Protecting forests and trees is essential for global agricultural productivity

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Balancing forest conservation and agricultural production is essential for a sustainable future. Here we review the scientific evidence for the relationships between forests and agricultural productivity across different scales, summarizing the contexts under which trees limit, maintain, or enhance agricultural productivity. While synergies and trade-offs occur at local scales, a regional-scale meta-analysis reveals mostly positive effects of forests and average national-level agricultural productivity is projected to decline once forest cover loss exceeds ~48%, with a 95% confidence interval [44, 50]. Given that 70% of countries have already reached or exceeded this threshold, implementing targeted forest conservation and restoration policies may be critical to optimize national food security. At a global scale, mass deforestation remains a key threat to international food production.

In recent decades, there has been a growing awareness of the need to conserve and restore natural areas in agricultural landscapes, including forests and wetlands, to tackle the joint threats of biodiversity loss and climate change[1,2]. However, despite growing political momentum for the protection of these ecosystems[3,4,5], progress is still extremely limited[6,7]. A major challenge at the political level is the concern that commitments to nature will come at the expense of agricultural productivity. For example, the development of the landmark EU Nature Restoration law was entangled in a conflict with the agricultural sector, with concerns that nature protection will limit the land available for agriculture in the coming decades[8,9].

The balance between natural forests and agriculture thus presents one of our greatest sustainability challenges, as concerns grow about a possible trade-off between ecological integrity and food production[10,11]. However, despite the widespread assumption that forests or woody landscape features come at the expense of agricultural production[8,12], empirical evidence does not support this direct trade-off under all contexts and scales. A growing body of research highlights that, although forests and farmland can't always coexist in the same small area (i.e. at the farm scale), integrating a natural diversity of woody plants in landscapes with farms can enhance soil and water quality, microclimate, and pollinator activity[13,14], leading to enhancement in yields in certain contexts[15]. These synergies between agriculture and forests are even more apparent at larger spatial scales[16–18], where the maintenance of forests is in fact essential for agricultural productivity. As such, the continued loss of forests could jeopardize food production at national and continental scales, just as ecological degradation destabilized human civilization in the past[19]. Understanding when and where these benefits occur may be critical for balancing environmental needs with the food demands of a growing population.

Despite the critical importance of this topic, we still lack a scientific consensus on the relationship between forests or woody vegetation and agricultural productivity across spatial scales. A considerable body of literature explores the local trade-offs and synergies between forests and agricultural productivity, mostly in the tropics[20], but conflicting results in different regions have obscured the search for unifying trends[21–25]. In this review, we synthesize the scientific evidence for the relationships between forests, trees, or hedges and agricultural productivity from local to global scales. Using quantitative insights from large-scale yield datasets, modeling studies, and historical examples of forest and tree removal, we summarize the contexts under which forests and woody vegetation can increase, maintain, or decrease agricultural productivity.

1. Ecological mechanisms of tree impacts on agricultural productivity

Plants compete for essential resources such as space, light, water, nutrients, and pollinators. This competition can occur through direct mechanisms, like antagonism, or indirect ones, such as resource exploitation[26,27]. When competitive imbalance between species is high, the weaker species may risk being displaced[26,27]. The existence of such competitive dynamics among plants has driven the development of contemporary cropping systems where non-focal plant species, including trees, are removed to minimize competition and enhance crop productivity.

However, while removing non-crop species can limit the negative effects of competition, it also eliminates beneficial interactions, such as commensalism and facilitation, which are central to crop production. In fact, coexistence theory suggests that when interacting species occupy distinct ecological niches, positive interactions may outweigh the negative competitive effects[28]. Such "niche dissimilarity" is often large between crop plants and woody trees[29,30], giving rise to a range of positive associations that can enhance the productivity of both.

Importantly, the interplay between these positive and negative interactions is scale-dependent[31]. Even if competition may occur between species at smaller scales, the influence of direct competition diminishes as we move to larger scales, such as entire farms or landscapes. At these broader scales, the impacts of forests on crop development are expected to become more and more beneficial, indirectly improving soil conditions, regulating temperature and moisture, and enhancing pollination services. In the following sections, we explore the ecological mechanisms driving these indirect interactions, focusing on how trees and forests influence agricultural productivity.

Soil and nutrient retention

Changes in soil health may be the most immediate and consistent impact of integrating trees within agricultural landscapes[32]. Trees contribute substantial organic matter to the soil through leaf litter and root exudates. The resulting accumulation of soil organic carbon (SOC)[33] facilitates the formation of soil aggregates, improving soil structure and enhancing its ability to retain nutrients and moisture. A study in northern Ethiopia found that under tree canopies, SOC, total nitrogen, available phosphorus, and exchangeable potassium increased by 12-92%, 22-125%, 31-71%, and 32-152%, respectively, compared to areas outside the canopy[34]. Comparable findings have been reported in several regional and global meta-analyses[35–37]. This change in soil properties can directly affect crop yields. A meta-analysis of 150 farms showed that for every 1% increase in SOC from external carbon additions, crop yields increased by an average of 0.4%[38].

Additionally, tree litter and root exudates provide essential resources to microbial communities, including amino acids, sugars, and organic acids[39]. This leads to increased microbial biomass, which is vital for nutrient cycling and soil structure formation, enhancing soil health in tree-integrated cropping systems compared to sole cropping systems[40–42]. In eastern Iowa, USA, systems with trees had higher microbial biomass stocks (1.70 Mg C and 0.24 Mg N per hectare) compared to conventional systems (1.36 Mg C and 0.14 Mg N per hectare)[40]. Trees also help optimize fertilizer use and mitigate their environmental impacts by decreasing nitrogen and phosphorus fertilizer residues by 20% to 100%[43]. Overall, the integration of trees and crops can enhance soil health, provide soil stability against erosion, increase nutrient availability, minimize the need for external fertilizers, and reduce the risks associated with agrochemicals.

Microclimate

Trees influence microclimates in agricultural systems in three ways. First, they provide shade, reducing surface temperatures and buffering against temperature extremes[44–46]. Second, their enhanced evapotranspiration contributes to evaporative cooling[46,47]. Third, trees offer protection from wind and heavy rainfall[44,48]. Tree's buffering effects on temperature can be substantial, with great potential for climate change adaptation in agriculture[49,50]. For example, individual trees in Ethiopian smallholder wheat cropping systems and Ghanaian cocoa farms reduce maximum daily temperatures by up to 6°C and 7°C, respectively, compared to unshaded areas[51,52]. However, the impact of trees on agricultural microclimates depends on factors like tree density, spatial arrangement, and tree species' functional traits[44,45,49,53–55]. Higher tree densities have been linked to greater buffering effects on temperature and relative humidity in cocoa and coffee farms[49,53], while the effectiveness of trees as windbreaks is determined by the height, length, density, and orientation of tree rows[44,56].

The microclimate changes can positively affect crops and pasture systems by maintaining optimal growing conditions[49,57,58]. In temperate regions, trees can extend grazing seasons and enhance forage growth[59]. Additionally, providing shade for livestock reduces heat and cold stress, leading to better feed conversion, increased weight gain, and higher milk yields[59–61]. However, certain tree species and planting densities can cause excessive shading and increased evapotranspiration, potentially reducing crop productivity by limiting light for photosynthesis and intensifying competition for water[49,57,62,63]. For example, in Ghanaian cocoa farms, tree species that reduced light by 32% had no negative impact on yield, whereas trees reducing light by 88% adversely affected yield[45]. Moreover, yield responses to shading vary widely among crops and cultivars, depending on factors such as shade tolerance, farm age, and local biophysical conditions[44,57,62]. For example, in Belgium's temperate alley cropping systems—agricultural practices that involve growing rows of crops between rows of trees—maize, potato, winter wheat, and winter barley yields were minimally affected by young tree rows, while significant yield reductions were observed for maize and potato near mature trees [64]. Similarly, in *Coffea arabica* cultivars, increasing shade had mixed effects—ranging from no change, to decreases, to an initial increase followed by a decrease at higher shade levels[62]. These examples highlight the complexity of tree's impact on agricultural production, even within a single crop. Despite these challenges, co-cultivation of trees and arable crops can be planned and designed to optimize microclimate benefits for specific crops and cultivars, while minimizing negative impacts on productivity.

Pollination services and pest control

Forests harbor a greater diversity of pollinators than any other biome[65–68], making them essential for stabilizing crop yields across both time and space[69–71]. The economic value of agricultural pollination is estimated at US$195 to $387 billion annually[72] – a figure likely underestimated given the rising consumption of pollinator-dependent crops[73].

Trees provide diverse resources for pollinators, including flowers, resins, and nesting sites. In tropical regions, mass-flowering trees support various important bee species[74,75]. Non-floral tree resources like honeydew and sugary secretions[76,77] also benefit pollinators[78,79]. Tree resins aid in bee nesting by providing waterproofing and anti-parasitoid properties[77], while old forest fragments offer nesting sites[80,81]. Tree leaves protect ground-nesting bees[48] and extrafloral resources attract pest-controlling animals[82], reducing pesticide use[83,84].

Landscapes with more than 20% natural forest cover have been shown to be particularly effective at boosting the diversity of pollinators and pest controllers that enhance crop productivity[85,86]. Forest areas near croplands, especially in regions with 20-40% forest cover, maximize pollination services[87,88]. For example, coffee yields in Costa Rica increased by 20% within 1 km of forests [89], while in Colombia, the presence of 15–62% natural habitat within 500 m of crops increased fruit production by 39%[90]. Forested landscapes also help reduce the spread of crop pests[91,92], with studies from Germany[93] and Canada[94] showing decreased herbivory and increased crop yields due to increased natural and semi-natural areas.

Thus, restoring forest patches near croplands can significantly improve ecosystem services and crop productivity, both locally and regionally[95,96]. In Brazil's Atlantic Forest, targeted restoration to locally increase forest areas around coffee fields could potentially double production in half of the municipalities, by enhancing pollination service[96]. Economic models suggest that the benefits of increased pollination services from forest restoration could fully outweigh the costs, especially in areas already having at least 10% forest cover[97].

Water quantity and quality

Forests regulate water yields in agricultural watersheds, depending on ecosystem type and spatial and temporal scales[98]. Forests increase water interception and soil infiltration during storms while maintaining the streamflow in dry seasons, mitigating the impacts of both droughts and floods[98,99], with direct impacts on agricultural production. For instance, a 10% rise in upstream forest cover in the Brazilian Amazon led to a 3.2% increase in milk production due to improved water regulation, which enhanced pasture availability and cow health[100]. However, in dry regions, large tree plantations can reduce water yield, though evidence suggests that intermediate tree cover in the dry tropics can increase groundwater recharge[101]. Restoration projects must therefore consider the natural vegetation of the watershed[102]. Forests also contribute to atmospheric moisture through evapotranspiration, influencing precipitation patterns vital for agriculture, and benefiting downstream and downwind agricultural areas[98,103,104]. Degraded Amazon forests exhibit reduced evapotranspiration (2 to 34%), impacting dry-season water availability[105]. Reducing deforestation in the Amazon is key to maintaining rainfall levels, preserving agricultural productivity, and avoiding projected annual agricultural losses of up to US$ 1 billion by 2050[106].

Agriculture impacts water quality through runoff and leaching, where rainfall and irrigation water carry nutrients, pesticides, and sediments into nearby water bodies. Forests enhance water quality by reducing runoff, filtering pollutants, preventing sedimentation, and maintaining water clarity[107–109]. In Southeast Asia, protecting 114 million ha of forests could prevent 2.9 Mt of nitrogen pollutants from affecting agricultural lands and water bodies[110]. Similarly, restoring riparian forests in agricultural watersheds in the Atlantic Forest of Brazil can reduce river nitrogen by 23% and soil loss by 20%[111,112]. By improving water quality, forests reduce water treatment costs, encouraging sustainable agricultural practices such as conserving native vegetation in agricultural properties[113,114].

2. Local scale

Trade-offs between trees and agriculture

The trade-offs in land use between forests and agriculture may be most apparent at the level of individual farms. Of course, it is rarely possible to maximize agricultural production if the land is dominated by a diverse forest. As such, in most high-income countries, arable crops are typically not cultivated together with trees at the farm level[115]. To avoid competition for resources, agricultural development in these regions usually results in the exclusive cultivation of either crops or trees within managed settings. Under these contexts, co-cultivation can be challenging, particularly in regions where agriculture is highly dependent on machinery for industrial-scale land management.

The industrialization of agriculture (notably after 1945) was a result of the conversion of “family farms” into large commercial enterprises with an emphasis on monocultures[116]. Industrialized agriculture has become highly mechanized, leading to larger, uniformly organized farms[117] and lower food prices. This mechanization, which includes the use of fertilizer spreaders, field sprayers, combine harvesters, and ploughs, requires unobstructed, treeless fields to achieve optimal productivity[118]. As agricultural machinery has increased in size, trees have been systematically removed from arable cropping landscapes in many industrialized countries[119].

Now that agricultural systems have been adapted to large-scale monocultures, reintroducing trees to arable fields is challenging. Although scientific studies and on-farm case studies have shown the ecological and economic advantages of integrating trees with arable crop systems, the adoption of such practices remains challenging because it can reduce the efficiency of agricultural processing. Several factors contribute to this reluctance[84,120,121]: i) high implementation costs, ii) inadequate financial incentives for providing ecosystem services, iii) market prices for products from trees are often not higher than those from non-mixed cultivation, iv) lack of education and awareness about the benefits of co-cultivation, and v) insufficient field demonstrations, which are far more convincing to farmers than scientific papers.

The uptake of co-cultivating trees and arable crops is more successful in the Global South, where such practices have not been fully abandoned, making markets more receptive[122]. Additionally, lower labor costs, smaller field sizes, and less mechanization facilitate the adoption of these practices. However, industrialization has more recently become the dominant driver of forest loss in the Global South. The expansion of commodity crops such as oil palm, soy, and cattle has led to permanent conversion of forests and other tree-based systems, making the re-establishment of co-cultivation of trees and crops more difficult[123].

Synergies in agricultural systems with trees

While trees and crops may compete for space and resources, leading to direct trade-offs in arable farming, this relationship can become synergistic at the whole-farm level. Niche differentiation between trees and crops often allows for positive, facilitative interactions in many contexts. The most famous example of this is agroforestry[124], which includes both the establishment of trees on farmland and the introduction of livestock and crops into forests to maximize synergistic interactions between the tree and non-tree components.

Trees within agroforestry practices serve various roles. They can provide environmental protection for agricultural components and beyond (e.g. windbreaks, shade trees), enhance agricultural productivity directly (e.g. nitrogen-fixing trees, shrubs, or mulch to improve soil conditions for annual crops, tree fodder for livestock, resources for pest controllers), and produce farm outputs including fruits, nuts, fuelwood, and timber[124]. While the focus is usually on the benefits that trees bring to the agricultural components, the trees themselves can also benefit from crop husbandry and livestock interactions, such as pest and weed control and fertilization from animal manure.

Agroforestry systems can be categorized based on their components: silvoarable systems (trees with crops), silvopastoral systems (trees with animals), and agrosilvopastoral systems (trees with crops and animals)[125]. Within these overarching systems, agroforestry practices can be further classified according to the balance, integration, and spatial arrangement of the components (trees/shrubs, livestock, and/or annual crops, Figure 1). Each of these approaches can have benefits for increasing agricultural production, but the social or ecological context will strongly determine which system is most appropriate and effective for a given region.

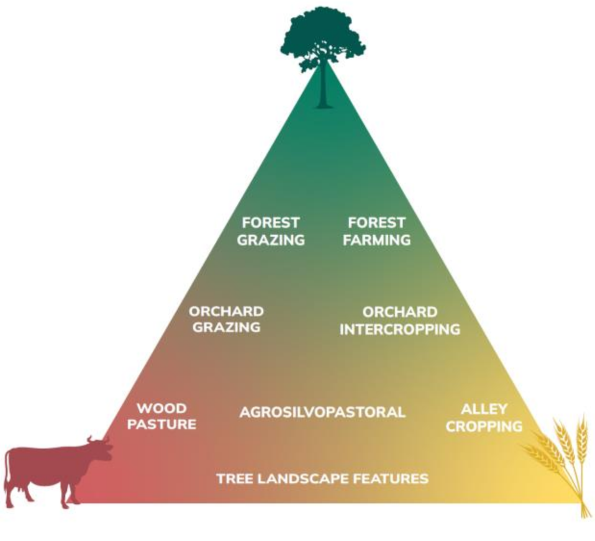

Fig. 1. Agroforestry practices vary in their balance of the tree, animal, and temporary crop components (adapted from Burgess and Rosati, 2018[126]).

Balancing synergies and trade-offs

There is a growing political movement (e.g. European Green Deal[127]) to maintain a wide range of ecosystem services from landscapes. Hedges, shrubs, and trees in farmland are essential elements to fulfill these functions. They are known to provide and protect natural resources (soil[128], water[129,130], air[131]), safeguard biodiversity, enable recreation, enhance the landscape's aesthetic value[132], and protect against hazards (e.g. landslides, floods). However, economic comparisons of landscapes with and without trees and hedges often lack evidence of the associated costs, benefits, and risks[133,134]. This is because private benefits (marketable products such as crop yields) are accounted for, while the public benefits (provision of ecosystem services such as water quality) are rarely identified or capitalised[133,134].

Plot-scale agroforestry practices can be evaluated with the Land Equivalent Ratio (LER), which measures the productivity of mixed-species systems (crops and trees) compared to monocultures[135]. An LER greater than 1 indicates higher productivity in the mixed system. For instance, a LER of 1.4 means that a 100-ha agroforestry farm produces as much crop and tree products as a 140-ha farm where trees and crops are separated. In temperate zones, long-term experiments (10 to 30-year duration) show that poplar-based and walnut-based alley-cropping systems exhibit LERs between 1.2 and 1.6[136,137], indicating significant yield gains. Some agroforestry systems mixing fruit trees and herbaceous crops display LERs as high as 2[138]. In the tropics, long-term experiments are not yet available, but short-term measurements (less than 10 consecutive years) suggest high productivity in agroforestry systems[139–141], with LERs up to 1.8 recorded for teak and maize systems[141].

While these LER studies indicate that agroforestry usually outperforms monocultures, the limited number of available LER data makes it challenging to draw general conclusions at the biome level. Furthermore, LERs evaluate the combined yields of trees and crops, rather than directly comparing crop yields in agroforestry with those in monocultures. Indeed, when comparing crop yields alone, results vary depending on location, climate, management, and tree and crop species involved. For instance, crop yields tend to increase in tropical and arid regions [21,22], while in temperate zones, decreases in arable yields or product quality have sometimes been observed[23], with mostly neutral effects on grass yields[24,25]. These variations can be attributed to a delicate balance between competition and facilitation processes in agroforestry systems. While resource competition between trees and crops is always happening, facilitative interactions are more sporadic, occurring only under specific conditions, which leads to an unstable balance between negative and positive effects[142]. This explains why different outcomes can be observed from year to year at the same site or between locations[143–145]. For example, tree shade can either benefit crops by mitigating excess light or reduce yields in cloudier climates[146]. Water and nutrient sharing are generally less affected, due to the plasticity of root systems and the niche differentiation[29,30]. Typically, tree roots can access deeper resources that crops or pastures cannot, although the reverse can occasionally occur[147,148]. Consequently, agroforestry systems should be carefully tailored to the specific site and crop requirements, with a focus on maximizing positive facilitative interactions.

Recent studies suggest that agroforestry at the field level can compete with conventional agricultural land use not only in tropical and dry regions but also in temperate zones, especially when environmental benefits are included in the overall assessment[149]. This indicates that agroforestry can provide farmers with similar or even higher income, along with greater long-term production stability, compared to monoculture systems[150]. However, so far only carbon storage in biomass and soil[151,152], as well as early examples of water conservation[129,130], have been successfully translated into direct monetary benefits or income for farmers.

When accounting for both public and private benefits, landscapes with trees are economically and environmentally more advantageous than those without[25,153]. Furthermore, the positive impact of trees and hedges on agricultural productivity could help reduce the economic gap between payments for landscape conservation and agricultural revenues, particularly in large-scale farming operations.

3. Regional scale

Although local scale impacts are primarily influenced by direct interactions between trees and crops, regional—landscape to national—scale implications are subject to a wider variety of interacting factors. Broader climatic patterns, landscape connectivity, and regional biodiversity interactively determine the effects of trees on agricultural productivity. At the regional scale, forest cover can enhance ecosystem services such as water regulation[98,99], pest control[93], and pollination[89] across large agricultural areas, leading to increased agricultural yields. Moreover, the regional interplay between forests and agriculture often reflects complex socio-economic and policy dynamics, necessitating a more integrated approach to land-use planning that balances conservation efforts with agricultural needs[154].

Impact of forest cover on agricultural yields

Although agricultural expansion is a key driver of deforestation[123], recent regional-scale studies show that agricultural productivity does not always come at the expense of forest conservation. To explore these dynamics, we collected 56 observations from 14 sites worldwide by searching published articles on the Web of Science and Google Scholar using the keywords "forest" and "agricultural/cropland productivity" (Fig. 2 and Supplementary Data 1). Our analysis revealed that 87% of the sites experienced a decrease in agricultural productivity (ranging from 2.8% to 55.1%) following forest cover loss. Conversely, increases in forest cover led to an increase in overall landscape-scale agricultural productivity in 95% of the reported cases, with productivity gains ranging from 0.4% to 79.5%. This positive relationship between forest cover and agricultural yields is shown in positive *Y:F* ratios, which represent the *percentage yield change* relative to the *percentage change in forest cover*. Our findings suggest that the relationship between forests and agriculture at the regional scale is more synergistic than competitive, highlighting the potential for forest conservation to coexist with and even enhance agricultural productivity.

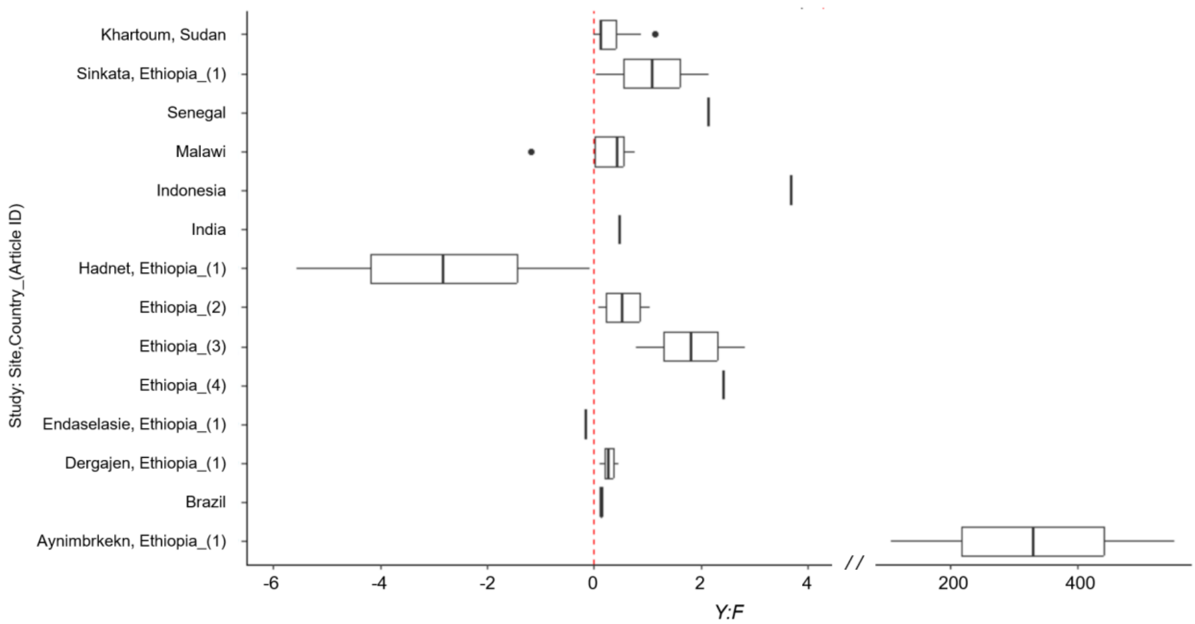

Fig. 2. Observed relationship between forest cover and yield changes across study sites. Boxplots showing the observed *Y:F* ratio (percentage yield change relative to percentage forest cover change) across 14 study sites. The y-axis displays the study sites, identified by site name (if available), country, and article ID for cases where multiple studies were conducted in the same country. Positive *Y:F* values indicate a positive correlation between yield changes and forest cover, whereas negative values reflect a decrease in yield with increased forest cover. Refer to Supplementary Data 1 for a complete list of the articles used in the analysis.

Studies have shown positive associations between forest cover and agricultural productivity in countries with high deforestation rates and a strong dependence on agriculture, such as Brazil[18,155], Ethiopia[156], Indonesia[17], and Malawi[157]. In the Brazilian Amazon, forest conservation policies reduced deforestation by 45–56% and increased cattle productivity by 14–36%[18]. Furthermore, forest conservation in Brazil has been identified as a more significant factor in improving coffee yields than climate, topography, and management practices[158]. In Indonesia, deforestation led to a significant 45% decline in local agricultural productivity between 2001 and 2014, which translated to a production loss of $26.3 billion in 2014 [17]. The study suggests that mitigating deforestation could enhance agricultural productivity, with a 1% reduction in forest clearing potentially increasing agricultural productivity by 3.7%, highlighting the critical role of forests in supporting regional agricultural output[17]. The Aynimbrkekn region in Ethiopia stands out with an exceptionally high *Y:F* value (Fig. 2). Despite suffering extensive deforestation, which led to reduced crop yields[159], large-scale eucalyptus planting initiatives in the 1980s kept local tree cover constant and led to high *Y:F* values.

In European countries, where there is less pressure to convert forests into agricultural land, a positive relationship between forest area and agricultural productivity has also been observed. A 1% increase in forest area led to a 3.1% rise in price-weighted agricultural production for cereals and a 0.6% increase for vegetables and fruits[160]. However, when livestock products were included, the effect of forest cover ranged from neutral to slightly negative[160].

The positive association between forest cover and agricultural productivity may be partly attributed to the lower productivity of newly converted farmlands[161]. In fact, one-third to one-half of newly cleared forests for agricultural use often remain unused, due to human-related factors such as conflicts over land tenure and deteriorating markets as well as ecological factors such as land degradation and changes in local climate, which create unsuitable conditions for agricultural production[161].

4. Global scale

Over the past two decades, global cropland expansion has nearly doubled, with half of this growth coming at the expense of forests, particularly in the tropics[7]. Between 2011 and 2015, agriculture was responsible for at least 90% of tropical deforestation[161]. Despite international commitments to end deforestation, agricultural expansion persists[123], with 4.1 million hectares of forest lost in 2022 alone, predominantly in tropical regions[162].

The large-scale loss of natural forests, as seen in modern times, has historically reduced agricultural productivity and, in extreme cases, led to societal collapses. Figure 3 highlights historical examples where changes in tree cover significantly impacted climate and societies. During the early stages of Earth's history, around 3.3 billion years ago, the atmosphere was primarily composed of CO_2 and CH_4, leading to much warmer conditions than today[163,164]. The evolution of trees and the development of forest ecosystems helped reduce CO_2 levels, cooling the planet and creating more habitable conditions[165].

However, the emergence of *Homo sapiens* brought significant environmental changes, particularly through deforestation. Historical examples, such as the collapse of Ancient Greece [19,166], Mayan civilization and Easter Island [19], and the Dust Bowl in the USA[167], serve as stark reminders of how deforestation led to catastrophic outcomes. These cases illustrate the potential consequences of forest removal and highlight the critical need for sustainable resource management to ensure agricultural productivity and societal resilience. To put it simply and starkly, "without forests, there would be no human beings"[168].

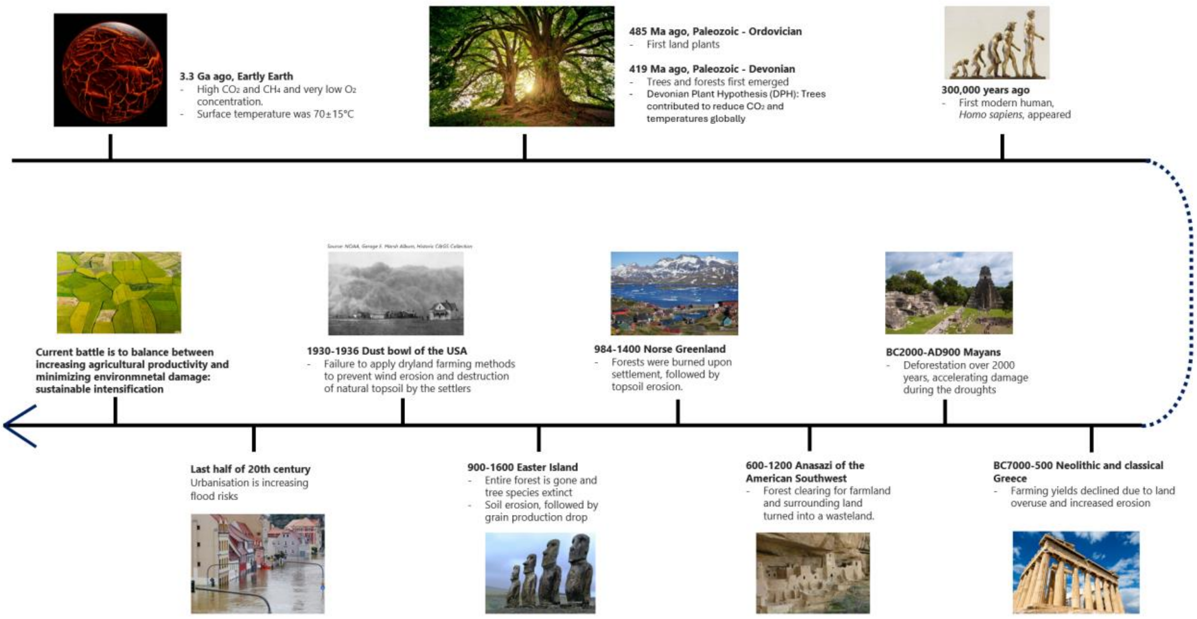

Fig. 3. Timeline of historical examples related to the emergence and removal of forests and their impacts on societies. This timeline highlights events in history where deforestation and environmental degradation significantly affected human societies. Historical examples include deforestation in Neolithic Greece, the Mayan civilization, the Anasazi of the American Southwest, Easter Island, and Norse Greenland. More recent examples, such as the Dust Bowl in the USA and the growing flood risks due to urbanization, underscore the recurring pattern of environmental degradation leading to societal challenges. These events emphasize the importance of balancing agricultural productivity with the preservation of forests and ecosystems. (Image source of Dust Bowl in the USA: https://photolib.noaa.gov/Collections/National-Weather-Service/Meteorological-Monsters/Dust/emodule/647/eitem/3001)

Global empirical relationship between yields and forest cover loss

Drawing from local and regional studies on the relationship between forests and agriculture, we introduce a theoretical framework to describe how forest loss impacts agricultural yields in countries with natural forests (Fig. 4a). In regions where most forests remain intact, clearing forests is often necessary to create space for agriculture. In contrast, in regions where natural forests have already been heavily removed, the impact of further deforestation depends on agriculture's reliance on ecosystem functions provided by forests. If agriculture has a low dependency on forest-related ecosystem functions, such as soil quality, climate regulation, and pollinators, further deforestation may continue to boost yields. At medium levels of dependency, yields may stagnate as ecosystem functions decline. In highly dependent systems, further forest loss could reduce yields. Under this system, forest loss is expected to have opposite effects in largely intact *versus* highly deforested countries, with a tipping point marking the transition between these extremes (Fig. 4a). This yield prediction aligns with previous findings that provisioning services, such as agricultural production, increase up to a certain biodiversity threshold, after which they begin to decline[169,170].

To test these hypotheses, we analyzed country-level cereal yield and forest cover data from 1990 to 2020, sourced from FAOSTAT [171]. We focused on countries that experienced more than a 10% change in forest cover during this period, resulting in a selection of 22 countries, mostly located in the Global South. Using the potential tree cover map from Bastin *et al.* (2019)[172], we estimated how close each country's actual tree cover in each given year is to its potential tree cover. We applied a mixed-effects model using a natural cubic spline term for relative forest cover loss to test whether there was a non-linear relationship between area-normalized yield and forest cover loss across countries (see Supplementary Methods).

Our findings strongly support the unimodal theory of nature's limits (Fig. 4b). Specifically, in countries with low forest cover loss, further deforestation was associated with increased agricultural yields. However, yields peaked when approximately 44% to 50% of forest cover had been lost (95% confidence interval), with a median peak at 48%. Beyond this point, yields began to decline as forest loss continued. This ~48% of forest loss threshold may represent a global tipping point, where trade-offs between forest cover and agricultural productivity turn into synergies. However, only a small number of countries have fully crossed this tipping point, indicating that our identified tipping point is a projection derived from current trends rather than actual observed data. While this threshold may vary by country, depending on factors like climate, agro-ecology, and country size, our analysis suggests that approximately 70% of countries had already surpassed their optimal forest loss level for agricultural productivity by 2020 and are likely to experience yield reductions with further deforestation (see Supplementary Data 2 for the full list of the investigated countries).

Fig. 4c shows country-level *Y:F* ratios from 2000 to 2020 based on forest cover and cereal yield data obtained from FAOSTAT[171]. A positive *Y:F* value indicates that forest cover and yields either increased or decreased together during this period. For example, most European countries and the United States display positive *Y:F* values. By contrast, negative *Y:F* values, for example in Canada, indicate that forest cover and yields followed opposite trends. Indeed, Canada's high negative *Y:F* value is likely due to its very low forest cover change (< 0.1%) during the investigated period. Some countries, such as Brazil, show very low |*Y:F*| values, ranging between -0.2 and 0.2, indicating little to no change in the relationship between forest cover and yields.

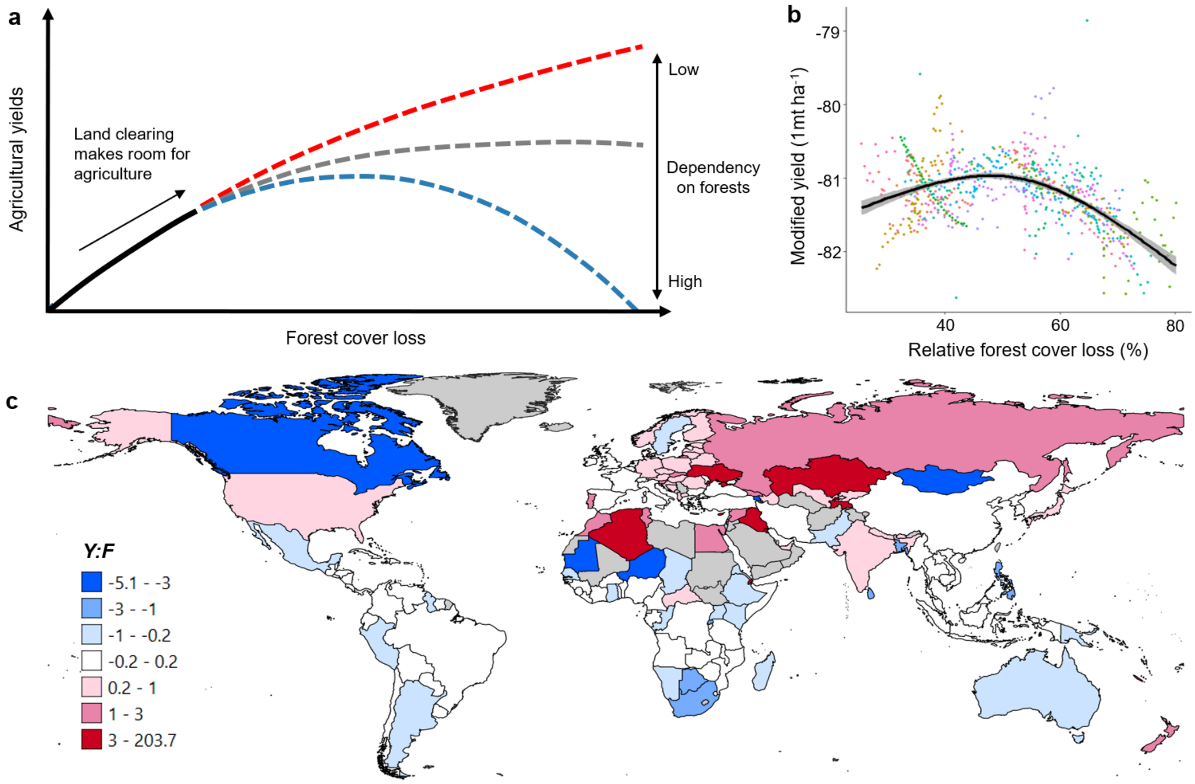

Fig. 4. Relationship between forest cover and agricultural yields. a, Theoretical agricultural yield pattern by percentage forest cover loss. In regions with low forest loss, deforestation can increase agricultural yields by expanding land for agriculture. However, in regions with significant forest loss, the effects of further deforestation on yields can vary. Additional deforestation may lead to increased, maintained, or reduce yields depending on agriculture's dependency on the ecosystem functions provided by forests, such as soil quality, climate regulation, and pollination. A tipping point is reached when forest loss begins to harm yields more than the gains from farmland expansion. **b,** Agricultural yield relative to forest cover loss, modelled using a linear mixed-effects model with natural cubic spline applied to forest cover loss. The modified yield is an adjusted version of cereal yields that accounts for the partial effects of relative forest cover loss, while controlling for yearly trends and country-specific variations. Relative forest cover loss represents the percentage difference between a country's potential forest cover[172] and its actual forest cover[171]. Each data point is color-coded to indicate the respective country. See Supplementary Methods for detailed methodology and visualization of country-specific relationships. **c,** Country-level *Y:F* ratio from 2000 to 2020, where *Y:F* reflects the percentage increase in agricultural yields per 1% increase in forest cover. Negative *Y:F* values (blue) indicate reduced yields with increasing forest cover, while positive *Y:F* values (red) show

yield gains. Gray areas indicate insufficient data for analysis.

Impact of deforestation on global food security

Deforestation has significant impacts on global food security, primarily through soil erosion, climate change, and biodiversity loss. Globally, soil erosion displaces 2.5 Pg C annually[173], and a meta-analysis of tropical deforestation sites shows that deforested areas experience a topsoil carbon decline of 21% to 58% within 10 to 100 years[174]. Soil quality also deteriorates gradually after deforestation[174–177], with potential impacts on crop growth. Future projections indicate that high-income countries with significant fertilizer use may experience less soil erosion, while low- and middle-income countries in tropical and subtropical regions, such as Africa and South and Southeast Asia, are expected to see a significant increase[178].

Deforestation also exacerbates climate change by releasing carbon stored by trees into the atmosphere and changing rainfall and temperature patterns. In 2022, deforestation resulted in 2.7 Gt of CO_2 emissions[162], contributing to intensifying global warming. Even if global commitments limit warming to 1.5°C — a target now accepted as unachievable — an estimated 8% of current farmland will become inhospitable to crop production[162]. This is likely to open up new forest frontiers for agriculture, resulting in more deforestation and concomitant biodiversity loss[179], further accelerating climate change. Extreme local warming from deforestation[180] also threatens crop yields[181] and exposes outdoor workers to dangerous heat levels[182]. Moreover, converting tropical forests to agriculture increases fire risks fourfold[183], further jeopardizing agricultural productivity and the safety of local communities. Finally, climate change also impacts food security by lowering the micronutrient content of many cereal crops and legumes[184], affecting nearly two billion people who rely on these crops for essential minerals[185].

Predicting the impact of deforestation on biodiversity loss and food production is challenging due to the intricate relationships between biodiversity and ecosystem services[186]. However, continued tropical deforestation is projected to "precipitate a mass extinction event over the next couple of centuries" [187]. This would disproportionately impact smallholder low-input farming, the backbone of global food security [188], as such systems rely strongly on ecosystem services linked to biodiversity[189]. While high-input commercial farming may initially seem less vulnerable due to the reliance on synthetic/inorganic inputs, these systems will likely still suffer from losses in key ecosystem services such as pollination and natural pest control.

The loss of biodiversity also directly impacts food security by reducing access to wild foods, such as fruits, vegetables, and mushrooms, which provide essential nutrients and support dietary diversity for many rural communities[190]. In tropical regions, wild meat harvested from forests supports around 150 million households[191]. More generally, the ongoing decline in agrobiodiversity is narrowing the genetic base of our global food systems[192], increasing society's vulnerability to food insecurity. Numerous examples show the dangers of monoculture farming, where genetic uniformity has led to crop failures and famines[193].

Conclusion

Trees and forests influence food security at multiple scales. At the local scale, despite the apparent trade-offs between forest and farmland, integrating agroforestry practices has shown promising results, especially in tropical and arid zones[21,22,139–141]. In temperate regions, agroforestry often enhances the combined yields of trees and crops, though individual crop yields can drop due to the unstable balance between competition and facilitation. Effective agroforestry design and management that maximize synergistic interactions are key to overcoming these challenges.

At the regional scale, the balance between synergies and trade-offs tends towards positive impacts of forests on agriculture. Many quantitative studies have demonstrated positive relationships between forest cover and agricultural productivity in countries such as Brazil[18,155], Indonesia[17], Ethiopia[156], and across Europe[160]. These findings indicate that maintaining or restoring forests can enhance food security at broader scales. Our data visualization approach further supports this conclusion, revealing that, on average, agricultural yields are projected to decline once forest cover loss exceeds around 48%. Beyond this tipping point, agricultural systems lose the ecosystem services provided by natural forests.

Given that almost 70% of countries have surpassed this threshold of forest degradation, implementing targeted forest conservation and restoration policies is critical to ensure food security in these regions.

Promoting diverse, natural mixtures of trees, rather than large monoculture plantations, is essential for maximizing the services provided by forests, including soil health, climate regulation, pollination, and pest control. Mixed natural forests enhance ecosystem resilience and ensure a stable provision of ecosystem services critical for agriculture[194]. In contrast, monoculture plantations are often less resilient, more vulnerable to disturbances[195], and reduce water resources for crops[102], thereby increasing the risk of crop failure and lowering productivity. To sustain long-term agricultural productivity and food security, it is crucial to protect natural forests and implement diverse agroforestry systems that incorporate a variety of tree species.

At large scales, from national to global, the positive relationships between forests and agriculture highlight the complexity of balancing local land-use conflicts with broader food security goals. Targeted land-use policies are needed to maximize the synergies between forests and agricultural systems across different regions. With the global population currently over 8 billion and expected to grow by an additional 2 billion by mid-century, ensuring access to nutritious, safe, and sufficient food is critical[196–198]. To secure agricultural productivity for current and future generations, it is essential to prioritize the conservation and restoration of natural forests and trees across the globe.

Competing interest declaration

The authors declare no competing interests.

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Author contributions

GY, CMZ, GRS, and TWC conceived the ideas and designed the methodology. GY organized the research team and led the analysis. All authors contributed to writing and revising the paper, and all approved the final version for submission.

References

1. Malhi, Y. *et al.* Climate change and ecosystems: Threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B: Biological Sciences* **375**, (2020).

2. Seddon, N. *et al.* Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B: Biological Sciences* **375**, (2020).

3. United Nations. *United Nations Framework Convention on Climate Change*. vol. 1771 (1992).

4. CBD. *Sustaining Life on Earth: How the Convention on Biological Diversity Promotes Nature and Human Well-Being*. *Secretariat of the convention on Biological Diversity* (2000).

5. United Nations. Transforming our world: The 2030 agenda for sustainable development. https://sustainabledevelopment.un.org/post2015/transformingourworld/publication. (2015).

6. Song, X. P. *et al.* Global land change from 1982 to 2016. *Nature* **560**, (2018).

7. Potapov, P. *et al.* Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nat Food* **3**, (2022).

8. Schauenberg, T. Farmers revolt against EU's historic nature restoration law. *DW* (2023).

9. Kolarz, S. *Draft Nature Restoration Law Raises Controversy within the EU*. (2023).

10. Jastrzębska, M., Kostrzewska, M. & Saeid, A. Sustainable agriculture: A challenge for the future. in *Smart Agrochemicals for Sustainable Agriculture* (2021). doi:10.1016/B978-0-12-817036-6.00002-9.

11. Angelsen, A. Policies for reduced deforestation and their impact on agricultural production. *Proc Natl Acad Sci U S A* **107**, (2010).

12. Alblas, E. & van Zeben, J. 'Farming out' biodiversity: Implementing EU nature law through agri-environmental schemes. *Earth System Governance* **17**, (2023).

13. Pantera, Mosquera-Losada, M. R., Herzog, F. & den Herder, M. Agroforestry and the environment. *Agroforestry Systems* **95**, (2021).

14. Jose, S. Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems* **76**, (2009).

15. He, X. *et al.* Integrating agricultural diversification in China's major policies. *Trends Ecol Evol* **37**, 819–822 (2022).

16. Sousa, J. S. B., Longo, M. G. & Santos, B. A. Landscape patterns of primary production reveal agricultural benefits from forest conservation. *Perspect Ecol Conserv* **17**, (2019).

17. Yamamoto, Y., Shigetomi, Y., Ishimura, Y. & Hattori, M. Forest change and agricultural productivity: Evidence from Indonesia. *World Dev* **114**, (2019).

18. Koch, N., Zu Ermgassen, E. K. H. J., Wehkamp, J., Oliveira Filho, F. J. B. & Schwerhoff, G. Agricultural Productivity and Forest Conservation: Evidence from the Brazilian Amazon. *Am J Agric Econ* **101**, (2019).

19. Diamond, J. *Collapse: How Societies Choose to Fail or Succeed: Revised Edition.* (Penguin, 2011).

20. Reed, J. *et al.* Trees for life: The ecosystem service contribution of trees to food production and livelihoods in the tropics. *For Policy Econ* **84**, (2017).

21. Félix, G. F., Scholberg, J. M. S., Clermont-Dauphin, C., Cournac, L. & Tittonell, P. Enhancing agroecosystem productivity with woody perennials in semi-arid West Africa. A meta-analysis. *Agron Sustain Dev* **38**, (2018).

22. Kuyah, S. *et al.* Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. *Agron Sustain Dev* **39**, (2019).

23. Staton, T., Breeze, T. D., Walters, R. J., Smith, J. & Girling, R. D. Productivity, biodiversity trade-offs, and farm income in an agroforestry versus an arable system. *Ecological Economics* **191**, (2022).

24. Rivest, D., Paquette, A., Moreno, G. & Messier, C. A meta-analysis reveals mostly neutral influence of scattered trees on pasture yield along with some contrasted effects depending on functional groups and rainfall conditions. *Agric Ecosyst Environ* **165**, 74–79 (2013).

25. Amorim, H. C. S. *et al.* Temperate silvopastures provide greater ecosystem services than conventional pasture systems. *Sci Rep* **13**, 1–12 (2023).

26. Lotka, A. J. The growth of mixed populations: Two species competing for a common food supply. *Journal of the Washington Academy of Sciences* **22**, 461–469 (1932).

27. Volterra, V. Variations and Fluctuations of the Number of Individuals in Animal Species living together. *ICES Journal of Marine Science* **3**, (1928).

28. Chesson, P. Mechanisms of maintenance of species diversity. *Annu Rev Ecol Syst* **31**, (2000).

29. Pavlidis, G. & Tsihrintzis, V. A. Environmental Benefits and Control of Pollution to Surface Water and Groundwater by Agroforestry Systems: a Review. *Water Resources Management* **32**, (2018).

30. Wolz, K. J., Branham, B. E. & DeLucia, E. H. Reduced nitrogen losses after conversion of row crop

agriculture to alley cropping with mixed fruit and nut trees. *Agric Ecosyst Environ* **258**, (2018).

31. Bertness, M. D. & Callaway, R. Positive interactions in communities. *Trends Ecol Evol* **9**, (1994).

32. Fahad, S. *et al.* Agroforestry Systems for Soil Health Improvement and Maintenance. *Sustainability (Switzerland)* **14**, (2022).

33. Liang, C., Schimel, J. P. & Jastrow, J. D. The importance of anabolism in microbial control over soil carbon storage. *Nat Microbiol* **2**, (2017).

34. Mesfin, S. & Haileselassie, H. Evaluation of soil physico-chemical properties as affected by canopies of scattered agroforestry trees on croplands. *South African Journal of Plant and Soil* **39**, (2022).

35. Kiran, K. K., Pal, S., Chand, P. & Kandpal, A. Carbon sequestration potential of agroforestry systems in Indian agricultural landscape: A Meta-Analysis. *Ecosyst Serv* **62**, (2023).

36. Hübner, R. *et al.* Soil carbon sequestration by agroforestry systems in China: A meta-analysis. *Agric Ecosyst Environ* **315**, (2021).

37. De Stefano, A. & Jacobson, M. G. Soil carbon sequestration in agroforestry systems: a meta-analysis. *Agroforestry Systems* (2017) doi:10.1007/s10457-017-0147-9.

38. Zhang, N. *et al.* Environment and agricultural practices regulate enhanced biochar-induced soil carbon pools and crop yield: A meta-analysis. *Science of the Total Environment* **905**, (2023).

39. Beule, L., Vaupel, A. & Moran-Rodas, V. E. Abundance, Diversity, and Function of Soil Microorganisms in Temperate Alley-Cropping Agroforestry Systems: A Review. *Microorganisms* **10**, (2022).

40. Eddy, W. C. & Yang, W. H. Improvements in soil health and soil carbon sequestration by an agroforestry for food production system. *Agric Ecosyst Environ* **333**, (2022).

41. Zhu, Q., Yan, K., Dong, Y. & Wang, Y. Rhizosphere bacterial communities and soil nutrient conditions reveal sexual dimorphism of Populus deltoides. *J For Res (Harbin)* **34**, (2023).

42. Marsden, C., Martin-Chave, A., Cortet, J., Hedde, M. & Capowiez, Y. How agroforestry systems influence soil fauna and their functions - a review. *Plant Soil* **453**, (2020).

43. Pavlidis, G. & Tsihrintzis, V. A. *Pollution Control by Agroforestry Systems: A Short Review*. *European Water* vol. 59 (2017).

44. Jacobs, S. R. *et al.* Modification of the microclimate and water balance through the integration of trees into temperate cropping systems. *Agric For Meteorol* **323**, (2022).

45. Blaser-Hart, W. J. *et al.* The effectiveness of cocoa agroforests depends on shade-tree canopy height. *Agric Ecosyst Environ* **322**, (2021).

46. Speak, A., Montagnani, L., Wellstein, C. & Zerbe, S. The influence of tree traits on urban ground surface shade cooling. *Landsc Urban Plan* **197**, (2020).

47. Meili, N. *et al.* Tree effects on urban microclimate: Diurnal, seasonal, and climatic temperature differences explained by separating radiation, evapotranspiration, and roughness effects. *Urban For Urban Green* **58**, (2021).

48. Smith, M. M. *et al.* Windbreaks in the United States: A systematic review of producer-reported benefits, challenges, management activities and drivers of adoption. *Agric Syst* **187**, (2021).

49. Blaser, W. J. *et al.* Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. *Nat Sustain* **1**, (2018).

50. Verchot, L. V. *et al.* Climate change: Linking adaptation and mitigation through agroforestry. *Mitig Adapt Strateg Glob Chang* **12**, (2007).

51. Sida, T. S., Baudron, F., Kim, H. & Giller, K. E. Climate-smart agroforestry: Faidherbia albida trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. *Agric For Meteorol* **248**, (2018).

52. Abdulai, I. *et al.* Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. *Glob Chang Biol* **24**, (2018).

53. Lin, B. B. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. *Agric For Meteorol* **144**, (2007).

54. Isaac, M. E., Gagliardi, S., Ordoñez, J. C. & Sauvadet, M. Shade tree trait diversity and functions in agroforestry systems: A review of which traits matter. *Journal of Applied Ecology* (2024) doi:10.1111/1365-2664.14652.

55. Zeppetello, L. R. V. *et al.* Consistent cooling benefits of silvopasture in the tropics. *Nat Commun* **13**, (2022).

56. Brandle, J. R., Hodges, L. & Zhou, X. H. Windbreaks in North American agricultural systems. in *Agroforestry Systems* vols 61–62 (2004).

57. Piato, K. *et al.* Effects of shade trees on robusta coffee growth, yield and quality. A meta-analysis. *Agron Sustain Dev* **40**, (2020).

58. Vizinho, A. *et al.* Using and Creating Microclimates for Cork Oak Adaptation to Climate Change. *Land (Basel)* **12**, (2023).

59. Kallenbach, R. L., Kerley, M. S. & Bishop-Hurley, G. J. Cumulative forage production, forage quality and livestock performance from an annual ryegrass and cereal rye mixture in a Pine Walnut Silvopasture. *Agroforestry Systems* **66**, (2006).

60. Blackshaw, J. K. & Blackshaw, A. W. Heat stress in cattle and the effect of shade on production and behaviour: A review. *Aust J Exp Agric* **34**, (1994).

61. Pent, G. J. & Fike, J. H. Lamb productivity on stockpiled fescue in honeylocust and black walnut silvopastures. *Agroforestry Systems* **93**, (2019).

62. Koutouleas, A. *et al.* Shade effects on yield across different Coffea arabica cultivars — how much is too much? A meta-analysis. *Agron Sustain Dev* **42**, (2022).

63. Dufour, L., Metay, A., Talbot, G. & Dupraz, C. Assessing light competition for cereal production in temperate agroforestry systems using experimentation and crop modelling. *J Agron Crop Sci* **199**, (2013).

64. Pardon, P. *et al.* Effects of temperate agroforestry on yield and quality of different arable intercrops. *Agric Syst* **166**, (2018).

65. Harrison, T., Gibbs, J. & Winfree, R. Forest bees are replaced in agricultural and urban landscapes by native species with different phenologies and life-history traits. *Glob Chang Biol* **24**, (2018).

66. Smith, C., Harrison, T., Gardner, J. & Winfree, R. Forest-associated bee species persist amid forest loss and regrowth in eastern North America. *Biol Conserv* **260**, (2021).

67. da Silva Carneiro, L. *et al.* Orchid bees respond to landscape composition differently depending on the multiscale approach. *Landsc Ecol* **37**, (2022).

68. Alison, J. *et al.* Woodland, cropland and hedgerows promote pollinator abundance in intensive grassland landscapes, with saturating benefits of flower cover. *Journal of Applied Ecology* **59**, (2022).

69. Hünicken, P. L. *et al.* Insect pollination enhances yield stability in two pollinator-dependent crops. *Agric Ecosyst Environ* **320**, 107573 (2021).

70. Garibaldi, L. A., Aizen, M. A., Klein, A. M., Cunningham, S. A. & Harder, L. D. Global growth and stability of agricultural yield decrease with pollinator dependence. *Proceedings of the National Academy of Sciences* **108**, 5909–5914 (2011).

71. Senapathi, D. *et al.* Wild insect diversity increases inter-annual stability in global crop pollinator communities. *Proceedings of the Royal Society B: Biological Sciences* **288**, (2021).

72. Porto, R. G. *et al.* Pollination ecosystem services: A comprehensive review of economic values, research funding and policy actions. *Food Secur* **12**, (2020).

73. Aizen, M. A. *et al.* Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. 1–12 (2019) doi:10.1111/gcb.14736.

74. Frankie, G. W. *et al.* Diversity and abundance of bees visiting a mass flowering tree species in disturbed seasonal dry forest, Costa Rica. *J Kans Entomol Soc* **70**, (1997).

75. Ramalho, M. Stingless bees and mass flowering trees in the canopy of Atlantic Forest: a tight relationship. *Acta Bot Brasilica* **18**, (2004).

76. Requier, F. & Leonhardt, S. D. Beyond flowers: including non-floral resources in bee conservation

schemes. *J Insect Conserv* **24**, (2020).

77. Chui, S. X., Keller, A. & Leonhardt, S. D. Functional resin use in solitary bees. *Ecol Entomol* **47**, (2022).

78. dos Santos, C. F., Halinski, R., de Souza dos Santos, P. D., Almeida, E. A. B. & Blochtein, B. Looking beyond the flowers: associations of stingless bees with sap-sucking insects. *Science of Nature* **106**, (2019).

79. Koch, H., Corcoran, C. & Jonker, M. Honeydew collecting in Malagasy stingless bees (Hymenoptera: Apidae: Meliponini) and observations on competition with invasive ants. *African Entomology* **19**, (2011).

80. Roubik, D. W. Nest and Colony Characteristics of Stingless Bees from Panamá (Hymenoptera: Apidae). *J Kans Entomol Soc* **56**, (1983).

81. Galbraith, S. M., Cane, J. H., Moldenke, A. R. & Rivers, J. W. Salvage logging reduces wild bee diversity, but not abundance, in severely burned mixed-conifer forest. *For Ecol Manage* **453**, (2019).

82. Rezende, M. Q., Venzon, M., dos Santos, P. S., Cardoso, I. M. & Janssen, A. Extrafloral nectary-bearing leguminous trees enhance pest control and increase fruit weight in associated coffee plants. *Agric Ecosyst Environ* **319**, (2021).

83. Rosa-Schleich, J., Loos, J., Mußhoff, O. & Tscharntke, T. Ecological-economic trade-offs of Diversified Farming Systems – A review. *Ecological Economics* **160**, (2019).

84. Staton, T., Breeze, T. D., Walters, R. J., Smith, J. & Girling, R. D. Productivity, biodiversity trade-offs, and farm income in an agroforestry versus an arable system. *Ecological Economics* **191**, (2022).

85. Fahrig, L. Rethinking patch size and isolation effects: The habitat amount hypothesis. *J Biogeogr* **40**, 1649–1663 (2013).

86. Sirami, C. *et al.* Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions. *Proc Natl Acad Sci U S A* **116**, 16442–16447 (2019).

87. Villard, M. A. & Metzger, J. P. Beyond the fragmentation debate: A conceptual model to predict when habitat configuration really matters. *Journal of Applied Ecology* **51**, 309–318 (2014).

88. Riva, F., Koper, N. & Fahrig, L. Overcoming confusion and stigma in habitat fragmentation research. *Biological Reviews* (2024) doi:10.1111/brv.13073.

89. Ricketts, T. H., Daily, G. C., Ehrlich, P. R. & Michener, C. D. Economic value of tropical forest to coffee production. *Proc Natl Acad Sci U S A* **101**, (2004).

90. Obregon, D., Guerrero, O. R., Stashenko, E. & Poveda, K. Natural habitat partially mitigates negative pesticide effects on tropical pollinator communities. *Glob Ecol Conserv* **28**, (2021).

91. Avelino, J., Romero-Gurdián, A., Cruz-Cuellar, H. F. & Declerck, F. A. J. Landscape context and scale differentially impact coffee leaf rust, coffee berry borer, and coffee root-knot nematodes. *Ecological Applications* **22**, 584–596 (2012).

92. Howard, C., Fountain, M. T., Brittain, C., Burgess, P. J. & Garratt, M. P. D. Perennial flower margins reduce orchard fruit damage by rosy apple aphid, Dysaphis plantaginea (Homoptera: Aphididae). *Journal of Applied Ecology* (2024) doi:10.1111/1365-2664.14598.

93. Thies, C., Steffan-Dewenter, I. & Tscharntke, T. Effects of landscape context on herbivory and parasitism at different spatial scales. in *Oikos* vol. 101 (2003).

94. Galpern, P., Vickruck, J., Devries, J. H. & Gavin, M. P. Landscape complexity is associated with crop yields across a large temperate grassland region. *Agric Ecosyst Environ* **290**, (2020).

95. Le Provost, G. *et al.* Land-use history impacts functional diversity across multiple trophic groups. *Proceedings of the National Academy of Sciences* **117**, 1573–1579 (2020).

96. González-Chaves, A. D. *et al.* Evidence of time-lag in the provision of ecosystem services by tropical regenerating forests to coffee yields. *Environmental Research Letters* **18**, (2023).

97. d'Albertas, F., Sparovek, G., Pinto, L. F. G., Hohlenwerger, C. & Metzger, J. P. Yield increases mediated by pollination and carbon payments can offset restoration costs in coffee landscapes. *One Earth* **7**, (2024).

98. Zhang, M. & Wei, X. Deforestation, forestation, and water supply. *Science (1979)* **371**, 990–991 (2021).

99. Kuang, X. *et al.* The changing nature of groundwater in the global water cycle. *Science (1979)* **383**, (2024).

100. Wu, Y. *et al.* Do forests provide watershed services for farmers in the humid tropics? Evidence from the Brazilian Amazon. *Ecological Economics* **183**, (2021).

101. Ilstedt, U. *et al.* Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. *Sci Rep* **6**, (2016).

102. Hua, F. *et al.* The biodiversity and ecosystem service contributions and trade-offs of forest restoration approaches. *Science (1979)* **376**, 839–844 (2022).

103. Ellison, D., N. Futter, M. & Bishop, K. On the forest cover–water yield debate: from demand- to supply-side thinking. *Glob Chang Biol* **18**, 806–820 (2012).

104. D'Odorico, P. *et al.* The Global Food-Energy-Water Nexus. *Reviews of Geophysics* **56**, 456–531 (2018).

105. Lapola, D. M. *et al.* The drivers and impacts of Amazon forest degradation. *Science (1979)* **379**, (2023).

106. Leite-Filho, A. T., Soares-Filho, B. S., Davis, J. L., Abrahão, G. M. & Börner, J. Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. *Nat Commun* **12**, (2021).

107. Neary, D. G., Ice, G. G. & Jackson, C. R. Linkages between forest soils and water quality and quantity. *For Ecol Manage* **258**, 2269–2281 (2009).

108. Mello, K. D., Valente, R. A., Randhir, T. O. & Vettorazzi, C. A. Impacts of tropical forest cover on water quality in agricultural watersheds in southeastern Brazil. *Ecol Indic* **93**, (2018).

109. Qiu, M., Wei, X., Hou, Y., Spencer, S. A. & Hui, J. Forest cover, landscape patterns, and water quality: a meta-analysis. *Landsc Ecol* **38**, 877–901 (2023).

110. Sarira, T. V., Zeng, Y., Neugarten, R., Chaplin-Kramer, R. & Koh, L. P. Co-benefits of forest carbon projects in Southeast Asia. *Nat Sustain* **5**, 393–396 (2022).

111. Mello, K. D., Randhir, T. O., Valente, R. A. & Vettorazzi, C. A. Riparian restoration for protecting water quality in tropical agricultural watersheds. *Ecol Eng* (2017) doi:10.1016/j.ecoleng.2017.06.049.

112. Guidotti, V. *et al.* Changes in Brazil's Forest Code can erode the potential of riparian buffers to supply watershed services. *Land use policy* **94**, (2020).

113. Metzger, J. P. *et al.* Why Brazil needs its Legal Reserves. *Perspect Ecol Conserv* **17**, 91–103 (2019).

114. Grolleau, G. & McCann, L. M. J. Designing watershed programs to pay farmers for water quality services: Case studies of Munich and New York City. *Ecological Economics* **76**, 87–94 (2012).

115. FAO. *The Future of Food and Agriculture – Trends and Challenges*. (2017).

116. Wender, M. J. *Goodbye Family Farms and Hello Agribusiness: The Story of How Agricultural Policy Is Destroying the Family Farm and the Environment. Available at: Https://Digitalcommons.Law.Villanova.Edu/Elj/Vol22/Iss1/6*. (2011).

117. White, E. V. & Roy, D. P. A contemporary decennial examination of changing agricultural field sizes using Landsat time series data. *Geo* **2**, 33–54 (2015).

118. Oksanen, T. & Visala, a. *Path Planning Algorithms for Agricultural Machines*. *Agricultural Engineering International the CIGR Ejournal* vol. IX (2007).

119. Colaizzi, P. D., Gowda, P. H., Marek, T. H. & Porter, D. O. Irrigation in the texas high plains: A brief history and potential reductions in demand. *Irrigation and Drainage* **58**, (2009).

120. Graves, A. R., Burgess, P. J., Liagre, F. & Dupraz, C. Farmer perception of benefits, constraints and opportunities for silvoarable systems: Preliminary insights from Bedfordshire, England. *Outlook Agric* **46**, (2017).

121. Sollen-Norrlin, M., Ghaley, B. B. & Rintoul, N. L. J. Agroforestry benefits and challenges for adoption in Europe and beyond. *Sustainability (Switzerland)* **12**, (2020).

122. Amare, D., Wondie, M., Mekuria, W. & Darr, D. Agroforestry of Smallholder Farmers in Ethiopia: Practices and Benefits. *Small-scale Forestry* **18**, (2019).

123. Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A. & Hansen, M. C. Classifying drivers of global forest

loss. *Science (1979)* **361**, (2018).

124. Bene, J. G., Beall, H. W. & Côté, A. *Trees, Food and People: Land Management in the Tropics*. *International Development Reasearch Centre* (1977).

125. Nair, P. K. R. Classification of agroforestry systems. *Agroforestry Systems* **3**, (1985).

126. Burgess, P. J. & Rosati, A. Advances in European agroforestry: results from the AGFORWARD project. *Agroforestry Systems* **92**, (2018).

127. Fetting, C. 'The European Green Deal', ESDN Report. *European Commission* **53**, (2020).

128. Veldkamp, E. *et al.* Multifunctionality of temperate alley-cropping agroforestry outperforms open cropland and grassland. *Commun Earth Environ* **4**, 1–10 (2023).

129. Nisbet, T. R. *et al.* Forest Green Infrastructure to Protect Water Quality: A Step-by-Step Guide for Payment Schemes. in *Green Infrastructure and Climate Change Adaptation: Function, Implementation and Governance* (ed. Futoshi Nakamura) (Springer, 2022). doi:10.1007/978-981-16-6791-6.

130. Valatin, G. *et al.* Approaches to cost-effectiveness of payments for tree planting and forest management for water quality services. *Ecosyst Serv* **53**, (2022).

131. García de Jalón, S. *et al.* Dry deposition of air pollutants on trees at regional scale: A case study in the Basque Country. *Agric For Meteorol* **278**, 107648 (2019).

132. Junge, X., Schüpbach, B., Walter, T., Schmid, B. & Lindemann-Matthies, P. Aesthetic quality of agricultural landscape elements in different seasonal stages in Switzerland. *Landsc Urban Plan* **133**, 67–77 (2015).

133. Zabala, J. A., Martínez-Paz, J. M. & Alcon, F. A comprehensive approach for agroecosystem services and disservices valuation. *Science of the Total Environment* **768**, (2021).

134. Edens, B. *et al.* Establishing the SEEA Ecosystem Accounting as a global standard. *Ecosyst Serv* **54**, (2022).

135. Mead, R. & Willey, R. W. The concept of a 'land equivalent ratio' and advantages in yields from intercropping. *Exp Agric* **16**, (1980).

136. Dupraz, C., Querné, A., Talbot, G. & Dufour, L. *What Explanations for the Surprising Productivity of Temperate Agroforestry Systems as Measured by Their Land Equivalent Ratio? In Agro2010, the XIth ESA Congress.* (eds J. Wery, I. Shili-Touzi, & A. Perrin) 271-272 (2010).

137. Huang, W. & Xu, Q. Overyield of Taxodium ascendens-intercrop systems. *For Ecol Manage* **116**, 33–38 (1999).

138. Lehmann, L. M. *et al.* Productivity and economic evaluation of agroforestry systems for sustainable production of food and non-food products. *Sustainability (Switzerland)* **12**, (2020).

139. Osman, A. N., Ræbild, A., Christiansen, J. L. & Bayala, J. Performance of cowpea (Vigna unguiculata) and pearl millet (Pennisetum glaucum) intercropped under parkia biglobosa in an agroforestry system in Burkina Faso. *Afr J Agric Res* **6**, (2011).

140. Miah, M. G. *et al.* Transformation of jackfruit (Artocarpus heterophyllus Lam.) orchard into multistory agroforestry increases system productivity. *Agroforestry Systems* **92**, (2018).

141. Khasanah, N. *et al.* Oil Palm Agroforestry Can Achieve Economic and Environmental Gains as Indicated by Multifunctional Land Equivalent Ratios. *Front Sustain Food Syst* **3**, (2020).

142. Vandermeer, J. Maximizing crop yield in alley crops. *Agroforestry Systems* **40**, (1998).

143. Ivezić, V., Yu, Y. & Werf, W. van der. Crop Yields in European Agroforestry Systems: A Meta-Analysis. *Front Sustain Food Syst* **5**, (2021).

144. Ngaba, M. J. Y. *et al.* Meta-analysis unveils differential effects of agroforestry on soil properties in different zonobiomes. *Plant Soil* **496**, (2024).

145. Zhu, X. *et al.* Reductions in water, soil and nutrient losses and pesticide pollution in agroforestry practices: a review of evidence and processes. *Plant Soil* **453**, (2020).

146. Dupraz, C. *et al.* Influence of latitude on the light availability for intercrops in an agroforestry alley-cropping system. *Agroforestry Systems* **92**, (2018).

147. Noordwijk, M. van, Lawson, G., Hairiah, K. & Wilson, J. Root distribution of trees and crops: competition and/or complementarity. in *Tree-crop interactions: agroforestry in a changing climate* (2015). doi:10.1079/9781780645117.0221.

148. Hugenschmidt, J. & Kay, S. Unmasking adaption of tree root structure in agroforestry Systems in Switzerland using GPR. *Geoderma Regional* **34**, (2023).

149. Thiesmeier, A. & Zander, P. Can agroforestry compete? A scoping review of the economic performance of agroforestry practices in Europe and North America. *For Policy Econ* **150**, 102939 (2023).

150. Giannitsopoulos, M. L. *et al.* Whole system valuation of arable, agroforestry and tree-only systems at three case study sites in Europe. *J Clean Prod* **269**, (2020).

151. Paul, C. *et al.* Carbon farming: Are soil carbon certificates a suitable tool for climate change mitigation? *J Environ Manage* **330**, (2023).

152. Bartkowski, B. *et al.* Potential of the economic valuation of soil-based ecosystem services to inform sustainable soil management and policy. *PeerJ* **2020**, 1–31 (2020).

153. Kay, S. *et al.* Agroforestry is paying off – Economic evaluation of ecosystem services in European landscapes with and without agroforestry systems. *Ecosyst Serv* **36**, 100896 (2019).

154. Reed, J., Van Vianen, J., Deakin, E. L., Barlow, J. & Sunderland, T. Integrated landscape approaches to managing social and environmental issues in the tropics: learning from the past to guide the future. *Glob Chang Biol* **22**, (2016).

155. Moffette, F., Skidmore, M. & Gibbs, H. K. Environmental policies that shape productivity: Evidence from cattle ranching in the Amazon. *J Environ Econ Manage* **109**, (2021).

156. Yang, K. F., Gergel, S. E. & Baudron, F. Forest restoration scenarios produce synergies for agricultural production in southern Ethiopia. *Agric Ecosyst Environ* **295**, (2020).

157. Abman, R. & Carney, C. Agricultural productivity and deforestation: Evidence from input subsidies and ethnic favoritism in Malawi. *J Environ Econ Manage* **103**, (2020).

158. González-Chaves, A., Carvalheiro, L. G., Garibaldi, L. A. & Metzger, J. P. Positive forest cover effects on coffee yields are consistent across regions. *Journal of Applied Ecology* **59**, (2022).

159. Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degrad Dev* **26**, (2015).

160. Tan, D. *et al.* The effects of environmental degradation on agriculture: Evidence from European countries. *Gondwana Research* **106**, (2022).

161. Pendrill, F. *et al.* Disentangling the numbers behind agriculture-driven tropical deforestation. *Science (1979)* **377**, eabm9267 (2022).

162. Fletcher, C. *et al.* Earth at risk: An urgent call to end the age of destruction and forge a just and sustainable future. *PNAS Nexus* **3**, (2024).

163. Kasting, J. F. & Howard, M. T. Atmospheric composition and climate on the early Earth. in *Philosophical Transactions of the Royal Society B: Biological Sciences* vol. 361 (2006).

164. Hessler, A. M. Earth’s Earliest Climate. *Nature Education Knowledge* **3**, 24 (2011).

165. Pawlik, Ł. *et al.* Impact of trees and forests on the Devonian landscape and weathering processes with implications to the global Earth’s system properties - A critical review. *Earth Sci Rev* **205**, (2020).

166. Runnels, C. N. Environmental degradation in ancient Greece. *Sci Am* **272**, (1995).

167. Hurt, R. D. *The Dust Bowl : An Agricultural and Social History*. (Nelson-Hall, Chicago, 1981).

168. The value of forests. *Nat Plants* **10**, 1–1 (2024).

169. Bakkes, J. *et al. The Cost of Policy Inaction. The Case of Not Meeting the 2010 Biodiversity Target*. *Environment* vol. 0044 (2008).

170. Burian, A. *et al.* Biodiversity–production feedback effects lead to intensification traps in agricultural landscapes. *Nat Ecol Evol* **8**, (2024).

171. FAOSTAT. FAOSTAT Statistical database. *Food and Agricultural Organization of the United Nations, FAO*

(2023).

172. Bastin, J. F. *et al.* The global tree restoration potential. *Science (1979)* **364**, (2019).

173. Borrelli, P. *et al.* An assessment of the global impact of 21st century land use change on soil erosion. *Nat Commun* **8**, (2017).

174. Veldkamp, E., Schmidt, M., Powers, J. S. & Corre, M. D. Deforestation and reforestation impacts on soils in the tropics. *Nat Rev Earth Environ* **1**, (2020).

175. Paul, S., Flessa, H., Veldkamp, E. & López-Ulloa, M. Stabilization of recent soil carbon in the humid tropics following land use changes: Evidence from aggregate fractionation and stable isotope analyses. *Biogeochemistry* **87**, (2008).

176. López-Ulloa, M., Veldkamp, E. & de Koning, G. H. J. Soil Carbon Stabilization in Converted Tropical Pastures and Forests Depends on Soil Type. *Soil Science Society of America Journal* **69**, (2005).

177. Robinson, D. A. *et al.* Soil natural capital in Europe; A framework for state and change assessment. *Sci Rep* **7**, (2017).

178. Borrelli, P. *et al.* Land use and climate change impacts on global soil erosion by water (2015-2070). *Proc Natl Acad Sci U S A* **117**, (2020).

179. Raven, P. H. & Wagner, D. L. Agricultural intensification and climate change are rapidly decreasing insect biodiversity. *Proc Natl Acad Sci U S A* **118**, (2021).

180. Zeppetello, L. R. V. *et al.* Large scale tropical deforestation drives extreme warming. *Environmental Research Letters* **15**, (2020).

181. Battisti, D. S. & Naylor, R. L. Historical warnings of future food insecurity with unprecedented seasonal heat. *Science (1979)* **323**, (2009).

182. Diaz, C. D. *et al.* Increased extreme humid heat hazard faced by agricultural workers. *Environ Res Commun* **11**, (2023).

183. Trancoso, R. *et al.* Converting tropical forests to agriculture increases fire risk by fourfold. *Environmental Research Letters* **17**, (2022).

184. Myers, S. S. *et al.* Increasing CO2 threatens human nutrition. *Nature* **510**, (2014).

185. Fanzo, J. C. & Downs, S. M. Climate change and nutrition-associated diseases. *Nat Rev Dis Primers* **7**, (2021).

186. Mace, G. M., Norris, K. & Fitter, A. H. Biodiversity and ecosystem services: A multilayered relationship. *Trends Ecol Evol* **27**, (2012).

187. Giam, X. Global biodiversity loss from tropical deforestation. *Proc Natl Acad Sci U S A* **114**, (2017).

188. Tscharntke, T. *et al.* Global food security, biodiversity conservation and the future of agricultural intensification. *Biol Conserv* **151**, (2012).

189. Rasmussen, L. V. *et al.* Joint environmental and social benefits from diversified agriculture. *Science (1979)* **384**, 87–93 (2024).

190. Vasquez, W. & Sunderland, T. The rights way forward: Reconciling the right to food with biodiversity conservation. *ORYX* **39**, (2023).

191. Nielsen, M. R., Meilby, H., Smith-Hall, C., Pouliot, M. & Treue, T. The Importance of Wild Meat in the Global South. *Ecological Economics* **146**, (2018).

192. Dawson, I. K. *et al.* Contributions of biodiversity to the sustainable intensification of food production. *Glob Food Sec* **21**, (2019).

193. Thrupp, L. A. Linking agricultural biodiversity and food security: The valuable role of agrobiodiversity for sustainable agriculture. *Int Aff* **76**, (2000).

194. Huuskonen, S. *et al.* What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia? *For Ecol Manage* **479**, (2021).

195. Liu, C. L. C., Kuchma, O. & Krutovsky, K. V. Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. *Glob Ecol Conserv* **15**,

(2018).

196. Godfray, H. C. J. *et al.* Food security: The challenge of feeding 9 billion people. *Science (1979)* **327**, (2010).

197. *The State of Food Security and Nutrition in the World 2023*. *The State of Food Security and Nutrition in the World 2023* (2023). doi:10.4060/cc3017en.

198. United Nations. *World Population Projected to Reach 9.8 Billion in 2050, United Nation*. *Department of Economic and Social Affairs* (2017).

Supplementary Methods

Supplementary Methods for Figure 4b

Data

We used country-level cereal yields and actual forest cover data for each year from 1990 to 2020 from FAOSTAT[1] and the 30-arc-sec restoration potential of the tree cover map published by Bastin *et al.* (2019)[2]. To calculate the country-level maximum amount of forest cover, we first used the potential tree cover map[2]. We filtered only pixels with more than 10% of tree cover and calculated the total area of these pixels within each country using Google Earth Engine[3]. The total area of filtered pixels on the total area of the country ($\frac{Total\ area\ of\ pixels\ with\ more\ than\ 10\%\ of\ tree\ cover}{Total\ area\ of\ country}$) represents country-level potential forest cover, which we consider the maximum amount (100 %) of forest cover that one country can have.

Then, we calculated the country-level relative forest loss (%) from this maximum for each year from 1990 to 2020 with the following equation:

$$Relative\ forest\ loss\ (\%) = \frac{Potential\ forest\ cover - actual\ forest\ cover}{Potential\ forest\ cover} \times 100 \qquad (1)$$

Four countries, Micronesia, Turkmenistan, Kuwait, and the United Arab Emirates, showed higher actual forest cover compared to potential forest cover and were thus excluded. These countries are small islands or generally occupied by desert, so we concluded that filtering out these countries would not impact our global analysis. Since we aim to address the relationship between forest loss and agricultural yields only for countries that can support natural forests, we also excluded all other countries with less than 30% of potential forest cover.

Modelling

To test the proposed unimodal theory of nature's limits (Fig. 4a), we applied a linear mixed-effects model to analyze the relationship between cereal yields and relative forest loss using the R lme4 package[5]. To capture a flexible non-linear relationship between these two variables, we used a natural cubic spline for forest loss. The model also included the *year* variable, which is a numeric variable representing the year of observation from 1990 to 2020, as a control variable assuming its linear effect on yield to account for temporal trends in yield; it also included *country* as a random effect to control for country-level variability. The model was specified as follows:

$$yield \sim ns(forest\ loss) + year + (1\ |\ country) \qquad (1)$$

To assess potential multicollinearity between *forest loss* and *year*, we calculated the Generalized Variance Inflation Factor (GVIF) for these predictors. The GVIF values for both variables were approximately 1, indicating no significant multicollinearity between these variables. Therefore, both predictors were included in the model. To guarantee that the model accurately analyzes yield trends by relative forest loss within each country, we included only countries with at least 10% changes in relative forest loss between 1990 and 2020, resulting in 22 countries (Supplementary Table 1).

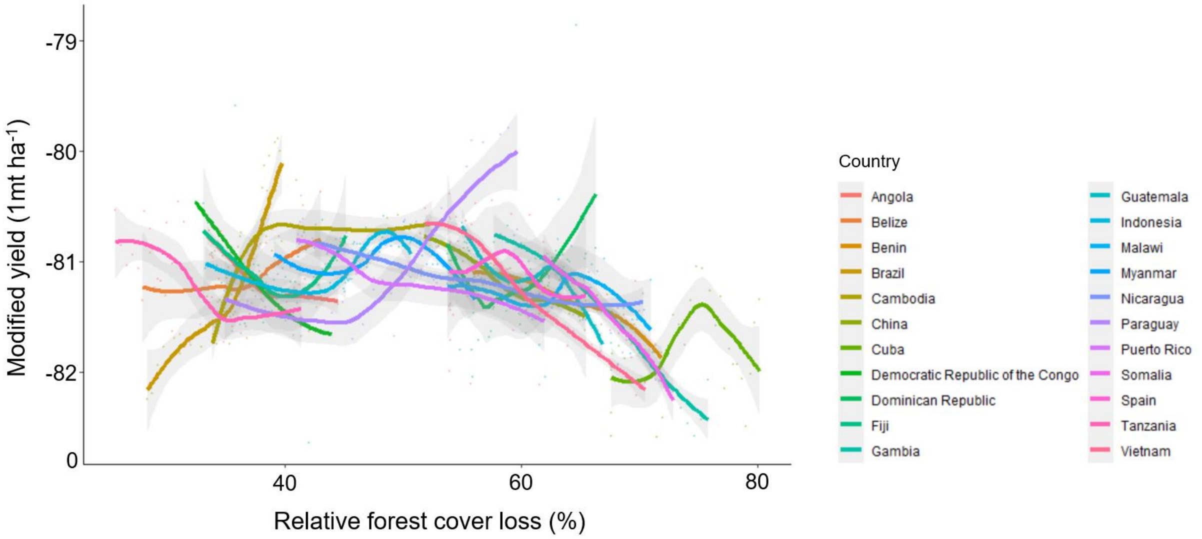
We identified the best-fitting model via the Bayesian Information Criterion (BIC). The BIC of the model continuously decreased as the degrees of freedom for the spline increased. However, the biggest decline was from the degree of 1 to the degree of 2 (75). From the degree of 2, the BIC decrease was comparatively minor (less than 22 when investigated until the degree of freedom of 10). We thus decided to retain the model with the degree of freedom of 2. This final model showed BIC 13719 with Pseudo-R^2 0.93 (total) or 0.10 (fixed effects). The model showed a lower BIC compared to the same model without the random effect of *country* (with a BIC decrease of 1606), the fixed effect of *year* (with a BIC decrease of 405), and both effects (with a BIC decrease of 1641). Therefore, these variables were retained in the final model. This model exhibited an unimodal pattern, indicating a peak in cereal yields at a specific level of forest loss.

To estimate the location of this tipping point while accounting for the uncertainty, we employed parametric bootstrapping with 1000 iterations. Predictions were generated from the spline model using R bootMer[5] and predict[6] functions. The 95% confidence intervals for the forest loss values corresponding to the maximum predicted yield were determined by calculating the 2.5th and 97.5th percentiles of the bootstrapped predictions.

Additionally, to visualize each data point and the average relationship between relative forest loss and yields together, we created a modified version of the yield variable based on the partial effect of forest cover loss, by applying the R remef function[7] to our model (Equation 1). This modification allowed us to isolate the relationship between forest loss and yield while controlling yearly trends and country-specific variations, all while retaining the residuals of the data. We then visualized the relationship between relative forest cover loss and modified yield (Fig. 4b). Furthermore, to analyze country-specific relationships, we applied the locally weighted scatterplot smoothing (loess) method, which produced distinct smoothed lines for each country, capturing local trends in the data (Supplementary Figure 1). This analysis shows that very few countries have fully crossed the tipping point, indicating that our identified tipping point is a projection based on current trends rather than observed outcomes.

Supplementary Table 1 | List of 22 countries included in the polynomial model. Maximum forest loss (%), minimum forest loss (%), forest loss difference between the two (%), maximum yield (100g ha^{-1}), minimum yield (100g ha^{-1}), and yield difference (100g ha^{-1}) during 1990 and 2020 were calculated then rounded.

Country	Maximum forest loss (%)	Minimum forest loss (%)	Forest loss difference (%)	Maximum yield (100g ha^{-1})	Minimum yield (100g ha^{-1})	Yield difference (100g ha^{-1})
Angola	45	33	11	10001	2680	7321
Belize	43	28	15	42895	18981	23914
Benin	72	56	16	15178	8479	6699
Brazil	40	28	11	53214	17551	35663
Cambodia	52	34	19	35656	13012	22644
China	65	52	14	63181	42373	20808
Cuba	80	68	13	31888	13244	18644
Democratic Republic of the Congo	44	32	11	8790	7658	1132
Dominican Republic	66	54	13	60902	36353	24549
Fiji	45	33	12	44754	7544	37210
Gambia	76	58	18	13053	4614	8439
Guatemala	67	55	12	25141	14919	10222
Indonesia	51	33	17	53310	38002	15308
Malawi	71	54	17	24670	4816	19854
Myanmar	56	39	17	38552	26995	11557
Nicaragua	70	43	28	24031	14171	9860
Paraguay	60	35	25	47065	16497	30568
Puerto Rico	62	41	21	31599	10698	20901
Somalia	73	62	11	11900	4104	7796
Spain	65	54	12	45015	17297	27718
Tanzania	41	26	16	20435	8581	11854
Vietnam	70	52	19	59471	30064	29407



Supplementary Figure 1 | Visualization of yield trends relative to forest loss for each 22 countries. Each country's yield trend was plotted separately using the loess smoothing method, with each trend line colored differently to represent each country.

Reference

1. FAOSTAT. FAOSTAT Statistical database. *Food and Agricultural Organization of the United Nations, FAO* (2023).
2. Bastin, J. F. *et al.* The global tree restoration potential. *Science (1979)* **364**, (2019).
3. Gorelick, N. *et al.* Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens Environ* **202**, (2017).
4. R Core Team. R: A Language and Environment for Statistical Computing. Preprint at (2022).
5. Bates, D., Mächler, M., Bolker, B. & Walker, S. Fitting Linear Mixed-Effects Models Using **lme4**. *J Stat Softw* **67**, (2015).
6. Fox, J. & Weisberg, S. An {R} Companion to Applied Regression, Third Edition. *Thousand Oaks CA: Sage.* (2019).
7. Hohenstein, S. & Kliegl, R. remef: Remove Partial Effects. R package version 1.0.7. https://github.com/hohenstein/remef/. Preprint at (2024).

Supplementary Data 1

ID	Article ID	Latitude	Longitude	Site (if applicable), Country	Forest cover change (%)	Yield change(%)	Reference
1	1	-16.04	34.80	Malawi	-13.5	-5.4	Amadu, F. O., Miller, D. C. & McNamara, P. E. Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: Evidence from southern Malawi. *Ecological Economics* **167**, doi:10.1016/j.ecolecon.2019.106443 (2020)
2	1	-16.92	35.25	Malawi	-25.0	-18.9	Amadu, F. O., Miller, D. C. & McNamara, P. E. Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: Evidence from southern Malawi. *Ecological Economics* **167**, doi:10.1016/j.ecolecon.2019.106443 (2020)
3	1	-16.07	35.14	Malawi	-36.5	-17.9	Amadu, F. O., Miller, D. C. & McNamara, P. E. Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: Evidence from southern Malawi. *Ecological Economics* **167**, doi:10.1016/j.ecolecon.2019.106443 (2020)
4	1	-15.39	35.34	Malawi	-5.8	6.7	Amadu, F. O., Miller, D. C. & McNamara, P. E. Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: Evidence from southern Malawi. *Ecological Economics* **167**, doi:10.1016/j.ecolecon.2019.106443 (2020)
5	2	-12.58	-56.76	Brazilian	-20.0	-2.8	Antonio Sumila, T. C., Pires, G. F., Fontes, V. C. & Costa, M. H. Sources of Water Vapor to Economically Relevant Regions in Amazonia and the Effect of Deforestation. *Journal of Hydrometeorology* **18**, 1643-1655, doi:10.1175/jhm-d-16-0133.1 (2017).
6	2	-12.58	-56.76	Brazilian	-40.0	-5.5	Antonio Sumila, T. C., Pires, G. F., Fontes, V. C. & Costa, M. H. Sources of Water Vapor to Economically Relevant Regions in Amazonia and the Effect of Deforestation. *Journal of Hydrometeorology* **18**, 1643-1655, doi:10.1175/jhm-d-16-0133.1 (2017).
7	2	-12.58	-56.76	Brazilian	-60.0	-11.4	Antonio Sumila, T. C., Pires, G. F., Fontes, V. C. & Costa, M. H. Sources of Water Vapor to Economically Relevant Regions in Amazonia and the Effect of Deforestation. *Journal of Hydrometeorology* **18**, 1643-1655, doi:10.1175/jhm-d-16-0133.1 (2017).
8	3	7.31	38.77	Ethiopia	-13.3	-32.3	Baudron, F., Schultner, J., Duriaux, J.-Y., Gergel, S. E. & Sunderland, T. Agriculturally productive yet biodiverse: human benefits and conservation values along a forest-agriculture gradient in Southern Ethiopia. *Landscape Ecology* **34**, 341-356, doi:10.1007/s10980-019-00770-6 (2019).
9	4	17.95	76.47	India	-51.5	-25.2	Chaturvedi, A. *et al.* Land use planning issues in management of common property resources in a backward tribal area. *Land Use Policy* **42**, 806-812 (2015).
10	5	15.50	32.56	Khartoum ,Sudan	69.2	79.1	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
11	5	15.50	32.56	Khartoum ,Sudan	40.9	36.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
12	5	15.50	32.56	Khartoum ,Sudan	29.0	22.9	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
13	5	15.50	32.56	Khartoum ,Sudan	22.5	14.7	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
14	5	15.50	32.56	Khartoum ,Sudan	17.5	10.8	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
15	5	15.50	32.56	Khartoum ,Sudan	16.3	7.3	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
16	5	15.50	32.56	Khartoum ,Sudan	12.8	6.3	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
17	5	15.50	32.56	Khartoum,Sudan	11.4	4.8	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
18	5	15.50	32.56	Khartoum,Sudan	10.7	3.6	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
19	5	15.50	32.56	Khartoum,Sudan	10.1	2.5	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
20	5	15.50	32.56	Khartoum,Sudan	8.4	2.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
21	5	15.50	32.56	Khartoum,Sudan	8.8	1.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
22	5	15.50	32.56	Khartoum,Sudan	6.8	1.9	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
23	5	15.50	32.56	Khartoum,Sudan	7.3	0.9	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
24	5	15.50	32.56	Khartoum,Sudan	6.2	0.9	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
25	5	15.50	32.56	Khartoum,Sudan	6.1	0.9	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
26	5	15.50	32.56	Khartoum,Sudan	5.8	0.9	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
27	5	15.50	32.56	Khartoum,Sudan	5.0	0.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
28	5	15.50	32.56	Khartoum,Sudan	5.7	0.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).

29	5	15.50	32.56	Khartoum,Sudan	4.7	0.0	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
30	5	15.50	32.56	Khartoum,Sudan	4.7	0.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
31	5	15.50	32.56	Khartoum,Sudan	4.5	0.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
32	5	15.50	32.56	Khartoum,Sudan	4.1	0.0	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
33	5	15.50	32.56	Khartoum,Sudan	4.1	0.0	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
34	5	15.50	32.56	Khartoum,Sudan	4.0	0.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
35	5	15.50	32.56	Khartoum,Sudan	3.8	0.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
36	5	15.50	32.56	Khartoum,Sudan	3.8	0.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
37	5	15.50	32.56	Khartoum,Sudan	3.5	0.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
38	5	15.50	32.56	Khartoum,Sudan	3.3	0.4	Hassan, R., Hertzler, G. & Benhin, J. K. A. Depletion of forest resources in Sudan: Intervention options for optimal control. *Energy Policy* **37**, 1195-1203, doi:10.1016/j.enpol.2008.10.049 (2009).
39	6			Senegal	14.3	30.6	Liu, S., Kairé, M., Wood, E., Diallo, O. & Tieszen, L. L. Impacts of land use and climate change on carbon dynamics in south-central Senegal. *Journal of Arid Environments* **59**, 583-604, doi:10.1016/j.jaridenv.2004.03.023 (2004).
40	7	38.670	7.670	Ethiopia	-9.5	-26.9	Meshesha, D. T., Tsunekawa, A. & Tsubo, M. Continuing land degradation: Cause-effect in Ethiopia's Central Rift Valley. *Land Degradation & Development* **23**, 130-143, doi:10.1002/ldr.1061 (2012).
41	7	38.670	7.670	Ethiopia	-62.7	-50.0	Meshesha, D. T., Tsunekawa, A. & Tsubo, M. Continuing land degradation: Cause-effect in Ethiopia's Central Rift Valley. *Land Degradation & Development* **23**, 130-143, doi:10.1002/ldr.1061 (2012).
42	8	9.220	116.000	Indonesia	1.0	3.7	Yamamoto, Y., Shigetomi, Y., Ishimura, Y. & Hattori, M. Forest change and agricultural productivity: Evidence from Indonesia. *World Development* **114**, 196-207 (2019).
43	9	9.030	-38.740	Ethiopia	75.1	79.5	Yang, K. F., Gergel, S. E. & Baudron, F. Forest restoration scenarios produce synergies for agricultural production in southern Ethiopia. *Agriculture Ecosystems & Environment* **295**, doi:10.1016/j.agee.2020.106888 (2020).
44	9	9.030	-38.740	Ethiopia	57.3	45.4	Yang, K. F., Gergel, S. E. & Baudron, F. Forest restoration scenarios produce synergies for agricultural production in southern Ethiopia. *Agriculture Ecosystems & Environment* **295**, doi:10.1016/j.agee.2020.106888 (2020).
45	9	9.030	-38.740	Ethiopia	39.8	10.6	Yang, K. F., Gergel, S. E. & Baudron, F. Forest restoration scenarios produce synergies for agricultural production in southern Ethiopia. *Agriculture Ecosystems & Environment* **295**, doi:10.1016/j.agee.2020.106888 (2020).
46	9	9.030	-38.740	Ethiopia	22.3	1.8	Yang, K. F., Gergel, S. E. & Baudron, F. Forest restoration scenarios produce synergies for agricultural production in southern Ethiopia. *Agriculture Ecosystems & Environment* **295**, doi:10.1016/j.agee.2020.106888 (2020).
47	10			Aynimbrkekn,Ethiopia	-0.1	-55.1	Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degradation & Development* **26**, 680-689, doi:10.1002/ldr.2275 (2015).
48	10			Aynimbrkekn,Ethiopia	-0.2	-21.4	Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degradation & Development* **26**, 680-689, doi:10.1002/ldr.2275 (2015).
49	10			Dergajen,Ethiopia	-95.2	-11.4	Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degradation & Development* **26**, 680-689, doi:10.1002/ldr.2275 (2015).
50	10			Dergajen,Ethiopia	10.3	4.7	Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degradation & Development* **26**, 680-689, doi:10.1002/ldr.2275 (2015).
51	10			Endaselasie,Ethiopia	-67.5	9.9	Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degradation & Development* **26**, 680-689, doi:10.1002/ldr.2275 (2015).
52	10			Endaselasie,Ethiopia	0.0	20.3	Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degradation & Development* **26**, 680-689, doi:10.1002/ldr.2275 (2015).
53	10			Hadnet,Ethiopia	331.1	-22.5	Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degradation & Development* **26**, 680-689, doi:10.1002/ldr.2275 (2015).
54	10			Hadnet,Ethiopia	7.8	-43.4	Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degradation & Development* **26**, 680-689, doi:10.1002/ldr.2275 (2015).
55	10			Sinkata,Ethiopia	116.4	4.6	Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degradation & Development* **26**, 680-689, doi:10.1002/ldr.2275 (2015).
56	10			Sinkata,Ethiopia	5.0	10.7	Belay, K. T. *et al.* Spatial Analysis of Land Cover Changes in Eastern Tigray (Ethiopia) from 1965 to 2007: Are There Signs of a Forest Transition? *Land Degradation & Development* **26**, 680-689, doi:10.1002/ldr.2275 (2015).

Supplementary Data 2

Country	Year	Forest cover (%)	Cereal yields (100g ha-1)	Potential forest cover (%)	Relative forest loss (%)
Albania	2020	28.79	52092	97.51557247	70.47651029
Angola	2020	53.43	9923	95.48013564	44.04071628
Antigua & Barbuda	2020	18.45	38000	75.27115244	75.48861761
Argentina	2020	10.44	51642	57.83823748	81.94965743
Armenia	2020	11.54	20558	85.86561643	86.56039463
Australia	2020	17.42	16505	37.90681709	54.04520522
Austria	2020	47.25	73864	93.62705703	49.53381907
Azerbaijan	2020	13.69	32273	40.86859584	66.50239697
Bahamas	2020	50.94	74455	66.51390574	23.41451095
Bangladesh	2020	14.47	49018	96.63849553	85.02667087
Barbados	2020	14.65	27656	89.63506118	83.65594913
Belarus	2020	43.19	35399	99.63403689	56.65135997
Belgium	2020	22.76	84306	94.7727866	75.98466731
Belize	2020	55.99	35263	97.36743511	42.49617448
Benin	2020	27.8	14328	97.18644297	71.39518728
Bhutan	2020	71.45	34352	83.64725687	14.58177749
Bolivia	2020	46.92	20240	79.48106218	40.96706975
Bosnia & Herzegovina	2020	42.73	60507	99.617813	57.10606496
Botswana	2020	26.92	10338	65.40943962	58.84386083
Brazil	2020	59.42	52554	98.30110035	39.55306727
Brunei Darussalam	2020	72.11	30000	98.96752158	27.1377126
Bulgaria	2020	35.86	43734	96.18203883	62.71653166
Burkina Faso	2020	22.72	12617	76.14497803	70.16218195
Burundi	2020	10.89	12787	93.00233517	88.2906166
Cape Verde	2020	11.34	157	81.4861725	86.08352847
Cambodia	2020	45.71	34265	94.18148055	51.46604223
Cameroon	2020	43.03	17365	97.80364572	56.00368506
Canada	2020	38.7	40919	69.02593811	43.93411946
Central African Republic	2020	35.8	7130	98.75033923	63.74695998
Chad	2020	3.43	8671	31.7506379	89.19706744
Chile	2020	24.49	62458	53.70257941	54.39697633
China	2020	23.34	62967	48.79754185	52.16972184
Colombia	2020	53.31	43986	98.5103456	45.88385649
Comoros	2020	17.69	17820	86.70120425	79.59659251
Congo	2020	64.26	8868	99.16475146	35.19874849
Costa Rica	2020	59.44	33571	98.76492811	39.81669289
Croatia	2020	34.65	69924	97.50953888	64.46501502
Cuba	2020	31.23	25723	96.46269363	67.62478962
Cyprus	2020	18.67	23814	94.18503946	80.17731892
Czech Republic	2020	34.68	60427	99.32701688	65.08502813
Democratic People's Republic of Korea	2020	50.08	34997	98.95658546	49.39194823
Democratic Republic of the Congo	2020	55.65	8778	98.28442696	43.37861885
Denmark	2020	15.71	69263	93.0506886	83.11672892
Dominica	2020	63.83	16445	89.25062315	28.48229206

Dominican Republic	2020	45.11	51300	97.94420146	53.94316424
Ecuador	2020	50.32	35309	97.83473109	48.56632258
El Salvador	2020	28.18	27320	98.86776775	71.49728305
Eritrea	2020	8.72	6405	43.66304889	80.02887974
Estonia	2020	57.04	44115	93.07246093	38.71441732
Eswatini	2020	28.93	12870	98.31307174	70.5735977
Ethiopia	2020	15.12	28613	69.45712458	78.23117485
Fiji	2020	62.4	36657	93.78380706	33.46399346
Finland	2020	73.73	35893	96.0270029	23.2195135
France	2020	31.51	63949	93.39308671	66.26088599
Gabon	2020	91.32	15876	99.13821499	7.88617688
Gambia	2020	23.98	6563	96.82127646	75.23271653
Georgia	2020	40.62	26459	93.82938493	56.70865792
Germany	2020	32.68	71333	97.12566838	66.3528699
Ghana	2020	35.1	24108	96.66855557	63.69036468
Greece	2020	30.27	41971	94.96121383	68.12382785
Grenada	2020	52.06	9955	90.44849683	42.44238232
Guatemala	2020	32.92	21864	99.07967898	66.77421613
Guinea	2020	25.19	13237	99.5631994	74.69948721
Guinea-Bissau	2020	70.41	13432	96.86842116	27.31377351
Guyana	2020	93.55	56335	99.51538721	5.994437016
Haiti	2020	12.6	9277	97.13830058	87.02880334
Honduras	2020	56.83	18666	98.90207171	42.53912075
Hungary	2020	22.5	66591	77.35259799	70.91241848
Iceland	2020	0.51	48580	85.11145623	99.40078572
India	2020	24.27	33834	81.69103978	70.29049934
Indonesia	2020	49.07	52486	98.04006594	49.94903407
Ireland	2020	11.35	71248	94.51534434	87.99136788
Israel	2020	6.47	38341	44.71471424	85.53049011
Italy	2020	32.35	56265	94.27959341	65.68716641
Jamaica	2020	55.11	11143	96.81948319	43.07963833
Japan	2020	68.41	64729	97.268234	29.66871384
Kazakhstan	2020	1.28	12877	42.79801896	97.00920736
Kenya	2020	6.34	18426	60.23828463	89.4751319
Kyrgyzstan	2020	6.86	32604	50.05532024	86.2951631
Laos	2020	71.9	39930	99.787008	27.94653188
Latvia	2020	54.81	46628	98.9817626	44.62616288
Lebanon	2020	14.01	31000	93.42553087	85.00409913
Lesotho	2020	1.14	4367	78.24111061	98.54296547
Liberia	2020	79.08	11481	99.5458665	20.55923286
Lithuania	2020	35.15	47342	98.46425873	64.30176751
Luxembourg	2020	34.45	57368	99.92450631	65.52397278
Madagascar	2020	21.36	24689	99.06840981	78.43914115
Malawi	2020	23.78	20044	80.26883896	70.37455592
Malaysia	2020	58.18	37064	99.01532721	41.24142026
Mauritius	2020	19.41	89425	87.86229907	77.90861359

Mexico	2020	33.79	38065	80.44365666	57.99544501
Montenegro	2020	61.49	32600	98.06659811	37.2977128
Mozambique	2020	46.73	7470	97.57779261	52.110005
Myanmar	2020	43.73	37276	98.53091157	55.61798901
Namibia	2020	8.06	5493	46.55737087	82.68802587
Nepal	2020	41.59	32033	83.36627688	50.11172196
Netherlands	2020	10.97	79199	78.45018033	86.01660321
New Caledonia	2020	45.84	85690	94.38903311	51.43503595
New Zealand	2020	37.57	90396	94.38808799	60.19624849
Nicaragua	2020	28.32	22237	92.53223093	69.39444806
Nigeria	2020	23.75	16205	88.63619583	73.20507748
North Macedonia	2020	39.71	36642	97.92309839	59.44777008
Norway	2020	33.44	46838	86.87331543	61.50716726
Panama	2020	56.81	33770	97.61433281	41.80157937
Papua New Guinea	2020	79.18	47936	98.26591906	19.42272483
Paraguay	2020	40.53	47065	98.73816957	58.9520444
Peru	2020	56.51	45572	73.56194209	23.18038596
Philippines	2020	24.11	37694	96.37684736	74.98361831
Poland	2020	30.98	46917	96.84973089	68.01230141
Portugal	2020	36.15	48813	94.66221922	61.81158619
Puerto Rico	2020	55.96	29463	94.82565776	40.98643624
Republic of Korea	2020	64.42	62119	97.98813825	34.25734875
Republic of Moldova	2020	11.75	18936	96.91097391	87.87547011
Romania	2020	30.12	33986	90.69405979	66.78944567
Russian Federation	2020	49.78	29051	78.86606312	36.88032846
Rwanda	2020	11.19	14736	91.77795648	87.80752979
Sao Tome and Principe	2020	54.06	20402	89.64378616	39.69464888
Senegal	2020	41.91	18216	71.3909079	41.2950455
Serbia	2020	32.38	65702	95.43409488	66.07082611
Sierra Leone	2020	35.12	16337	99.41766655	64.67428656
Slovakia	2020	40.06	61298	98.30663867	59.24995449
Slovenia	2020	61.47	73855	99.38069095	38.14693839
Solomon Islands	2020	90.14	18899	91.0449411	0.993949898
Somalia	2020	9.53	5025	34.62572562	72.47711108
South Africa	2020	14.06	51211	49.29886944	71.48007619
South Sudan	2020	11.33	8855	76.75821607	85.23936514
Spain	2020	37.18	45015	80.65468073	53.90224143
Sri Lanka	2020	34.16	47468	97.84633695	65.08811565
Suriname	2020	97.41	43191	99.2150315	1.819312532
Sweden	2020	68.7	59944	93.19750785	26.28558254
Switzerland	2020	32.12	69780	86.87750515	63.02840425
Syrian Arab Republic	2020	2.84	18323	37.9343464	92.51338096
Tajikistan	2020	3.05	34826	32.33922867	90.56872991
Thailand	2020	38.9	30139	96.76520084	59.79959772
Timor-Leste	2020	61.94	26585	97.8121958	36.67456344
Togo	2020	22.23	11503	98.91103462	77.52525784

Trinidad and Tobago	2020	44.48	15227	96.79906111	54.04914109
Turkey	2020	28.87	33415	87.55105331	67.02495412
Uganda	2020	11.66	30256	77.5231694	84.95933527
Ukraine	2020	16.72	42934	95.4755275	82.48765894
U.K. of Great Britain and Northern Ireland	2020	13.19	62410	92.75515604	85.77976625
Tanzania	2020	51.64	18283	87.13733765	40.73722999
United States of America	2020	33.87	81445	76.41446261	55.67592987
Uruguay	2020	11.6	49643	92.10902951	87.40622927
Vanuatu	2020	36.28	6175	86.06267891	57.84467732
Venezuela	2020	52.41	40348	96.89986014	45.91323463
Vietnam	2020	46.72	57973	97.57841023	52.12055629
Zambia	2020	60.28	24816	93.84699941	35.76779186
Zimbabwe	2020	45.09	11487	97.76607175	53.87970572