, higher carbon storage, and improved nutrient cycling and water use efficiency (Wolz et al., 2018; see Fig. 1 [5.]).

2.2. Semi-Wild Food Systems

The notion of "semi-wild" refers to minimally intrusive interventions in woodland ecosystems that aim at maximising the proliferation of edible "wild" foods (perennials, self-seeding annuals, and fungi) to enhance food productivity while maintaining other ecosystem services. We coin this term to depict woodland-based food production that does not fall into definitions of agroforestry as systems that integrate trees *into farming* (see 2.1 and Table 1), where trees seem a mere addendum to one annual crop or a stock of domesticated animals. By contrast, semi-wild systems generate edible crops from trees and the ecosystems they are part of.

Semi-wild systems seek a balance between total reliance on natural provision (mere foraging) and total control of nature through (agri) culture (mere cultivation). Here, "semi-wild" depicts a middle way between (1) foraging in the "wilderness", where the main productive forces are ecosystems themselves, and (2) cultivating in (agri)culture, where the dominant productive forces are fossil fuels and human labour. Semi-wild systems may be designed but at the same time "mimic", or rather: *work with*, natural processes.

Agriculture will not produce foodstuffs without incessant human intervention, whereas agroforestry and semi-wild systems, through the integration of structured semi-permanent perennial cropping, can, once they are established. Semi-wild cultivation may also increase the resilience of food supply to shocks induced by climate change or violent conflicts, as Redzić shows powerfully in relation to their role in the siege of Sarajevo in 1992–5 (Redzić, 2010).

Two different approaches to the design of a semi-wild system are notable. The first of these entails design "from scratch", where treeless arable or grazing land is reforested (Fig. 1 [4.]). This is an opportunity for land use change to create a double dividend from emissions reduction and carbon sequestration, if animal-source foods are reduced while vegetation on freed-up land is restored (Sun et al., 2022) To create a semi-wild system, however, afforestation must include maximisation of *edibles*. Existing examples are forest gardens (also referred to as food forestry), where young woodland is created while mimicking natural succession and maximising density of edible species (Bjorklund et al., 2019; Crawford, 2010). The second approach involves interventions within existing "natural" woodland, designed to change the proliferation of plants and fungi towards edibles (Fig. 1 [3.]).

In sum, the notion of semi-wild is meant to challenge the monofunctionalism, monoculturalism, and productivism of the Agricultural Treadmill (Ward, 1993), without suggesting to "go back" to the hunter-gatherers of the Holocene. It intends the development of/evolution towards food production fit for (overcoming) the Anthropocene (Crutzen, 2002), Capitalocene (Moore, 2016), or Apocalyptocene (Anson, 2020), but to do so would require political economic change. Between the extremes of nature/culture it largely relies on natural processes without being averse to considerate use of tools and technology – the combination of traditional knowledge and emerging technologies such as tree-mushroom inoculation, for example, may help in the design of semi-wild systems (see 4.3). However, land use, food supply, and dietary change are predominantly political decisions, hindered by vested interests of those who (still) profit from the current (agri-food) system.

3. Background and methods

The article draws on the analysis of a sample of literature across natural and social sciences identified via Web of Science. This included abstract screening of 344 articles, out of which 54 were chosen for full text review (Appendix A). We applied qualitative text interpretation to analyse the sample along the four main categories of climate change, biodiversity conservation, food production, and social benefits. In addition, we distinguished between barriers and enablers of woodland-based food systems, and used these analytical categories to identify thematic subthemes (Appendix B).

The background of this research derived from one of the author's decades of experience of foraging wild plants and mushrooms in the UK and Slovakia and his perception of two untapped potentials. An unused abundance of wild edibles, even in urban settings (Oncini et al., 2024), and at the same time a potential for optimising the ecosystem service of food provision from forests by what could be termed "semi-wild" food cultivation, where targeted, but non-intrusive, ecosystem interventions, such as inoculating dead wood with fungal spores outdoors, or encouraging the proliferation of edible perennials, aim at increasing forest productivity while maintaining other ecosystem services (see 2.2 and Fig. 1 [3.]). This led us not only to adopt a perspective wider than agroforestry, but also to incorporate a focus and search terms on mycelium and (ecto)mycorrhizal fungi in addition to plant food production.

Another piece of the puzzle was to include evidence on forest gardening and food forestry (Fig. 1 [4.]) which, unlike traditional agroforestry, usually depicts small-scale production units, often (but not necessarily) associated with permaculture design principles and driven by agro-ecological practitioners and grassroots movements in desire of alternatives to conventional agriculture.

Thus, in our search on Web of Science, we combined search terms focused on woodland-based food systems, in relation to the three areas representing important ecosystem services: climate mitigation, biodiversity conservation, and food production. This provided us with our corpus of texts for the analysis. We then analysed the literature in relation to these three sorts of ecosystem service benefits, but also added in three additional analytical goals: social benefits, f barriers, and enablers of woodland food production. We focused on the latter three categories to enable explanations for the seeming contradiction that, on the one hand, evidence for the productivity and multiple benefits of woodland-based food production seems strong, and on the other, these practices still represent a niche that few farmers or (wood)land owners are willing to populate. Thus, there is a need for elucidating political economic factors for explaining why there is no large-scale adoption despite the benefits (yet) in the Global North.

Our search focused on positive effects of woodland-based food production. However, there may already be an implicit bias in favour of agroforestry among scholars who focus on that topic. And we acknowledge that we may reinforce it to a degree while also making sure to include the most significant risks and trade-offs identified in the literature.

4. Benefits

We now turn to our analysis of existing literature regarding the four aspects we have identified.

4.1. Climate change

There is a widespread understanding of the importance of forestry for climate change mitigation through carbon sequestration in below and aboveground biomass. Forestry has long been central to climate governance approaches and agroforestry has been recognised as a tool for carbon sequestration in the Kyoto Protocol (Hall and House, 1994; Udawatta et al., 2019). Land Use, Land-use Change and Forestry is a central category in the United Nations Framework Convention on Climate Change. It is the basis of carbon offsetting and forestry initiatives, e.g. to reduce emissions from deforestation and forest degradation (REDD+) (Schroth et al., 2015), and along with mangrove and peat restoration it is currently the only demonstrated viable way to remove carbon from the atmosphere (Haskett et al., 2010). There is evidence that reforestation has potential to increase carbon stored in soil and aboveground biomass (Haskett et al., 2010; Silver et al., 2004) including on agricultural land, although this remains underestimated (Zomer et al., 2016).

Agroforestry, however, provides specific additional potential for carbon storage, for various reasons. These benefits apply widely, although sequestration rates are generally higher in moist rather than dry and warm rather than cold climates (Branca et al., 2013). Firstly, increases in soil organic carbon (SOC) are facilitated through greater biomass provision compared to arable or grazing land without woody species (Cardinael et al., 2018; Mirmasoudi et al., 2019). Secondly and related, microbial activity contributes to carbon storage. Fungal biomass is generally higher in forests dominated by ectomycorrhizal fungi compared to those dominated by arbuscular mycorrhizal fungi, and ectomycorrhizal fungi often produce edible fruiting bodies (Averill et al., 2014; Cheeke et al., 2017; Guerin-Laguette, 2021; this point is particularly prescient in light of the discussion in Section 4.3 regarding the integration of edible ectomycorrhiza into agroforestry systems). Fungi and bacteria also support carbon storage by aiding plant biomineralization (Garcia-Montero et al., 2017), and mycorrhizal fungi increase the carbon flow to soil (Cardoso and Kuyper, 2006). Thirdly, carbon stocks of above ground vegetation generally increase with tree density (Bockel and Schiettecatte, 2020; Kay et al., 2018; Schafer et al., 2019). Different forest categories have differing sequestration potential but nevertheless, the benefits of reforestation and ecosystem restoration through agroforestry are clear(Hall and House, 1994; Harland, 2017) and urban green infrastructure's capacity for carbon storage can even outweigh its ecological footprint, e.g. from maintenance and machinery use (Gomez-Villarino et al., 2021). Finally, if used for long-lived building products, timber from coppicing or pollarding, for example, constitutes an additional carbon sink (Hall and House, 1994; see also Arehart et al., 2021).

Additional mitigation advantages include reduced artificial fertilizer needs because of nutrient contributions from trees, especially nitrogen fixing species (Muschler, 2016), fuelwood displacement of fossil fuels (Hall and House, 1994), and indirect mitigation effects from spared food production emissions. A dietary shift away from animal-source foods in which spared land is reforested holds a double-dividend from reduced production emissions and increased carbon sequestration (Sun et al., 2022). Land formerly used for intensive animal agriculture could be repurposed for both nature conservation and woodland-based food production. Comparative evidence shows similar protein yields, yet additional mitigation advantages, of edible mycorrhizal fungi compared to beef from extensive agricultural grazing (Thomas and Vazquez, 2022) and that a modelled beef farm could only become an overall carbon sink by including fruit tree orchards (Mirmasoudi et al., 2019). Further, when compared to major food categories, edible mycorrhizal fungi were the only one that could present a net sequestration of carbon in production (Thomas and Jump, 2023).

Beyond sequestration and mitigation, agroforestry also holds climate adaptation advantages. Leading to physiological weakening or even destruction of forest stands (Moscatelli et al., 2017), climate change is a threat to ecosystems. Higher diversity, e.g. in polycultural agroforestry compared to conventional agroforestry (Wolz et al., 2018) as well as in semi-wild food systems, is a key to stable services from ecosystems, their resistance to climate extremes, and thus resilient food systems (Bardgett and Gibson, 2017; Ellison et al., 2017). Extensive tree cover is important for both ground water and flood moderation, important to the social benefits of climate adaptation that afforestation produces (Ellison et al., 2017).

However, some risks of changing agricultural practices and trade-offs are discussed in the literature. Some scholars and stakeholders raise concerns over food security as they generally regard afforestation and renewable energy generation on farms for climate mitigation as moving away from food production (Barnes et al., 2022), and even if agroforestry's advantage lies in combined carbon sequestration and food production, trade-offs between tree density and food production levels may arise (Kay et al., 2019). In some cases of newly implemented agroforestry developments, soil disturbance and erosion during planting are likely reasons for initial SOC losses (Mayer et al., 2022) and it should be noted that not all soil types are suitable. Waterlogged and anoxic soils can be particularly potent carbon stores, and the resulting drying of these soils through afforestation may lead to a significant release of carbon rather than a net sequestration (Forster et al., 2021). For these reasons, such soil types are subject to a growing awareness of the need for their protection (e.g. IUCN, 2024) and should be excluded from planting.

4.2. *Biodiversity Conservation and Restoration*

Next to climate change, global decline in biodiversity is among the most severe ecological crises linked to forest degradation and destruction (Thomas and Vazquez, 2022). Land use policies such as the European Biodiversity Strategy and the Communication on Green Infrastructure(Kay et al., 2019) as well as (plans for) national-level legislation(Barnes et al., 2022) and regional or local planning of (urban) green infrastructure (Gomez-Villarino et al., 2021) aim at ecosystem services enhancement and ecosystem restoration to which agroforestry is a key component (Kay et al., 2019).

Unlike natural forests and the wide range of mixed forestry-agriculture landscapes, both monocrop agriculture and mere forestry plantations lack biodiversity (Baird and Pope, 2022; Bockel and Schiettecatte, 2020; Ellison et al., 2017; Goncalves et al., 2021; Hall and House, 1994). Monoculture cropping exacerbates erosion and has led to a reduction in soil organic matter, reducing above and belowground biodiversity (Moscatelli et al., 2017), as has pasture intensification i (Laporta et al., 2021). Monoculture tree plantations lack species richness and related ecosystem services and are more susceptible to disease (Baird and Pope, 2022; Ellison et al., 2017). Whilst both unmanaged or extensively managed forests can berich in biodiversity, particularly in the Global North they are rarely considered as a source of food. Since current agroforestry, too, has monocultural tendencies, typically limited to simple systems that combine one timber tree species with one annual crop, diversification towards woody polyculture and tree crops is regarded a transformative, multifunctional land-use solution (Wolz et al., 2018).

By increasing biodiversity compared to treeless agriculture, agroforestry can contribute to enhanced ecosystem services and more resilient food supply (Altieri et al., 2015). Biodiversity is rarely quantified in the literature sample. One exception is the significantly higher biodiversity in terms of flowering resources that agroforestry test sites exhibited compared to non-agroforestry (Kay et al., 2018). Generally, ecosystems with high biodiversity absorb and sequester more carbon in soil and biota (Branca et al., 2013), involve better water uptake, water cycling, tree growth, and are more resistant against pests, soil erosion, droughts, and other climate extremes (Bardgett and Gibson, 2017; Ellison et al., 2017; Laporta et al., 2021). Tree species richness also correlates positively with fungal richness (Saitta et al., 2018).

Soil biodiversity is discussed in the context of agroecological methods. For example, arbuscular mycorrhizal fungi are introduced to encourage resource capture (Brodt et al., 2020), beneficial plant-soil biodiversity interactions enable nonchemical weeding and pest control (Koskey et al., 2021), and carbon and nitrogen losses can be reduced by legume-based cropping systems (Branca et al., 2013). In principle, these also apply to organic or regenerative agriculture, but interactions of trees with other plants and fungi can maximise the benefits of mixed species systems (Goncalves et al., 2021). While agriculture typically relies on annual crops, agroforestry involves perennials which do not need replanting every year. This can reduce soil disturbance and lead to more diverse soil microbial communities (Brodt et al., 2020).

Agroforestry systems apply multifunctional land management and promote biodiversity to enhance ecosystem services. Examples in the sample feature combinations of specific species (e.g. fruit orchards with livestock (Mirmasoudi et al., 2019), faba beans as cover crops enhancing mycorrhizal colonization of walnut (Thioye et al., 2022), chestnuts or various other tree species combined with mycorrhizal fungi (Guerin-Laguette, 2021; Guerin-Laguette et al., 2014; Thomas and Vazquez, 2022)), but also specific human-nature relations and resulting landscapes (e.g. Montado; Azul et al., 2011; Laporta et al., 2021)). While land-use abandonment may generally benefit biodiversity, this is not always the case. For example, silvo-pastoral Montado or Dehesa landscapes in parts of southern Portugal and central Spain illustrate how conserving biodiversity can require managing shrub encroachment to reduce the risk of wildfires impacting the biodiversity in Mediterranean ecosystems (Laporta et al., 2021).

Another emphasis in the literature is agroforestry's potential for ecosystem restoration. While there is no doubt about the need to protect existing forests, establishing new wooded areas is key to grant biodiversity space (Baird and Pope, 2022). Spectacular restorations of degraded, deforested land are mostly evidenced in Global South contexts, e.g. Noel Kempff's project in Bolivia (Brown et al., 2000; Haskett et al., 2010), or the reversed desertification of the Loess Plateau in China (Harland, 2017). However, restoration is not only required in the context of dysfunctional landscapes. Research suggests to also apply restoration to "functional" land that is deforested and low in biodiversity due to monocultural use. For example, beef farms can be replaced with novel, biodiverse food production systems based on trees inoculated with edible mycorrhizal fungi (Guerin-Laguette, 2021; Thomas and Vazquez, 2022), and parking lots with perennial food forage systems (Brain et al., 2017).

Finally, afforestation and agroforestry may also entail some risks and disadvantages. For example, agroforestry systems have advantages for biodiversity, but may also present negative tree-crop interactions that can result in lower yields (see 4.3 and Castle et al., 2022; Hall and House, 1994; Torralba et al., 2016). Large-scale tree planting is necessary, but the introduction of species can have wider biodiversity impacts and requires the environmental contexts and consequences to be considered. For example, research is needed on tree establishment and how seeds and saplings interact with mycorrhizal, saprotrophic, and pathogenic fungi (Baird and Pope, 2022). If forests are utilized for a bio-based economy, to which agroforestry can contribute, risks of over-exploitation and ends competing with biodiversity must be considered (Neumann et al., 2016).

4.3. Food Production

What makes woodland-based food systems promising are their multiple benefits – their potential to turn food systems from a carbon source into a sink, from a cause of mass extinction into habitat, while conserving soils and providing healthy and sustainable foods in sufficient or even ample quantity (Bockel and Schiettecatte, 2020; Thomas and Vazquez, 2022). However, the ways in which agroforestry systems and their variants can be seen as "productive" require closer examination. In changing contexts, the literature identifies agroforestry with both low and high productivity.

The ways in which agroforestry systems are highly productive have to do with the diversity of their components and hence their outputs. Models to predict long-term yields for silvoarable, arable, and forestry systems have shown silvoarable systems to be very productive (Graves et al., 2007), with up to 30 % more marketable biomass per land unit compared to crops and trees grown separately (Cardinael et al., 2018). Against assumptions that trees require competition in densely spaced forestry systems to produce high quality timber, experiments have shown that widely spaced trees in agroforestry plots grew satisfactorily, often faster than in monoculture forestry plots (Balandier and Dupraz, 1998). Leaf biomass production has been shown significantly higher in intercropping systems compared to control groups, increasingly so with the years after planting (Chifflot et al., 2006).

Specific reasons for high biomass productivity are efficient use of water, nutrient, and light by the ecosystem throughout the year (Cardinael et al., 2018). Tree crops such as apple, walnut, hazelnut, or olives can be integrated into annual crop cultivation to stimulate rhizoculture, i.e. techniques to optimise activity of roots, mycorrhizae, and other organisms in the soil which may also reduce the need for fertilisation (Garcia-Montero et al., 2017). For example, walnuts increase mineral N availability, even for legumes such as chickpeas, and are beneficial for crop growth compared to chickpeas grown as a sole crop (Mahieu et al., 2016). Fungi can mediate nutrient competition between plant species (Perry et al., 1989) which can lead to higher yields in woody polyculture compared to monoculture (Wolz et al., 2018).

Next to beneficial choice of species, specific spatial designs of agroforestry systems yield further benefits. Functioning as a windbreak barrier (Muschler, 2016), trees create micro climates and protect annual crops, provide housing for crop pollinators, improve water use efficiency, and yield, e.g. of durum wheat (Campi et al., 2009). In the specific case of forest gardens, it is the vertical dimension, with multiple layers of edible species from treetops to ground cover and roots, as well as the dense design that is considered beneficial for productivity (Bjorklund et al., 2019).

Moreover, emerging technology such as the inoculation of trees with edible fungi has the potential of multifactorial benefits. Cultivation of *Lactarius indigo* mushrooms in mixed-species woodland conditions not only yields a level of protein per unit area similar to or higher than extensive beef farming, it also enhances biodiversity through an increased structurally complex habitat and sequesters carbon in addition (Thomas and Vazquez, 2022). Here, the relationship is symbiotic and often mutualistic. In contrast to microbial or fungal inoculation of soil for agricultural enhancement (Koskey et al., 2021; Sharma et al., 2010; Srivastava and Singh, 2022), once planted into suitable bioclimatic conditions, these relationships produce edible fungi fruiting bodies of high value. This approach is widely employed in cultivation of the *Tuber* genus (truffles) to the extent that ~80–90 % of all harvested truffles in France are now cultivated (Reyna and Garcia-Barreda, 2014). Appreciated species from the genus *Lactarius* are also reliably cultivated and other cosmopolitan genera such as *Suillus* and *Astraeus* offer high potential (Guerin-Laguette, 2021; Thomas and Jump, 2023). Truffle cultivation depends on the creation of low density stands maintained in an arrested successional state, thus limiting their ecosystem service benefits – such as water filtration and carbon sequestration – and these systems themselves are vulnerable to climate change (Thomas and Büntgen, 2019). However, approaches with other genera may be compatible with medium-high density planting and biodiverse stands (Guerin-Laguette, 2021) facilitating greater ecosystem service provision. Further, depending on habitat type and tree age, greenhouse gas (GHG) flux estimates of these systems reach -858 kg CO_2-eq kg^{-1} protein production (Thomas and Jump, 2023). Beyond global truffle cultivation activities, this approach remains currently small-scalebut is highly scalable and if combined with the forestry activity of the last decade, may have provided calorific output to feed 18.9 million people annually (Thomas and Jump, 2023). As an emerging and niche technology, much more research is needed to enhance the diversity and reliability of the offering. A focus on native species, ensures maximal associated biodiversity and conservational benefits whilst mitigating unintended consequences. Although recreating a natural process, albeit in enhanced concentration, the greatest risk is the technologically intensive approach as a bottle-neck in uptake.

Although agroforestry systems have the potential to increase food production, occasionally there is no increased benefit over previous land use and in some cases there may be a negative tree-crop interaction (Castle et al., 2022; Torralba et al., 2016). There is also literature that attests agroforestry only moderate productivity compared to agriculture. Agroforestry has a clear advantage in the provision of *regulating* ecosystem services such as carbon sequestration rates and flowering resources but, unlike Chifflot et al. (2006), Kay et al. found *provisioning* ecosystem services such as annual biomass yield to be higher in non-agroforestry arable land use (Kay et al., 2018). A concern are thus crop yield losses and economic impacts for farmers changing to agroforestry which is also considered as costly compared to other sustainability practices such as improving nutrient management or tillage and residue (Fitton et al., 2011). More specifically, woody and perennial plants used in agroforestry systems tend to have lower yields (Hall and House, 1994), and there can be trade-offs for productivity associated with high tree cover (Kay et al., 2019; Zomer et al., 2016). Higher values of carbon sequestration in systems with fast growing tree species and good soil conditions were also associated with some reduction in food and feed production (Kay et al., 2019). Another concern is that if extensification results in lower yields in one region, it potentially triggers intensification or deforestation elsewhere (Mayer et al., 2022). Where agroforestry plantations are unsuccessful, this can be due to animal damage in silvopastoral systems or choice of unsuitable tree species for local soil and climate conditions (Balandier and Dupraz, 1998).

4.4. Social Benefits

The potential of woodland-based food systems does not end with climate change mitigation, biodiversity restoration, and food production, but also involves multiple social benefits.While monocultures are unappealing to many people, integrating trees in agriculture can increase the diversity and attractiveness of landscapes (Smith et al., 2013). Beyond the aesthetic value, this entails social and cultural benefits such as recreation, physiological relaxation, and cultural experience (Marchi et al., 2018). This may involve leisure or touristic outdoor activities such as hiking, hunting, fishing, mountain biking, and equestrianism which can result in improved health and enjoyment through sports and wildlife watching (Smith et al., 2013).

In the form of eco-tourism, this can contribute to individual livelihoods and thriving communities (Goncalves et al., 2021; Marchi et al., 2018; Smith et al., 2013). For example, proliferating and harvesting edible fungi could contribute to "myco-tourism" while also contributing to a green economy and a source of rural income (Guerin-Laguette, 2021; Oria-de-Rueda et al., 2010). Importantly, this way of diversifying the production can alleviate farmers' risks of yield losses (see 3.3) (Barnes et al., 2022; Goncalves et al., 2021). Group interviews also show that due to their aesthetic and pedagogic value forest gardens are appreciated as benign working environments (Bjorklund et al., 2019). In sum, agroforestry bears the potential of stimulating the rural economy (Marchi et al., 2018; Smith et al., 2013).

However, beneficial impacts are not confined to the local scale. Firstly, safer employment and development in rural areas can help reduce the migration of young people to urban areas (Marchi et al., 2018). Secondly, enhanced water and climate-related ecosystem services benefit people regionally and globally. The benefits manifest not just where the trees are planted, but well beyond the local or catchment scale and often far from where decisions on tree planting or removal are made, showing their relevance at a geopolitical level (Ellison et al., 2017). Thirdly, poverty reduction and greater food security are benefits of global importance (Branca et al., 2013; Haskett et al., 2010). Even though poverty alleviation or prevention is often discussed in the context of the Global South, due to the effects of extreme climate and environmental degradation this is becoming increasingly important in temperate climates and the Global North.

Other aspects encompass benefits ranging from tradition to social innovation and creativity. Trees have been used in combination with crops and livestock since the dawn of agriculture (Muschler, 2016) and as such agroforestry landscapes have cultural heritage value (Smith et al., 2013). This value is embedded in traditional, silvo-pastoral landscapes such as Montado and the Dehesa (Azul et al., 2011; Laporta et al., 2021), but also other locations with land uses such as woodland and orchard grazing, alpine wooded pastures, pannage, and parklands (Smith et al., 2013). By preserving landscapes that are forageable or otherwise functional beyond mere commercial interests, well managed forest operations can thus also maintain traditional cultural services and the rights and needs of native people (Marchi et al., 2018). At the same time, there is ample opportunity for (re)creating communities that are more resilient and productive. Concepts such as permaculture design are guided by ethics and principles, using a systems lens with feedback loops for adaptation and mimicking the diversity, functionality and resilience of natural ecoystems (Brain et al., 2017). Restoring degraded landscapes and creating abundance with these holistic principles can be of particular benefit for social groups such as women (Harland, 2017) and, more generally, promote independence and thriving of peripheral spaces, economies, and livelihoods. Land use change that is necessary for sustainable transformation is thus also an opportunity for multiple social benefits.

5. Barriers and enablers

Complex issues such as the properties of an optimal agri-food system are unsurprisingly controversial, as are the benefits and disadvantages of woodland-based food systems. Overall, while acknowledging some risks and challenges, scholars of our literature sample are very much in favour of expanding woodland-based food systems in temperate climates. However, not only in face of remaining concerns, but even more so out of strong conviction of their multiple benefits arises the question why they are not (yet) widely implemented. Thus, here we summarise the barriers to, and enablers of, upscaling them ascertained in the literature. Firstly, by sketching socio-cultural factors and practical foci shaping the agri-food system. Secondly, by elaborating on the concerted effort necessary to change it.

The first point is about the cultural but also systemic and practical inclination of agri-*culture*, its dominant values and economic mechanisms, towards productivism. This involves a narrow focus on production, maximising plant and animal growth, and thus the marketable outputs in monocropping contexts, which has been a barrier to expansion of trees on farms (Barnes et al., 2022; Bjorklund et al., 2019; Brodt et al., 2020). A core driver of this focus on monocropping has been the drive for mechanisation to shed labour and enhance productivity. Even more broadly, overcoming unsustainable production and consumption practices requires re-examining a materialistic culture based on resource depletion and economic growth, along with the norms that define appropriate behaviour towards other species, how we raise domesticated animals, and affect or protect wild animals (Harland, 2017).

To exploit effectively, the capitalist political economy tends to divide labour, functions and sectors, and producers from consumers. A particular expression of these divisions in the literature is the monofunctionalism expressed in policies based on a strict division between agriculture and forestry (Bjorklund et al., 2019). Locally, this manifests in new urban green infrastructure allocating separate areas for annual crop cultivation and forestry, rather than integrating tree species with edible crops (Gomez-Villarino et al., 2021; Oncini et al., 2024). It also generally manifests in the dominance of monocultural production. Within agroforestry, monocultural tendencies are present in the dominance of "simple" alley cropping systems, where only one tree species is combined with one type of annual crop or livestock (Wolz et al., 2018). The paradigm of monocultural productivism aligns with a focus on short-term profits, visible in concerns over the costs at farm-level of planting trees and potential crop yield losses entailed by a transition towards agroforestry (Fitton et al., 2011; Wolz et al., 2018).

The opposing paradigm is sustainable multi-functionalism based on polyculture. It promotes systems that "optimize multiple benefits […] gained from ecology-based interventions" (Bardgett and Gibson, 2017) and produce sufficient food while placing equal value on the generation of ecosystem services, for example, in perennial intercropping systems (Bjorklund et al., 2019; Wolz et al., 2018). This may include sustainable biotechnological processes, e.g. renewed global interest in bioinoculants to improve soil health or combine crops from trees with edible fungi (Guerin-Laguette, 2021; Hyde et al., 2019; Koskey et al., 2021; Thomas and Vazquez, 2022). The multifunctionality of polyculture lies not only in a more diverse range of crops produced by a farm, but also in the benefit of combining yields from woody polyculture (Wolz et al., 2018) with climate mitigation and an array of adaptation benefits such as better groundwater recharge (Ellison et al., 2017; Zomer et al., 2016).

The second aspect is the need for a concerted effort to upscale woodland-based food systems. The literature focuses on agroforestry, but the points made are applicable to more dense and diverse systems as well. Establishing multifunctional woodland-based food systems is a challenge to be faced in four areas:

Research – is needed that expands our knowledge of interactions (e.g. tree-crop and tree-fungi relations) (Goncalves et al., 2021; Perez-Moreno et al., 2021), with input from both farmers actively experimenting and controlled field trials (Brodt et al., 2020). Scientific research involves dynamic modelling and design work to create and monitor agroforestry systems that deliver their potential regarding climate change, biodiversity, and food production (Brodt et al., 2020; Goncalves et al., 2021).

Translational work – that "translates" gained knowledge into optimised practices, requiring both research and engagement with farmers, policy makers, breeders, and agricultural scientists (Bardgett and Gibson, 2017). Specifically, this involves accessible species databases detailing ecosystem functionality, professional training in multi-cropping systems (Brodt et al., 2020), as well as integrated coordination of science, production practices, and spatial and urban planning (Gomez-Villarino et al., 2021; Kay et al., 2019).

Labour & organisation – involve management measures to facilitate practices, including either systematic development of labour reducing designs for viable agroforestry systems (Brodt et al., 2020) or means of mobilising labour in non-commercial ways, e.g. in forest gardens organised as community initiatives. Relevant variables are the distance between garden and residence, the labour hours available (Bjorklund et al., 2019), and inclusion of perennials and fungi while optimising species combination (Goncalves et al., 2021; Perez-Moreno et al., 2021). Adequate management aims at improving tree health and mycorrhizal fungi production and alleviating (e.g. wildfire) risks (Oria-de-Rueda et al., 2010). While alley cropping systems allow for mechanisation, there are trade-offs between the diversity and complexity of systems and the applicability of mechanisation. To help, tools and technologies for managing diverse and complex systems are needed that breed and combine species for high yields and prepare systems for more extreme climate conditions (Bjorklund et al., 2019; Goncalves et al., 2021).

Policy – needs to facilitate coordinated action beyond the individual farm (Kay et al., 2019), facilitating assemblages of networked stakeholders on a territorial scale (Koskey et al., 2021), and ensuring investment in research and updates to agricultural policy, thereby helping to surmount the relatively high management complexity of agroforestry operations (Wolz et al., 2018). Particularly important are Payment for Ecosystem Services schemes, which can generate financial incentives to realise the potential of woodland-based food systems as a negative emissions technology, by valuing the net carbon flow generated by afforestation and reduced agricultural emissions (Brodt et al., 2020; Laporta et al., 2021; Mayer et al., 2022; Winans et al., 2016).

6. Discussion

Multifactorial benefits are a recurring theme in the literature on woodland-based food production systems. The literature also suggests that monocultural productivism is a barrier to more complex, diverse systems and shows ways forward through research, its translation into practice, organisational and policy changes. However, these barriers must be considered against the urgency of long-term crises such as climate change and biodiversity loss at the scale of mass extinction (Ceballos et al., 2015), as well as the more recent cost of living crisis. In the light of existential threats to humanity and indeed all life on Earth, the reason *why*, despite their benefits, woodland-based systems are not yet upscaled, requires further discussion. Research gaps, unlinked theory and practice, and retentive policy alone seem not convincing enough. Here, we provide a discussion that links our review findings to the wider political economy of agri-food systems.

The starting point are concerns over trade-offs between trees and food. While it is widely acknowledged that trees benefit mitigation goals, dismissal and hesitancy from agricultural and commercial points of view are based on the apprehension that integrating trees may result in (1) lower quantities of food and (2) profit losses for farmers. In other words, a transition would be a threat to food security and farmer livelihoods, and thus uneconomic in relation to the imperative of providing food and sustaining those who earn their living with that.

Of course, this concern can be questioned for its general validity. However, previous reviews have shown that “the effect of agroforestry practices on the yields of crops is not well documented and sometimes contradictory” (Branca et al., 2013, p. 646). To the extent that there are documented productivity losses, these may be as much constrained by questions of labour availability, land ownership, and commercial imperatives, as by the technical-biological qualities of an agroforestry system. Ultimately, whether losses of productivity and profits are to be expected, or not, may be relevant to individual farmers today, but less so from a general, macroeconomic perspective (that may include policies to ensure farmer livelihoods). Productivity and profit losses are made the key determinant of the practical *value* of agroforestry. This reveals a persistent economistic framing that *devalues* a range of vital benefits of woodland-based food systems. These benefits go beyond mere outputs of commodities and capital but are no less economically relevant (see Table 2 for an overview).

Firstly, woodland-based food systems can be productive – on mid and long-term. Growing trees takes time and aggregated evidence on agroforestry shows that “short-term impacts may be negative” and “yield benefits emerge only over time” (Branca et al., 2013, p. 646). Likewise, growing a forest garden follows natural succession processes over the course of years until the system can reach its productive potential. It should be acknowledged, though, that woodland-based systems effectively sequester carbon before food outputs are at their maximum. However, the current agri-food and economic system reacts extremely sensitively in face of missing short-term profits.

Secondly, the nutritional and environmental quality of the harvest matters (Stratton et al., 2020), not just the quantity. Avoidance of pesticides and synthetic fertilisation and reliance on natural processes in woodland-based systems will benefit production – its material flows and nutrient cycles – and, thereby, nutrient replenishment of crops for healthy ecosystems and foods (see, for example, Prashar and Shah, 2016). Current agriculture provides high quantities of food from degraded, compacted soils (even in the context of grasslands (Bardgett et al., 2021) but relies on fossil fuels to replace nutrient capture otherwise provided by ecosystem services. Private investment and trading on (stock) markets drive productivism at the expense of sustainability.

Thirdly, there is value and safety in a diverse harvest, even when diversity is measured at national scales (Renard and Tilman, 2019).

Table 2
Ecosystem service benefits of woodland-based food systems beyond the foci on commodity output quantities and microeconomic profits.

Key point	Qualities of woodland-based food systems	Foci in the agri-food sector driven by the dominant political economy
1	Sequester carbon instantly, benefit from yields increasingly over time	Lack of financial or regulatory incentives for carbon sequestration; importance of short-term yield and profit maximisation
2	Nutritional and environmental quality of the harvest is high (plus in nutrients, reduction in pollutants)	Pesticides and synthetic fertilisation remain the norm and supported by vested interests of agri-chemical companies
3	Diverse harvest and perennials can increase local resilience by benefitting overall health of diets and avoiding total crop failure	Monocultural and monofunctional specialised large-scale production at global scale
4	Alternative proteins from fungi and nuts are vital to enable dietary sustainability transformations	Intensive livestock remains the norm despite the sector being a driving force of deforestation, GHG emissions, pollution, and diet-related diseases
5	Enhanced ecosystem services – e.g. air, water, wildlife, soil – are a *precondition* to economy, defined as any form of activity that supports human life	Economic focus on commodities for *capital* accumulation which, together with alienation from nature, means that in most economic activity the support of human life is at best a side-effect, at worst compromised

In sum: Diversity, as we find it in polycultural woodland-based food systems, is exactly what creates resilience against crises and creates value in the form of enhanced ecosystem services. That diversity, however, is largely incompatible with what is seen as “valuable” within the current political and economic system, where industrial monoculture produces financial, microeconomic value contributing to individual and corporate profits and capital accumulation, even if that’s at the expense of ecosystem services – the valuable preconditions for collective thriving on Earth.

Most of the crops grown on or near trees are types of food that would improve the overall health of diets in the Global North (Willett et al., 2019) – notably fungi, fruit, nuts and seeds, roots, leaves and shoots. Growing a variety of crops, as well as perennials, avoids total crop failure and provides resilience against more extreme climate. Our review suggests that plant species richness and vertical diversity (i.e. several trophic levels and spatial structuring of species above and belowground) can play an important role in enhancing primary productivity through resource complementarity (see Sections 4.2, 4.3). However, current agricultural businesses models are largely monofunctional, achieving economic viability and profitability through specialised and large-scale production, sold globally through multinational retailers.

Fourthly, foodstuffs rich in protein such as fungi and nuts can support dietary shifts away from animal-source foods. This would mitigate climate change by (1) reducing major direct sources of emissions such as meat and dairy production and (2) by sequestering carbon in below and above ground biomass of plants and fungi, as well as soils. Importantly, reducing the output of animal agriculture would also free up land available for reforestation (Sun et al., 2022). However, current (climate) politics does not sufficiently consider controlled degrowth in any sector (Keyßer and Lenzen, 2021), let alone of the influential meat and dairy industry.

Finally, ecosystem services have been taken for granted but valuing them economically now seems a precondition for sustaining a form of civilisation. Woodland-based systems are an opportunity to redefine the productivity of land operations by defocusing food commodities (or timber) and equally valuing clean air, water, wildlife, and soil. Since these "services" are not commodities directed at a buyer, financial valuation must be a matter of social regulation, not market processes. However, only policies and legislation can make ecosystems services financially lucrative and land operations based on them economically viable. The dominant political economy and its agri-food system do not value, indeed devalue ecosystem services – changing this is not a technicality but a question of policies that redistribute power and financial streams (see also Oncini et al., 2024). Specifically, politically feasible strategies are needed to restructure land ownership and generate sufficient incentives to mobilise finance and labour effectively to enable functional woodland-based food systems.

7. Conclusion

Faced with climate change, biodiversity loss, and other social-ecological crises, partly caused by the agri-food system, society must now ensure that food production will meet net zero targets. Woodland-based food systems, ranging from agroforestry to forest gardening, exhibit multifactorial benefits beyond mere food outputs. Compared to keeping crops, timber, and biodiversity separately (agriculture, forestry, conservation), woodland-based food systems spatially and conceptually integrate a range of ecological and cultural ecosystem services such as carbon sequestration, biodiversity enhancement, food production, and social benefits. Reviewing these benefits has shown serious potential for turning the agri-food system from a source into a sink of carbon, making food production more diverse and resilient, while providing convivial habitat for wildlife and people.

However, since these benefits are neither new nor obviously lead to commercial opportunities, it would be naïve to assume that these benefits alone (incl. greater awareness of ecosystem services) suffice to upscale woodland-based food systems significantly. The wider political economy drives a monofunctional and commodity output-oriented agri-food system that generates barriers to developing more diverse and complex systems. Our review suggests strongly that systemic changes may be required at every level. Various elements in the political-economic system need to be transformed to create and sustain an agri-food system that values ecosystem services. Firstly, practically, by restoring, enhancing, and drawing on them through the integration of woody polyculture. Secondly, financially, by remunerating those services and enabling livelihoods based on them. Thirdly, by consistently guiding the degrowth of the monocultural system. These steps are necessary not only to make woodland-based food systems viable, but also the agri-food system in particular, and the economic system as a whole for the benefit of all.

Funding

Faculty of Humanities, Research Recovery Funds 2021–22, The University of Manchester

CRediT authorship contribution statement

Matthew Paterson: Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Ivan Drlička:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Steffen Hirth:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Paul W. Thomas:** Writing – review & editing, Visualization, Validation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Paul W. Thomas reports a relationship with Mycorrhizal Systems Ltd that includes: board membership and equity or stocks.

Acknowledgements

We are grateful to Clara Gooding for drawing the illustrative figure in this article and David Johnson for his helpful comments on previous versions of the manuscript.

Appendix A

Key terms and search strings used to search for literature on Web of Science connecting woodlands with climate change mitigation, biodiversity conservation, and food production

We began the systematic literature review with a brainstorming within our project team and by including input from the project development stage that was provided by colleagues affiliated with the Sustainable Consumption Institute (SCI) and the Manchester Environmental Research Institute (MERI). Key terms to provide focus for the search were:

Table A1
Key terms of the research context

forest		
Afforestation		
Reforestation		
Rewilding		
Woodland expansion		
Regeneration, regenerative		
aboveground-belowground interactions		
mycelium		
hyph* , hyphal networks		
mycorrhiza		
extraradical mycelium		
controlled mycorrhization		
Mitigation	**Conservation**	**Food production**
Net zero	Biodivers*	Semi-wild
emissions	Conservatio*	Semi-cultivated
Zero carbon		Cultiv*
Low carbon	Convivial conservation	“Cultivation systems”
Climate change	Half Earth	Non-timber forest products
Carbon capture	“Bold” conservation	
Carbon storage		fungi, fruit, nuts and seeds, leaves, shoots, foliage, herbs, roots, wild game, medicinal plants
Soil build-up	Biosafety	
Humus	Zoonotic disease transmission	vegan organic
Nature based solutions	Habitat destruction	veganic
	Habitat decline	stockfree
	Biodiversity decline	biocyclic-vegan
	Biodiversity loss	permaculture
		forest garden*
		perennial
		Multiple ecosystem services
		polycultures
		canopy layers

Some of these key terms were discarded as search terms were tailored to focus on the most important ones only. The key terms were combined to longer search strings that were developed to show a manageable amount of hits (<200). A total of 344 studies were subjected to abstract screening and, after removal of both duplicates and studies that mainly focus on tropical climates, 54 studies were chosen for review.

Table A2
Search strings applied in Web of Science

Search strings with key words	Hits	Chosen for review
ALL= (("agroforestry" OR "food forest" OR "forest garden*" OR "permacultur*") AND ("mycelium" OR "mycorrhiza*") AND ("food" OR "NTFP" OR "non-timber forest product*" OR "edible") AND ("food secur*" OR "food sovereign*" OR "biodivers*" OR "conservation" OR "climate change" OR "net zero" OR "carbon capture" OR "nature based solutions"))	38	10
ALL= (("food produc*") AND ("mycelium" OR "mycorrhiza*") AND ("food" OR "NTFP" OR "non-timber forest product*" OR "edible") AND ("food secur*" OR "food sovereign*" OR "biodivers*" OR "conservation" OR "climate change" OR "net zero" OR "carbon capture" OR "nature based solutions"))	61	5
ALL= ("Ectomycorrhizal Fungi") AND (agroforestry OR ("tree*" AND food)) Then refined by filtering papers with: carbon storage (5 results); edible (20 results); fruiting (17 results); cultiv* (16 results); culinary (2 results); food secur* (5 results); then deleting duplicates.	143	13
ALL= ("net zero" OR "carbon storage" AND "climate change" AND mitigation NOT "tropic*") AND (agroforestry OR ("tree*" AND food) OR "food forest" OR "permacult* " OR "forest garden* ")	74	17
ALL= ("climate change" AND mitigation OR "Carbon sink" OR "carbon sequestration" OR "Carbon storage" OR "net zero" OR "low carbon") AND ("food forestry" OR "permacult*" OR "forest garden*" OR "soil built-up" OR "edible forest")	28	9
Total no. of studies	**344**	**54**

Appendix B

The analysis was done by help of an Excel template in which we connected the reference information and abstract to 8 categories: Climate change, biodiversity, food production, social benefits, barriers/enablers of agroforestry, additional comments, additional references (cited in reviewed studies), as well as relevance for the project overall. The categories contained paraphrasing or direct quotes drawn from the 54 studies chosen for full review. Out of these studies, we identified 17, 15, and 22 as of high, medium, and low relevance, respectively. After reviewing the sample of 54 studies, we added a secondary set of 10 references which were not captured by the literature search but quoted in the main sample and contained relevant evidence.

Data from these categories were then aggregated into a synthesis that provided subthemes for the 4 main dimensions (climate change, biodiversity, food production, social benefits) as well as the barriers and enablers of agroforestry. Subthemes and relevant literature comprised:

Table B1
Thematic synthesis of references

Main analytic category	Subthemes	References
Climate Change	Types/Practices of agroforestry and their relation to climate change	Hall and House, 1994; Harland, 2017; Wolz et al., 2018; Bjorklund et al., 2019
	Benefits of land use change/conversion	Haskett et al., 2010; Silver et al., 2004
	Carbon storage, generally	Zomer et al., 2016; Branca et al., 2013
	Carbon storage – soil organic carbon (SOC)	Cardinael et al., 2018; Mirmasoudi et al., 2019
	Carbon storage – fungal biomass as carbon sink	Averill et al., 2014; Cheeke et al., 2017; Guerin-Laguette, 2021; Garcia-Montero et al., 2017; Cardoso and Kuyper, 2006; Baird and Pope, 2022
	Carbon storage – Aboveground vegetation	Bockel and Schiettecatte, 2020; Kay et al., 2018; Schafer et al., 2019; Gomez-Villarino et al., 2021; Wolz et al., 2018
	Carbon storage – timber from aboveground vegetation	Hall and House, 1994
	Finances & carbon sequestration	Bockel and Schiettecatte, 2020
	Modelling of carbon sequestration	Mirmasoudi et al., 2019; Goncalves et al., 2021
	Climate mitigation	Muschler, 2016
	Benefits of ecto-mycorrhizal fungi (EMF)	Guerin-Laguette, 2021; Thomas and Vazquez, 2022; Perez-Moreno et al., 2021
	Tree-mushroom inoculation	Guerin-Laguette, 2021; Thomas and Vazquez, 2022
	Soil inoculation/crop-mushroom inoculation	Srivastava and Singh, 2022; Bardgett and Gibson, 2017
	Regeneration/Restoration	Harland, 2017; Laporta et al., 2021; Srivastava and Singh, 2022
	Climate change as a threat	Thomas and Vazquez, 2022; Moscatelli et al., 2017
	Long-known benefits of agroforestry	Hall and House, 1994; Udawatta et al., 2019; Thomas and Vazquez, 2022
	Disservices/trade-offs	Barnes et al., 2022; Kay et al., 2019; Mayer et al., 2022
Biodiversity Conservation	Agroecological methods	Branca et al., 2013; Bockel and Schiettecatte, 2020; Goncalves et al., 2021; Brodt et al., 2020; Koskey et al., 2021
	Biodiversity in policy	Gomez-Villarino et al., 2021; Barnes et al., 2022; Kay et al., 2019
	Benefits of agroforestry	Hall and House, 1994; Harland, 2017; Laporta et al., 2021; Brodt et al., 2020
	Benefits of inoculation/ecto-mycorrhizal fungi (EMF) systems	Guerin-Laguette, 2021; Thomas and Vazquez, 2022; Guerin-Laguette et al., 2014
	Benefits of (bio)diversity	Branca et al., 2013; Bardgett and Gibson, 2017; Ellison et al., 2017; Saitta et al., 2018
	Benefits of perennials	Hall and House, 1994; Brodt et al., 2020
	Land use change/Reforestation	Hall and House, 1994; Haskett et al., 2010; Baird and Pope, 2022
	Risks/disservices of monoculture	Hall and House, 1994; Bockel and Schiettecatte, 2020; Thomas and Vazquez, 2022; Moscatelli et al., 2017; Ellison et al., 2017; Baird and Pope, 2022; Goncalves et al., 2021; Laporta et al., 2021
	Risks/disservices of perennials	Hall and House, 1994
	Risks/disservices of forest management	Azul et al., 2011
	Risks/disservices of unmanaged forests	Laporta et al., 2021
	Trade-offs/disservices of bioeconomy	Neumann et al., 2016
	Risks of tree-planting	Baird and Pope, 2022
	Quantified biodiversity	Kay et al., 2018; Neumann et al., 2016
Food Production	Multiple benefits, incl. food	Bockel and Schiettecatte, 2020; Thomas and Vazquez, 2022
	Benefits of perennials	Haskett et al., 2010; Branca et al., 2013
	Evidence indicating productivity benefits of agroforestry	Cardinael et al., 2018; Garcia-Montero et al., 2017; Wolz et al., 2018; Goncalves et al., 2021; Laporta et al., 2021; Mahieu et al., 2016; Perry et al., 1989; Campi et al., 2009; Bjorklund et al., 2019
	Evidence indicating productivity disbenefits of agroforestry	Hall and House, 1994; Zomer et al., 2016; Branca et al., 2013; Kay et al., 2019; Bjorklund et al., 2019
	Disservices/costs	Mayer et al., 2022; Goncalves et al., 2021; Fitton et al., 2011
	Design optimisation	Bjorklund et al., 2019
	Land use change/restoration	Haskett et al., 2010; Harland, 2017; Ellison et al., 2017; Brain et al., 2017; Oria-de-Rueda et al., 2010
	Edible mushroom species	Guerin-Laguette, 2021; Thomas and Vazquez, 2022; Guerin-Laguette et al., 2014; Oria-de-Rueda et al., 2010; Hyde et al., 2019; Perez-Moreno et al., 2021
	Soil – activity of symbiotic organisms	Garcia-Montero et al., 2017; Cardoso and Kuyper, 2006; Wolz et al., 2018; Goncalves et al., 2021; Mahieu et al., 2016; Perry et al., 1989; Campi et al., 2009
	Spatial frugality/urban application of food forestry	Guerin-Laguette, 2021
	Improving ecosystem services	Ellison et al., 2017; Goncalves et al., 2021
	Food security through diversification	Udawatta et al., 2019; Bockel and Schiettecatte, 2020; Kay et al., 2018
Social benefits	Cultural ecosystem services	Smith et al., 2013; Marchi et al., 2018
	Benign working environment	Bjorklund et al., 2019
	Green infrastructure	Gomez-Villarino et al., 2021; Kay et al., 2019
	Ecosystem services – definition and societal significance	Kay et al., 2018; Ellison et al., 2017; Laporta et al., 2021; Neumann et al., 2016; Marchi et al., 2018
	Global benefits	Thomas and Vazquez, 2022; Ellison et al., 2017
	Income diversification	Guerin-Laguette, 2021; Bockel and Schiettecatte, 2020 Barnes et al., 2022; Goncalves et al., 2021; Oria-de-Rueda et al., 2010; Winans et al., 2016
	Poverty alleviation/prevention	Hall and House, 1994; Haskett et al., 2010; Zomer et al., 2016; Branca et al., 2013; Smith et al., 2013; Marchi et al., 2018
	Tradition	Muschler, 2016; Smith et al., 2013; Marchi et al., 2018
	Creating/designing social benefits	Brain et al., 2017
	Disservices/challenges	Hall and House, 1994; Baird and Pope, 2022
Barriers to woodland-based food systems	Productivism	Harland, 2017; Barnes et al., 2022; Kay et al., 2019; Brodt et al., 2020; Bjorklund et al., 2019
	Mono-functionalism/monoculture	Gomez-Villarino et al., 2021; Thomas and Vazquez, 2022; Wolz et al., 2018; Kay et al., 2019; Brodt et al., 2020; Bjorklund et al., 2019; Marchi et al., 2018
	Short-term profit focus	Fitton et al., 2011

(*continued on next page*)

Table B1 (*continued*)

Main analytic category	Subthemes	References
	Labour & organisation	Hall and House, 1994; Cardoso and Kuyper, 2006; Brodt et al., 2020; Bjorklund et al., 2019
	Translational barriers	Gomez-Villarino et al., 2021
	Carbon sequestration schemes	Haskett et al., 2010
Enablers of woodland-based food systems	Societal need for sustainable production	Bardgett and Gibson, 2017; Koskey et al., 2021; Bjorklund et al., 2019; Hyde et al., 2019
	Multiple/multifactorial benefits	Zomer et al., 2016; Wolz et al., 2018; Bardgett and Gibson, 2017; Mayer et al., 2022; Brodt et al., 2020
	Multi-functionalism/polyculture	Hall and House, 1994; Wolz et al., 2018; Brain et al., 2017; Oria-de-Rueda et al., 2010
	Diversity & complexity	Wolz et al., 2018; Kay et al., 2019; Koskey et al., 2021
	Labour & organisation	Brodt et al., 2020; Bjorklund et al., 2019; Oria-de-Rueda et al., 2010
	Carbon sequestration schemes	Zomer et al., 2016; Mayer et al., 2022; Laporta et al., 2021; Brodt et al., 2020; Winans et al., 2016
	Tools & technologies	Goncalves et al., 2021; Bjorklund et al., 2019; Perez-Moreno et al., 2021
	Scientific research	Goncalves et al., 2021; Brodt et al., 2020; Perez-Moreno et al., 2021
	Translational work	Bardgett and Gibson, 2017; Kay et al., 2019; Brodt et al., 2020

Data availability

Data will be made available on request.

References

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-resilient farming systems. Agron. Sustain. Dev. 35, 869–890. https://doi.org/10.1007/s13593-015-0285-2.

Anson, A., 2020. "Master Metaphor": Environmental Apocalypse and the Settler States of Emergency. Resilience 8, 60–81. https://doi.org/10.1353/res.2020.0037.

Arehart, J.H., Hart, J., Pomponi, F., D'Amico, B., 2021. Carbon sequestration and storage in the built environment. Sustain. Prod. Consum. 27, 1047–1063. https://doi.org/10.1016/j.spc.2021.02.028.

Averill, C., Turner, B.L., Finzi, A.C., 2014. Mycorrhiza-mediated competition between plants and decomposers drives soil carbon storage. Nature 505, 543–545. https://doi.org/10.1038/nature12901.

Azul, A., Mendes, S., Sousa, J., Freitas, H., 2011. Fungal fruitbodies and soil macrofauna as indicators of land use practices on soil biodiversity in Montado. Agrofor. Syst. 82, 121–138. https://doi.org/10.1007/s10457-010-9359-y.

Baird, A., Pope, F., 2022. Can't see the forest for the trees": The importance of fungi in the context of UK tree planting. FOOD ENERGY SECURITY. https://doi.org/10.1002/fes3.371.

Balandier, P., Dupraz, C., 1998. Growth of widely spaced trees. A case study from young agroforestry plantations in France. Agrofor. Syst. 43, 151. https://doi.org/10.1023/A:1026480028915.

Bardgett, R.D., Gibson, D.J., 2017. Plant ecological solutions to global food security. J. Ecol. 105, 859–864. https://doi.org/10.1111/1365-2745.12812.

Bardgett, R.D., Bullock, J.M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., Chomel, M., Durigan, G., L. Fry, E., Johnson, D., Lavallee, J.M., Le Provost, G., Luo, S., Png, K., Sankaran, M., Hou, X., Zhou, H., Ma, L., Ren, W., Li, X., Ding, Y., Li, Y., Shi, H., 2021. Combatting global grassland degradation. Nat. Rev. Earth Environ. 2, 720–735. https://doi.org/10.1038/s43017-021-00207-2.

Barnes, A., McMillan, J., Sutherland, L., Hopkins, J., Thomson, S., 2022. Farmer intentional pathways for net zero carbon: Exploring the lock-in effects of forestry and renewables. LAND USE POLICY 112. https://doi.org/10.1016/j.lusepol.2021.105861.

Bjorklund, J., Eksvard, K., Schaffer, C., 2019. Exploring the potential of edible forest gardens: experiences from a participatory action research project in Sweden. Agrofor. Syst. 93, 1107–1118. https://doi.org/10.1007/s10457-018-0208-8.

Bockel, L., Schiettecatte, L., 2020. Agriculture, Landscape and Food Value Chain Transformation as Key Engines in Climate Change Mitigation: A Review of Some Low-Carbon Policy Options and Implementation Mechanisms. Glob. Clim. Chang. Environ. POLICY: AGRICULTURE Perspect. https://doi.org/10.1007/978-981-13-9570-3_10.

Brain, R., Adams, J., Lynch, J., 2017. MITIGATING PROJECTED IMPACTS OF CLIMATE CHANGE AND BUILDING RESILIENCY THROUGH PERMACULTURE: A COMMUNITY "BEE INSPIRED GARDENS" MOVEMENT IN THE DESERT SOUTHWEST, USA, in: Brebbia, C., Sendra, J. (Eds.),. Presented at the SUSTAINABLE CITY XII, pp. 505–515. https://doi.org/10.2495/SC170441.

Branca, G., Lipper, L., McCarthy, N., Jolejole, M., 2013. Food security, climate change, and sustainable land management. A review. Agron. Sustain. Dev. 33, 635–650. https://doi.org/10.1007/s13593-013-0133-1.

Brand, U., Wissen, M., 2021. The Imperial Mode of Living: Everyday Life and the Ecological Crisis of Capitalism. Verso, London, New York.

Brodt, S., Fontana, N., Archer, L., 2020. Feasibility and sustainability of agroforestry in temperate industrialized agriculture: preliminary insights from California. Renew. AGRICULTURE FOOD Syst. 35, 513–521. https://doi.org/10.1017/S1742170519000140.

Brown, S., Masera, O., Sathaye, J., 2000. Project-based activities. in: Land Use, Land-Use Change, and Forestry, A Special Report of the IPCC. Cambridge. University Press, Cambridge, UK, pp. 283–338.

Büscher, B., Fletcher, R., 2019. Towards Convivial Conservation. Conserv. Soc. 17, 283. https://doi.org/10.4103/cs.cs_19_75.

Campi, P., Palumbo, A.D., Mastrorilli, M., 2009. Effects of tree windbreak on microclimate and wheat productivity in a Mediterranean environment. Eur. J. Agron. 30, 220–227. https://doi.org/10.1016/j.eja.2008.10.004.

Cardinael, R., Guenet, B., Chevallier, T., Dupraz, C., Cozzi, T., Chenu, C., 2018. High organic inputs explain shallow and deep SOC storage in a long-term agroforestry system - combining experimental and modeling approaches. BIOGEOSCIENCES 15, 297–317. https://doi.org/10.5194/bg-15-297-2018.

Cardoso, I.M., Kuyper, T.W., 2006. Mycorrhizas and tropical soil fertility. Agric., Ecosyst. Environ., Nutr. Manag. Trop. Agroecosystems 116, 72–84. https://doi.org/10.1016/j.agee.2006.03.011.

Castle, S.E., Miller, D.C., Merten, N., Ordonez, P.J., Baylis, K., 2022. Evidence for the impacts of agroforestry on ecosystem services and human well-being in high-income countries: a systematic map. Environ. Evid. 11, 10. https://doi.org/10.1186/s13750-022-00260-4.

Ceballos, G., Ehrlich, P.R., Barnosky, A.D., García, A., Pringle, R.M., Palmer, T.M., 2015. Accelerated modern human–induced species losses: Entering the sixth mass extinction. Sci. Adv. 1, e1400253. https://doi.org/10.1126/sciadv.1400253.

Cheeke, T.E., Phillips, R.P., Brzostek, E.R., Rosling, A., Bever, J.D., Fransson, P., 2017. Dominant mycorrhizal association of trees alters carbon and nutrient cycling by selecting for microbial groups with distinct enzyme function. N. Phytol. 214, 432–442. https://doi.org/10.1111/nph.14343.

Chifflot, V., Bertoni, G., Cabanettes, A., Gavaland, A., 2006. Beneficial Effects of Intercropping on the Growth and Nitrogen Status of Young Wild Cherry and Hybrid Walnut Trees. Agroforest Syst. 66, 13–21. https://doi.org/10.1007/s10457-005-3650-3.

Committee on Climate Change, 2020. Land use: Policies for a Net Zero UK.

Crawford, M., 2010. Creating a Forest Garden: Working with nature to grow edible crops. Green Books, Cambridge.

Crutzen, P.J., 2002. Geology of mankind. Nature 415, 23. https://doi.org/10.1038/415023a.

Ellison, D., Morris, C., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., van Noordwijk, M., Creed, I., Pokorny, J., Gaveau, D., Spracklen, D., Tobella, A., Ilstedt, U., Teuling, A., Gebrehiwot, S., Sands, D., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., Sullivan, C., 2017. Trees, forests and water: Cool insights for a hot world. Glob. Environ. Chang.-Hum. POLICY DIMENSIONS 43, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002.

Fitton, N., Ejerenwa, C., Bhogal, A., Edgington, P., Black, H., Lilly, A., Barraclough, D., Worrall, F., Hillier, J., Smith, P., 2011. Greenhouse gas mitigation potential of agricultural land in Great Britain. SOIL USE Manag. 27, 491–501. https://doi.org/10.1111/j.1475-2743.2011.00365.x.

Forster, E.J., Healey, J.R., Dymond, C., Styles, D., 2021. Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. Nat. Commun. 12, 3831. https://doi.org/10.1038/s41467-021-24084-x.

Garcia-Montero, L., Manzano, P., Alwanney, D., Valverde-Asenjo, I., Alvarez-Lafuente, A., Benito-Matias, L., Parlade, X., Ortuno, S., Morcillo, M., Gasco, A., Calderon-Guerrero, C., Mauro, F., Mendez, M., Sanchez-Medina, A., Andres, M., Quintana, J., Menta, C., Pinto, S., Pinto, L., Pita, P., Turkmen, C., Pascual, C., Ayuga, E., Torrent, F., Robredo, J., Martin-Ortega, P., Pera, J., Gomez, L., Almendros, G., Colinas, C., Verrecchia, E., 2017. Towards Integrated Understanding of the Rhizosphere Phenomenon as Ecological Driver: Can Rhizoculture Improve Agricultural and Forestry Systems? In: Lukac, M., Grenni, P., Gamboni, M. (Eds.), Presented at the SOIL BIOLOGICAL COMMUNITIES AND ECOSYSTEM RESILIENCE, pp. 43–75. https://doi.org/10.1007/978-3-319-63336-7_4.

Gomez-Villarino, M., Villarino, M., Ruiz-Garcia, L., 2021. Implementation of Urban Green Infrastructures in Peri-Urban Areas: A Case Study of Climate Change Mitigation in Madrid. Agron.-BASEL 11. https://doi.org/10.3390/agronomy11010031.

Goncalves, B., Morais, M., Pereira, S., Mosquera-Losada, M., Santos, M., 2021. Tree-Crop Ecological and Physiological Interactions Within Climate Change Contexts: A Mini-Review. Front. Ecol. EVOLUTION 9. https://doi.org/10.3389/fevo.2021.661978.

Graves, A.R., Burgess, P.J., Palma, J.H.N., Herzog, F., Moreno, G., Bertomeu, M., Dupraz, C., Liagre, F., Keesman, K., van der Werf, W., de Nooy, A.K., van den Briel, J. P., 2007. Development and application of bio-economic modelling to compare silvoarable, arable, and forestry systems in three European countries. Ecol. Eng., Carbon sequestration Landsc. Ecol. West. Eur. 29, 434–449. https://doi.org/10.1016/j.ecoleng.2006.09.018.

Guerin-Laguette, A., 2021. Successes and challenges in the sustainable cultivation of edible mycorrhizal fungi - furthering the dream. MYCOSCIENCE 62, 10–28. https://doi.org/10.47371/mycosci.2020.11.007.

Guerin-Laguette, A., Cummings, N., Butler, R.C., Willows, A., Hesom-Williams, N., Wang, Y., 2014. Lactarius deliciosus and Pinus radiata in New Zealand: towards the development of innovative gourmet mushroom orchards. Mycorrhiza 24, 511–523. https://doi.org/10.1007/s00572-014-0570-y.

Hall, D.O., House, J.I., 1994. Trees and biomass energy: Carbon storage and/or fossil fuel substitution? Biomass-.-. Bioenergy 6, 11–30. https://doi.org/10.1016/0961-9534(94)90081-7.

Harland, M., 2017. Permaculture: Tools for Making Women's Lives More Abundant. FEMINIST THEOLOGY 25, 240–247. https://doi.org/10.1177/0966735017693769.

Haskett, J., Schlamadinger, B., Brown, S., 2010. Land-based carbon storage and the European union emissions trading scheme: the science underlying the policy. Mitig. Adapt. Strateg. Glob. Chang. 15, 127–136. https://doi.org/10.1007/s11027-009-9202-9.

Hyde, K., Xu, J., Rapior, S., Jeewon, R., Lumyong, S., Niego, A., Abeywickrama, P., Aluthmuhandiram, J., Brahamanage, R., Brooks, S., Chaiyasen, A., Chethana, K., Chomnunti, P., Chepkirui, C., Chuankid, B., de Silva, N., Doilom, M., Faulds, C., Gentekaki, E., Gopalan, V., Kakumyan, P., Harishchandra, D., Hemachandran, H., Hongsanan, S., Karunarathna, A., Karunarathna, S., Khan, S., Kumla, J., Jayawardena, R., Liu, J., Liu, N., Luangharn, T., Macabeo, A., Marasinghe, D., Meeks, D., Mortimer, P., Mueller, P., Nadir, S., Nataraja, K., Nontachaiyapoom, S., O'Brien, M., Penkhrue, W., Phukhamsakda, C., Ramanan, U., Rathnayaka, A., Sadaba, R., Sandargo, B., Samarakoon, B., Tennakoon, D., Siva, R., Sriprom, W., Suryanarayanan, T., Sujarit, K., Suwannarach, N., Suwunwong, T., Thongbai, B., Thongklang, N., Wei, D., Wijesinghe, S., Winiski, J., Yan, J., Yasanthika, E., Stadler, M., 2019. The amazing potential of fungi: 50 ways we can exploit fungi industrially. FUNGAL DIVERSITY 97, 1–136. https://doi.org/10.1007/s13225-019-00430-9.

IUCN, 2024. UK Peatlands [WWW Document]. IUCN UK Peatland Programme. URL https://www.iucn-uk-peatlandprogramme.org/about-peatlands/uk-peatlands.

Kay, S., Crous-Duran, J., de Jalon, S., Graves, A., Palma, J., Roces-Diaz, J., Szerencsits, E., Weibel, R., Herzog, F., 2018. Landscape-scale modelling of agroforestry ecosystems services in Swiss orchards: a methodological approach. Landsc. Ecol. 33, 1633–1644. https://doi.org/10.1007/s10980-018-0691-3.

Kay, S., Rega, C., Moreno, G., den Herder, M., Palma, J., Borek, R., Crous-Duran, J., Freese, D., Giannitsopoulos, M., Graves, A., Jager, M., Lamersdorf, N., Memedemin, D., Mosquera-Losada, R., Pantera, A., Paracchini, M., Pari, P., Roces-Diaz, J., Rolo, V., Rosati, A., Sandor, M., Smith, J., Szerencsits, E., Varga, A., Viaud, V., Wawer, R., Burgess, P., Herzog, F., 2019. Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. LAND USE POLICY 83, 581–593. https://doi.org/10.1016/j.landusepol.2019.02.025.

Keyßer, L.T., Lenzen, M., 2021. 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. Nat. Commun. 12, 2676. https://doi.org/10.1038/s41467-021-22884-9.

Koskey, G., Mburu, S.W., Awino, R., Njeru, E.M., Maingi, J.M., 2021. Potential Use of Beneficial Microorganisms for Soil Amelioration, Phytopathogen Biocontrol, and Sustainable Crop Production in Smallholder Agroecosystems. Front. Sustain. Food Syst. 5.

Laporta, L., Domingos, T., Marta-Pedroso, C., 2021. It's a keeper: Valuing the carbon storage service of Agroforestry ecosystems in the context of CAP Eco-Schemes. LAND USE POLICY 109. https://doi.org/10.1016/j.lusepol.2021.105712.

Mahieu, S., Metay, A., Brunel, B., Dufour, L., 2016. Nitrogen fluxes in chickpea grown in Mediterranean agroforestry systems. Agroforest Syst. 90, 313–324. https://doi.org/10.1007/s10457-015-9856-0.

Marchi, E., Chung, W., Visser, R., Abbas, D., Nordfjell, T., Mederski, P., McEwan, A., Brink, M., Laschi, A., 2018. Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate. Sci. TOTAL Environ. 634, 1385–1397. https://doi.org/10.1016/j.scitotenv.2018.04.084.

Mayer, S., Wiesmeier, M., Sakamoto, E., Hubner, R., Cardinael, R., Kuhnel, A., Kogel-Knabner, I., 2022. Soil organic carbon sequestration in temperate agroforestry systems - A meta-analysis. AGRICULTURE ECOSYSTEMS Environ. 323. https://doi.org/10.1016/j.agee.2021.107689.

Mirmasoudi, S., Byrne, J., Kroebel, R., Johnson, D., MacDonald, R., 2019. Modelling historical and potential future climate impacts on Keremeos Creek, an Okanagan-Similkameen watershed, British Columbia, Canada: Part II. Forecasting change in farm-level greenhouse gas emissions. Can. WATER Resour. J. 44, 367–381. https://doi.org/10.1080/07011784.2019.1640138.

Moore, J.W., 2016. The Rise of Cheap Nature. In: Moore, J.W. (Ed.), Anthropocene or Capitalocene? Nature, History and the Crisis of Capitalism. PM Press, Oakland, CA, pp. 78–115.

Moscatelli, M., Bonifacio, E., Chiti, T., Cudlin, P., Dinca, L., Gomoryova, E., Grego, S., La Porta, N., Karlinski, L., Pellis, G., Rudawska, M., Squartini, A., Zhiyanski, M., Broll, G., 2017. Soil properties as indicators of treeline dynamics in relation to anthropogenic pressure and climate change. Clim. Res. 73, 73–84. https://doi.org/10.3354/cr01478.

Muschler, R., 2016. Agroforestry: Essential for Sustainable and Climate-Smart Land Use?, TROPICAL FORESTRY HANDBOOK, 2ND EDITION. https://doi.org/10.1007/978-3-642-54601-3_300.

Neumann, M., Moreno, A., Thurnher, C., Mues, V., Harkonen, S., Mura, M., Bouriaud, O., Lang, M., Cardellini, G., Thivolle-Cazat, A., Bronisz, K., Merganic, J., Alberdi, I., Astrup, R., Mohren, F., Zhao, M., Hasenauer, H., 2016. Creating a Regional MODIS Satellite-Driven Net Primary Production Dataset for European Forests. REMOTE Sens. 8. https://doi.org/10.3390/rs8070554.

Oncini, F., Hirth, S., Mylan, J., Robinson, C.H., Johnson, D., 2024. Where the wild things are: How urban foraging and food forests can contribute to sustainable cities in the Global North. Urban For. Urban Green. 93, 128216. https://doi.org/10.1016/j.ufug.2024.128216.

Oria-de-Rueda, J., Hernandez-Rodriguez, M., Martin-Pinto, P., Pando, V., Olaizola, J., 2010. Could artificial reforestations provide as much production and diversity of fungal species as natural forest stands in marginal Mediterranean areas? For. Ecol. Manag. 260, 171–180. https://doi.org/10.1016/j.foreco.2010.04.009.

Perez-Moreno, J., Guerin-Laguette, A., Rinaldi, A., Yu, F., Verbeken, A., Hernandez-Santiago, F., Martinez-Reyes, M., 2021. Edible mycorrhizal fungi of the world: What is their role in forest sustainability, food security, biocultural conservation and climate change? PLANTS PEOPLE PLANET 3, 471–490. https://doi.org/10.1002/ppp3.10199.

Perry, D.A., Margolis, H., Choquette, C., Molina, R., Trappe, J.M., 1989. Ectomycorrhizal Mediation of Competition between Coniferous Tree Species. N. Phytol. 112, 501–511.

Prashar, P., Shah, S., 2016. Impact of Fertilizers and Pesticides on Soil Microflora in Agriculture. In: Lichtfouse, E. (Ed.), Sustainable Agriculture Reviews: Volume 19, Sustainable Agriculture Reviews. Springer International Publishing, Cham, pp. 331–361. https://doi.org/10.1007/978-3-319-26777-7_8.

Redžić, S., 2010. Use of wild and semi-wild edible plants in nutrition and survival of people in 1430 days of siege of Sarajevo during the war in Bosnia and Herzegovina (1992-1995). Coll. Antropol. 34, 551–570.

Renard, D., Tilman, D., 2019. National food production stabilized by crop diversity. Nature 571, 257–260. https://doi.org/10.1038/s41586-019-1316-y.

Reyna, S., Garcia-Barreda, S., 2014. Black truffle cultivation: a global reality. For. Syst. 23, 317–328. https://doi.org/10.5424/fs/2014232-04771.

Saitta, A., Anslan, S., Bahram, M., Brocca, L., Tedersoo, L., 2018. Tree species identity and diversity drive fungal richness and community composition along an elevational gradient in a Mediterranean ecosystem. MYCORRHIZA 28, 39–47. https://doi.org/10.1007/s00572-017-0806-8.

Schafer, L., Lysak, M., Henriksen, C., 2019. Tree layer carbon stock quantification in a temperate food forest: A peri-urban polyculture case study. URBAN FORESTRY URBAN Green. 45. https://doi.org/10.1016/j.ufug.2019.126466.

Schroth, G., Bede, L., Paiva, A., Cassano, C., Amorim, A., Faria, D., Mariano-Neto, E., Martini, A., Sambuichi, R., Lobo, R., 2015. Contribution of agroforests to landscape carbon storage. Mitig. Adapt. Strateg. Glob. Chang. 20, 1175–1190. https://doi.org/10.1007/s11027-013-9530-7.

Sharma, S., Ramesh, A., Sharma, M., Joshi, O., Govaerts, B., Steenwerth, K., Karlen, D., 2010. Microbial Community Structure and Diversity as Indicators for Evaluating Soil Quality. In: Lichtfouse, E. (Ed.), BIODIVERSITY, BIOFUELS, AGROFORESTRY AND CONSERVATION AGRICULTURE, pp. 317–358. https://doi.org/10.1007/978-90-481-9513-8_11.

Silver, W.L., Kueppers, L.M., Lugo, A.E., Ostertag, R., Matzek, V., 2004. Carbon Sequestration and Plant Community Dynamics Following Reforestation of Tropical Pasture. Ecol. Appl. 14, 1115–1127. https://doi.org/10.1890/03-5123.

Smith, J., Pearce, B., Wolfe, M., 2013. Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? Renew. AGRICULTURE FOOD Syst. 28, 80–92. https://doi.org/10.1017/S1742170511000585.

Srivastava, P., Singh, N., 2022. Effects of microbial inoculants on soil carbon stock, enzymatic activity, and above ground and belowground biomass in marginal lands of Northern India. LAND Degrad. Dev. 33, 308–323. https://doi.org/10.1002/ldr.4153.

Stratton, A.E., Kuhl, L., Blesh, J., 2020. Ecological and Nutritional Functions of Agroecosystems as Indicators of Smallholder Resilience. Front. Sustain. Food Syst. 4.

Sun, Z., Scherer, L., Tukker, A., Spawn-Lee, S.A., Bruckner, M., Gibbs, H.K., Behrens, P., 2022. Dietary change in high-income nations alone can lead to substantial double climate dividend. Nat. Food 3, 29–37. https://doi.org/10.1038/s43016-021-00431-5.

Thioye, B., Legras, M., Castel, L., Hirissou, F., Chaftar, N., Trinsoutrot-Gattin, I., 2022. Understanding Arbuscular Mycorrhizal Colonization in Walnut Plantations: The Contribution of Cover Crops and Soil Microbial Communities. Agriculture 12 (1). https://doi.org/10.3390/agriculture12010001.

Thomas, P., Büntgen, U., 2019. A risk assessment of Europe's black truffle sector under predicted climate change. Sci. Total Environ. 655, 27–34. https://doi.org/10.1016/j.scitotenv.2018.11.252.

Thomas, P.W., Jump, A.S., 2023. Edible mycorrhiza cultivation potential by bioclimatic zone as a novel carbon negative food source and enhancer of food security. PNAS 120 (12), e2220079120. https://doi.org/10.1073/pnas.2220079120.

Thomas, P.W., Vazquez, L.-B., 2022. A novel approach to combine food production with carbon sequestration, biodiversity and conservation goals. Sci. Total Environ. 806, 151301. https://doi.org/10.1016/j.scitotenv.2021.151301.

Torralba, M., Fagerholm, N., Burgess, P.J., Moreno, G., Plieninger, T., 2016. Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. Agric., Ecosyst. Environ. 230, 150–161. https://doi.org/10.1016/j.agee.2016.06.002.

Udawatta, R., Rankoth, L., Jose, S., 2019. Agroforestry and Biodiversity. SUSTAINABILITY 11. https://doi.org/10.3390/su11102879.

Ward, N., 1993. The Agricultural Treadmill and the Rural Environment in the Post-Productivist Era. Sociol. Rural. 33, 348–364. https://doi.org/10.1111/j.1467-9523.1993.tb00969.x.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet Comm. 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Winans, K., Whalen, J., Rivest, D., Cogliastro, A., Bradley, R., 2016. Carbon Sequestration and Carbon Markets for Tree-Based Intercropping Systems in Southern Quebec, Canada. ATMOSPHERE 7. https://doi.org/10.3390/atmos7020017.

Wolz, K., Lovell, S., Branham, B., Eddy, W., Keeley, K., Revord, R., Wander, M., Yang, W., DeLucia, E., 2018. Frontiers in alley cropping: Transformative solutions for temperate agriculture. Glob. Chang. Biol. 24, 883–894. https://doi.org/10.1111/gcb.13986.

Ziai, A., 2015. Development Discourse and Global History: From Colonialism to the Sustainable Development Goals. Routledge, London.

Zomer, R., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., van Noordwijk, M., Wang, M., 2016. Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. Sci. Rep. 6. https://doi.org/10.1038/srep29987.