TRYING TO FEED THE WORLD WITHOUT DESTROYING IT

The Problems with Modern Agriculture and the Potential of Agroforestry as Part of the Solution

Abstract

Industrial agriculture is an important driver in climate change, biodiversity loss, and soil erosion by removing itself from ecological principles of circularity – i.e. away from a system of equal inputs and outputs – and instead focusing primarily on short term profits. Here, agroforestry is provided as a framework to help mitigate the environmental impacts of industrial agriculture: via its carbon sequestration potential; via its ability to provide habitat for important species; and via its ability to improve soil functionality and structure. In addition, agroforestry may improve the climate resilience of agricultural systems, for example by regulating temperature, nutrient and water cycles, and providing means of pest control. This perspective first provides a partial problem analysis of industrial agriculture. It then utilizes a literature review of agroforestry, to help determine the extent to which agroforestry can help lessen the impacts of food production upon the environment. Based upon this analysis, this review concludes that agroforestry practices, such as silvopasture and buffer strips, are economically viable and can be used within agricultural systems to promote biodiversity and soil quality, whilst reducing climate impact. However, policy change, education and knowledge sharing will be required for the realization of large scale agroforestry practices.

Layman Summary

The purpose of this study was to identify the environmental benefits that agroforestry may provide, and how agroforestry may be implemented into agricultural systems. First, a problem analysis of industrial agriculture was conducted, in order to clearly define the main problems in this system with regards to climate change, soil erosion and biodiversity loss. Then, a literature review of agroforestry was conducted, where agroforestry is defined as the purposeful planting of trees and shrubs within farming systems. Intensive agriculture is today damaging to the environment, and solutions are required: here, agroforestry is proposed as a partial solution. Agroforestry systems provide direct environmental benefits, such as: promoting biodiversity via the provision of increased habitat and resources; slowing climate change by carbon sequestration; improving soil quality by reducing soil erosion and via the addition of nutrients and soil carbon. Agroforestry may further promote environmental benefits indirectly: for example, agricultural systems may require less artificial fertilizers and pesticides. Agroforestry has been identified as an economically viable system, that is relatively easy to establish, promotes good yields whilst also providing many environmental benefits. Agroforestry has therefore been recommended as a tool to use in agricultural systems to help lower the environmental impacts of agriculture.

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List of Abbreviations

AF – Agroforestry
AMF – Arbuscular Mycorrhizal Fungi
CO_2 – Carbon Dioxide
CO_2eq – CO_2 equivalent
CH_4 – Methane
ES – Ecosystem Services
EU – European Union
FAO – Food and Agricultural Organization of the United Nations
GHG – Greenhouse Gas
GLASOD – Global Assessment of Human Induced Soil Degradation
GMO – Genetically Modified Organism
Gt – Gigatonne
$GtCO_2e$ – Gigatonnes of CO_2 Equivalent
GWP – Global Warming Potential
LUC – Land Use Change
$Mgha^{-1}yr^{-1}$ – Total Biomass (metric ton) per Hectare per Year
N – Nitrogen
NH_3 – Ammonia
NO_3^- – Nitrate
N_2 – Dinitrogen/Unreactive Nitrogen
N_2O – Nitrous Oxide
P – Phosphorus
PGPF – Plant Growth Promoting Fungi
PGPR – Plant Growth Promoting Rhizobacteria
PS – Percolation Stability
SOC – Soil Organic Carbon
SOM – Soil Organic Matter
$t\ ha^{-1}\ yr^{-1}$ – Tons per hectare per year
TN – Total Nitrogen

Section 1: Introduction

Since the 1960's, there have been great advancements in agriculture and food production, in what is known as the "Green Revolution", or the Third Agricultural Revolution. The introduction of new methods of intensive agricultural farming via petrochemical companies and improved agricultural practices has led to higher crop yields and an increase in animal husbandry, reducing famine worldwide, driving down food prices (Milani et al., 2022) and reducing poverty (John & Babu, 2021), in what will hereby be referred to as industrial agriculture. Today's agricultural output is ≈3-fold higher when compared to the beginning of the Green Revolution (Hurni et al., 2008), which has increased food production faster than population growth. Industrial agriculture is a modern and intensive method of farming and relies on the large-scale mechanization of farms in place of smaller farms. It removes itself from ecological principles, such as protecting biodiversity and relying on the interconnectedness of nature and instead focuses itself on high yields and profits with relatively little consideration for the ecological costs. In other words, industrial agriculture moves away from a circular system of equal inputs and outputs, to one with a large external input and skewed outputs. Such industrial practices include the application of chemical fertilizers and pesticides, monoculture, improved breeding techniques and the use of genetically modified organisms (GMOs) (Milani et al., 2022). Agricultural intensification is an important driver in the loss of biodiversity and ecosystem services worldwide (Pumariño et al., 2015), and contributes significantly to climate change and soil erosion (Figure 1). This now puts our future food systems at risk: what once bore us fruitful yields and improved food stability may now provide us with the opposite as it degrades the environment that it relies on.

Industrial agriculture has resulted in production systems that have contributed to reduced soil quality, reduced nutrient and water retention, and reduced biodiversity, thus hindering ecosystem services (ES). This results in an agricultural system that is less resilient to a changing climate, for example, by making cropping systems more vulnerable to the effects of climate change. Crops are dependent on the climate and industrial agriculture destabilizes global and local climate, promoting extreme weather patterns and thereby hindering the crops' ability to succeed whilst promoting wildfire formation. Climate change will also have a negative effect upon soil fertility and mineral acquisition for crops and may intensify food insecurity (St.Clair & Lynch, 2010). As glaciers recede because of climate change, this puts many agricultural areas at risk as they rely on glacial water for irrigation (Biemans et al., 2019). Industrial agriculture also contributes to climate change directly via GHG emissions, thereby potentially creating a positive feedback loop towards further negative effects. With biodiversity loss: ecosystems absorb less water, increasing the risks of flooding and droughts; there is a reduction in soil fertility, resulting in lower crop yields. Soil erosion reduces the level of fertile topsoil and reduces the ability of soil to store water, as well as increasing the likelihood of landslides, desertification, flooding, drought and dust storms.

While there are many agricultural practices that contribute to these issues, such as monoculture, tilling, and the application of synthetic fertilizers and pesticides, this paper will focus on the issues of deforestation for agriculture and will provide agroforestry (AF) as an alternative agroecological technique. This paper will compare three scenarios: forest, deforestation followed by intensive agriculture, and (semi) deforestation followed by AF. Various AF practices can be implemented into farming systems, agroecological or not, in order to reduce the environmental impacts of deforestation and industrial agriculture. While deforestation is often implemented to make space for agriculture, this paper will also discuss the extent to which conversion to AF can help restore ecosystem integrity and will discuss the best AF practices for improving specific aspects of ecosystem functioning.

AF is the intentional integration of trees and shrubs (and other plants) into farming systems, and has been associated with numerous benefits including: a farm's resilience and adaptability; improved microclimate; GHG mitigation; increased SOM; erosion control; better water use efficiency; reduced nutrient surplus; reduced chemical pollution; improved pest, disease and weed regulation; enhanced total farm productivity; greater biodiversity; more employment opportunity and other positive socio-cultural effects (Aguilera et al., 2020). Agroforestry systems can be used simply to improve the environmental status of the farm, for example by promoting biodiversity or by providing supporting and regulating services, or alternatively AF systems can be used for its provisioning services, for example by providing a food forest or multipurpose trees.

This essay is organized into two main sections: i) a problem analysis of the causes and effects of climate change, biodiversity loss and soil erosion in industrial agriculture, more specifically those related to deforestation and land conversion for industrial agriculture; and ii) agroforestry as an approach to help mitigate the issues detailed in the problem analysis. The problem analysis defined three major hub issues related to the negative impacts of industrial agriculture, namely climate change, biodiversity loss and soil erosion (Figure 1). Both the problem analysis and agroforestry-based mitigation strategies are thus organized around these three pillars.

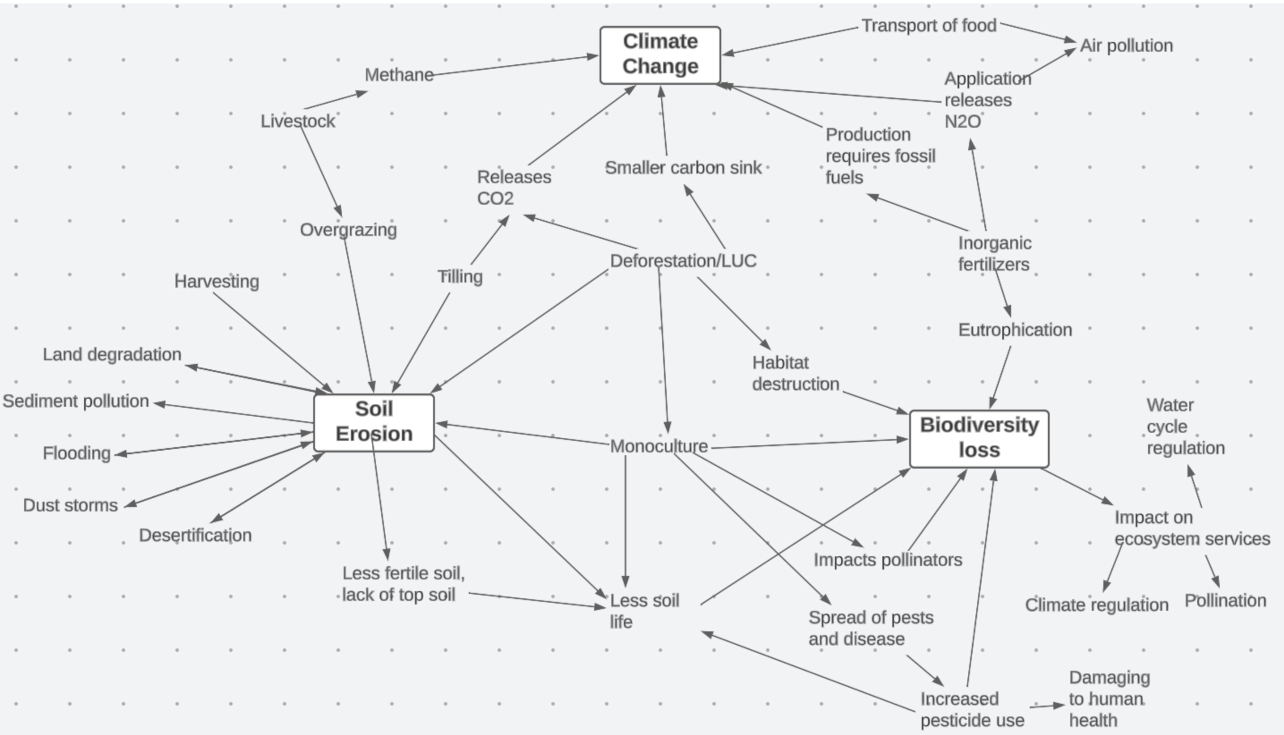

Figure 1: Deforestation and LUC are used to make space for industrial agriculture; the impacts of industrial agriculture upon the environment contribute to climate change, biodiversity loss and soil erosion, and the issues are complex and interconnected. The issues summarized here then can be either directly or indirectly associated with deforestation and LUC (figure made via lucid.app)

Section 2: Problem Analysis

2.1 Industrial Agriculture and Climate Change

Industrial agriculture consumes vast amounts of fossil fuels, water and topsoil in an unsustainable manner, and has contributed to global warming and environmental degradation (Horrigan et al., 2002). The global food system contributes 21-37% of annual greenhouse gas (GHG) emissions (Lynch et al., 2021), driving anthropogenic climate change, with agriculture contributing 9.3 billion tons of CO_2 equivalent (CO_2eq) in 2018, and crop and livestock production making up 57% of this total and land use and land use change (LUC) contributing 43% (FAO, 2020). The main contributors to accelerated climate change in agriculture are: deforestation and land use change (LUC); livestock; transport of food and feed; certain agricultural practices such as tilling; production and use of synthetic fertilizers. Here, the focus will be the effects of deforestation and LUC upon climate change, in relation to industrial agriculture.

2.1.1 Deforestation and Land Use Change

Agricultural land currently occupies 38% of the terrestrial surface of the earth (S. Huang et al., 2023), which has been made possible via LUC, primarily deforestation (Figure 2). It is estimated that land use and LUC emissions were 4 Gt CO_2eq in 2018 (FAO, 2020), with deforestation making up 74% of this total (Figure 2). Another study predicted that deforestation is responsible for 1.5Gt carbon losses per year (Hu et al., 2021). In the Amazonia, 80% of the deforestation of the rainforest has been cleared to make way for cattle production, which consists primarily of cattle ranching and feed production (largely soy) (Skidmore et al., 2021). Around 20% of the beef and soya imported into the EU from Brazil has been linked to illegal deforestation of the Amazon Rainforest (Rajão et al., 2020), and much of the soy produced is also used as animal feed in the EU.

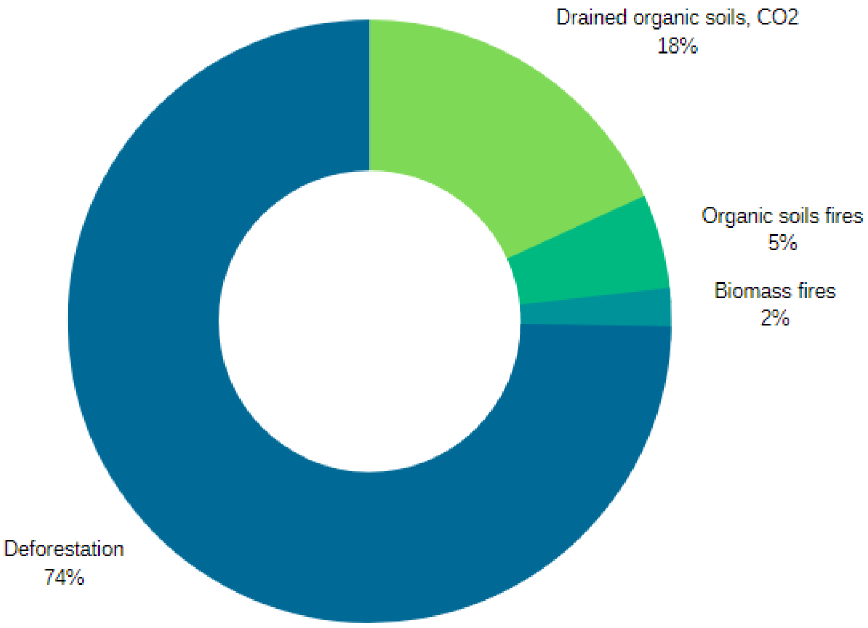

Figure 2: Contribution of activities to total agricultural land use and LUC emissions in 2018 (3.9 Gt CO2eq) (Data source: FAO 2020)

Deforestation and LUC impact atmospheric CO_2 in two main ways: i) reduced carbon storage; and ii) increased GHG emissions. Trees are the most efficient carbon capture technology that exists, and thus fewer trees lead to less CO_2 absorption from the air via photosynthesis. It is estimated that between 2007-2016, the terrestrial carbon sink removed 33.7% of total anthropogenic emissions from industry and land use change (LUC) (Keenan & Williams, 2018). Terrestrial ecosystems including forests, grasslands and wetlands currently store ≈3,000GtC (≈550GtC stored in biomass (Bar-On et al., 2018) and ≈2400GtC stored in the soil (Jobbagy & Jackson, 2000)), compared with the ≈800GtC of atmospheric carbon (Dignac et al., 2017). Thus, the terrestrial carbon sink is essential in mitigating the effects of Anthropogenic-driven climate change. With the rise of deforestation, it is now predicted that parts of the Amazonia are now releasing more GHGs than they are storing (Gatti et al., 2021). There is also a reduced capacity of soil to store carbon from deforestation: global soil organic carbon (SOC) storage has been reduced by 31-52% as a result of forest conversion to agricultural land (X. Wang et al., 2017). Furthermore, as climate change accelerates, ecosystems will show a reduced capacity to sequester carbon in these warmer conditions (Mosquera-Losada et al., 2023).

As trees are cut down or burned, large stocks of stored carbon are released into the atmosphere as CO_2. The FAO has estimated that deforestation has accounted for 420 million hectares of lost forest between 1990-2000 ("Global Forest Resources Assessment 2020," 2020), and LUC (primarily deforestation) has been responsible for 18% of global GHG emissions (Chapagain & James, 2013). As deforestation and global warming increases, the capacity of ecosystems to sequester carbon is decreased (Landry et al., 2021), and the likelihood of forest fires is increased, further driving climate change as biomass is converted into CO_2. The CO_2 released from fires as a result of LUC for agriculture are not included in the total figures for GHGs released from agriculture (S. Huang et al., 2023).

2.2 Industrial Agriculture and Biodiversity

Industrial agriculture is today damaging biodiversity, via land use change (LUC) and the subsequent application of agrochemicals, habitat destruction or pollution. It is essential that we protect biodiversity as it enables a stable climate and provides many ecosystem services (ES) such as the pollination of plants and the provision of clean water. Today, biodiversity loss has been identified as a major threat in the disruption of the Holocene (Rockström et al., 2009), and it is predicted that we are headed for a sixth mass extinction event, the first to be caused by anthropogenic activity (Cafaro, 2015).

2.2.1 Deforestation and Land Use Change

LUC has been identified has been identified by the Intergovernmental Platform for Biodiversity and Ecosystem Services as the key driver for biodiversity loss (Brondizio et al., 2019). In the Brazilian Amazon, 780,000 km^2 of forest has been lost in the last 30 years, which has been responsible for half of Brazil's carbon emissions and the loss of over 2,000 native species (Skidmore et al., 2021). The conversion of natural habitat to agricultural land alters the species composition (Aratrakorn et al., 2006) and reduces the number of species, for example by the elimination of 48-60% of bird species in Malaysia following conversion of forest to oil palm plantation (Aratrakorn et al., 2006), and has reduced the diversity and availability of pollinator habitats (Centeno-Alvarado et al., 2023). The presence of birds and pollinators is essential in maintaining important ecological functions such as pest control and pollination (Yahya et al., 2022), and therefore food security (Klein et al., 2006). Globally, pollinators are declining, with many species becoming extinct due to lack of habitat and corridors (Ramos-Jiliberto et al., 2020), which is exacerbated by other factors, such as pesticide use (Kenna et al., 2023) and monocropping (Aizen et al., 2019).

Higher levels of biodiversity have been associated with higher levels of ecosystem functioning (Delgado-Baquerizo et al., 2016; Tilman et al., 2014; H. Wang et al., 2022), including interspecific complementarity, greater use of limiting resources, decreased disease and improved nutrient cycle feedbacks that increase nutrient stores and supply rates in the long term (Tilman et al., 2014). This is essential in providing ES such as climate regulation, water filtration and air purification, and pollination and soil stability. For example, forests can maintain the hydrological cycle by absorbing and releasing water through their leaves and roots, as well as stabilizing the soil, providing clean water, preventing flooding and/or droughts and providing a stable climate. High levels of biodiversity can also mitigate the effects of pollution and eutrophication (H. Wang et al., 2022). The effects of a loss of biodiversity are: the exacerbation of local air conditions and air quality (Huang et al., 2023), increased likelihood of nitrogen addition, elevated CO_2, drought, flooding, fires and other drivers of environmental change (Tilman et al., 2014). Deforestation also decreases microbial biomass and diversity in soil, which provide essential ES such as soil functionality and the provision of fertile soil, and organic waste decomposition (J. Guo et al., 2022; Panklang et al., 2022).

2.2.2 Chemical Fertilizers

Deforestation has also been indirectly associated with eutrophication (Kong et al., 2022), as it allows polluted water and fertilizers to flow more easily into aquatic systems, and also provides fewer denitrifying bacteria (Kuusemets et al., 2001; Lowrance, 1992). Up to 70% of applied synthetic fertilizers are not used by crops (Henryson et al., 2020), thus excess nitrogen (N) from fertilizers are released to the environment in different forms: as its unreactive state (N_2), emitted to the air as a GHG in the form of nitrous oxide (N_2O), or released into the soil or water systems as nitrate (NO_3^-) or ammonia (NH_3) (Henryson et al., 2020), thereby disrupting the nitrogen cycle. 55% of the anthropogenic nitrogen fixation can be attributed to fertilizer production, 27% to biological nitrogen fixation in agriculture, and 18% from combustion processes (Fowler et al., 2015). Nitrogen (primarily in the form NO_3^-), leaching from agricultural fields is the leading cause of anthropogenic N input into marine environments (Steffen et al., 2015), and it is estimated that ≈24% of anthropogenic N released in coastal watersheds reaches coastal ecosystems (Malone & Newton, 2020). Phosphates from fertilizers are also released into soil and water systems, and together with nitrates are the leading causes of eutrophication (Malone & Newton, 2020). It is predicted that 31% of the global freshwater has undesirable levels of periphyton growth (McDowell et al., 2020); 76% of this growth has been mapped to agricultural land as a result of P-enrichment (McDowell et al., 2020). Periphyton is associated with freshwater eutrophication and is the collection of material growing in freshwater that can form a complex community of algae, bacteria, fungi and invertebrates. Eutrophication causes blooms of toxic algae and decreases aquatic (both coastal and freshwater) biodiversity and can cost billions of dollars annually to remediate (McDowell et al., 2020). While nitrogen deposition primarily affects aquatic ecosystems, it also causes changes in forests, impacting tree productivity, tree nutrition, sensitivity of trees to biotic and abiotic stresses, understory vegetation composition and ectomycorrhizal fungal communities (Schmitz et al., 2019). Nitrogen saturation in these forested areas then sets off a series of reactions that result in a loss of plant species diversity, soil acidification and growth reduction (Schmitz et al., 2019).

2.3 Industrial Agriculture and Soil Erosion

Soil is the most important factor in food production and 95-97% of agricultural output is based on cultivation and grazing lands (Hurni et al., 1996; Pimentel et al., 1987). However, today's intensive and industrial agricultural practices are degrading the soil at an unprecedented rate, putting future food security at risk. It is estimated that the impact of soil erosion results in the losses of between 36 Gt (Borrelli et al., 2017) and 75 Gt (FAO, 2016) of soil annually, leading to global losses of $400 billion in agricultural output per year (FAO, 2016). Global agricultural activities contribute 3.2Gt of soil erosion per year, with a soil erosion rate of 0.22Mg ha^{-1} yr^{-1} (Hu et al., 2021). This is equivalent to the loss of approximately 12 million hectares land per year (FAO, n.d.). Although this represents only 1% of cultivated land, if we continue with current agricultural practices with no countermeasures, it is likely that soil will be totally depleted in the next 200 years (Hurni et al., 2008).

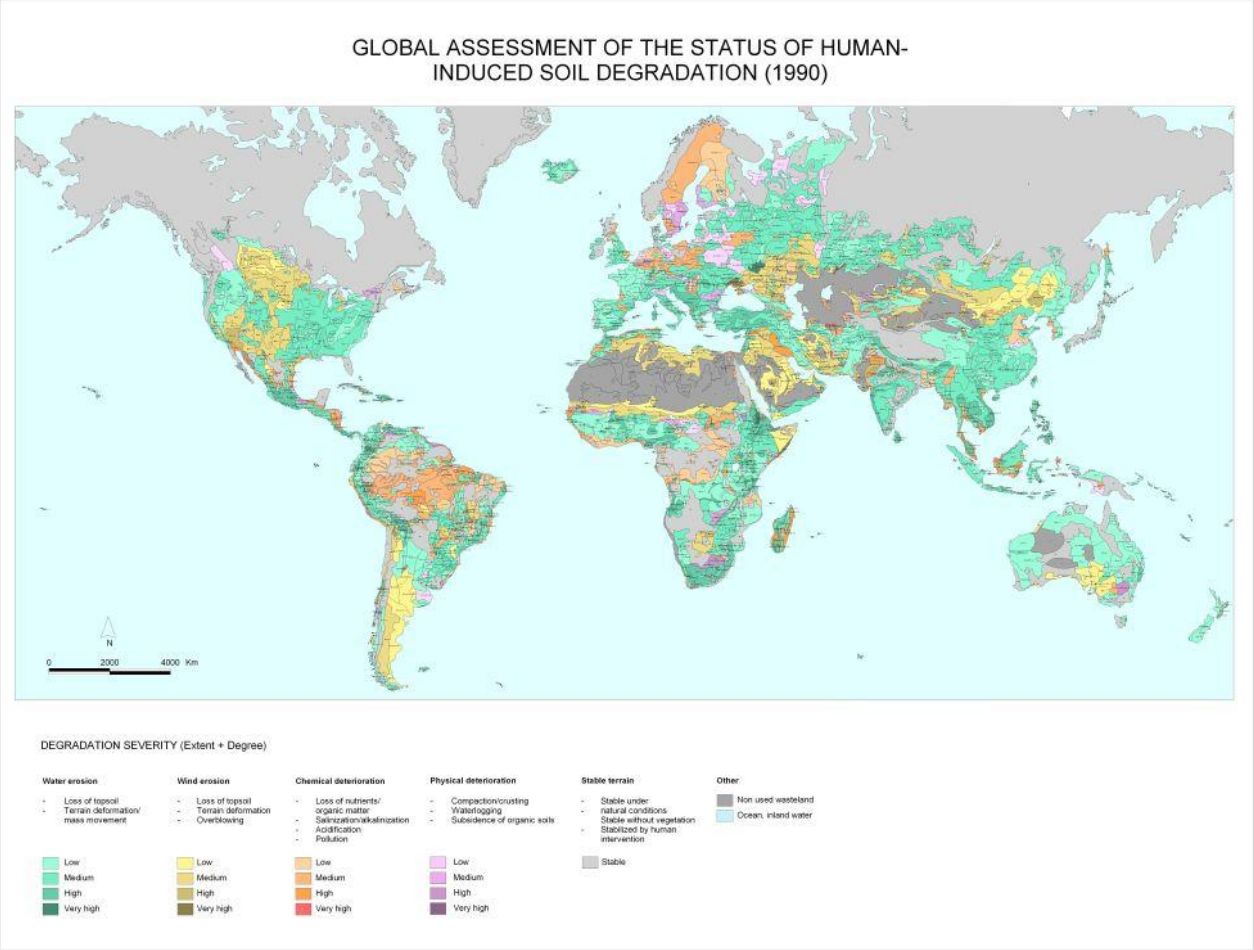

Figure 3: Global Assessment of Human-Induced Soil Degradation (GLASOD), shows the causes and extent of soil erosion between 1987-1990. Figure taken from (Favis-Mortlock, 2017)*, which was adapted from* (Oldeman et al., 1990)

The *Global Assessment of Human Induced Soil Degradation* (GLASOD) (Figure 3) was a major milestone in estimating the problem of soil erosion at a global level, and was conducted between 1987-1990 (Oldeman et al., 1990). Although this research is outdated, it remains relevant as land and soil degradation continues. This research concluded that 15.1% of the terrestrial surface, or one-third of agricultural land, is affected by soil degradation (Oldeman et al., 1990). The major Anthropogenic activities causing soil degradation are: deforestation (30%), overgrazing (35%) and agricultural overuse (28%) (Oldeman et al., 1990). Other sources state that up to 90% of agricultural land suffers from erosion, from slight to moderate erosion (10%), to moderate to severe erosion (80%) (Pimentel et al., 1995); whereas Kaiser (2004) states that "soil loss is not likely to be a major constraint to food security". Such opposing research outcomes may be because authors use different sources, measurements and modelling to draw their conclusions, and probably the truth lies somewhere in the middle, as is demonstrated in the GLASOD study.

Long term erosion rates of soil are greater in regions of crop land than from natural lands and erode at a rate of 6 Mgha^{-1}yr^{-1} and 2 Mgha^{-1}yr^{-1}, respectively, in the United States (Nearing et al., 2017). Where land has been more recently brought into production, for example in northeastern China, rates of soil erosion were 15 Mgha^{-1}yr^{-1} (Nearing et al., 2017). The natural factors that relate to soil degradation are outside of the scope of this review, however the anthropogenic factors will be covered below.

2.3.1 The Effects of Soil Erosion

In agricultural production, soil erosion is most associated with the removal of topsoil, which is an essential factor in the production of fertile crops, and results in a reduced soil truncation (Poesen et al., 2001). Topsoil removal "implies nutrient loss, reduction of rooting depth, water and nutrient storage capability ... [and thus] reduced plant production" (Hurni et al., 2008); in other words, soil erosion causes a reduction in soil fertility in cultivated areas. Soil erosion promotes the formation of landslides (F. Huang et al., 2020), dust storms (which further accelerate soil erosion) (Duniway et al., 2019; X. Wang et al., 2006), desertification (D'Odorico et al., 2013) and flooding (Robinson & Blackman, 1990), and contributes to eutrophication: phosphorus (Ekholm & Lehtoranta, 2012) and nitrogen (Nearing et al., 2017), as well as pesticides are transported via eroded soils and rainfall to water bodies. Erosion also causes pollution, in the form of sediment, which is, by mass, the greatest pollutant we have, causing "tremendous societal cost in terms of stream degradation, disturbance to wildlife habitat, floodings and direct costs for dredging, levees and reservoir storage losses" (Nearing et al., 2017).

Whilst soil erosion is damaging to the environment, it also results in the losses of $400 billion dollars annually to compensate (Pimentel et al., 1995), primarily due to nutrient losses, but also water loss and loss of soil depth.

2.3.2 Deforestation, LUC and Soil Erosion

Deforestation contributes to soil erosion by reducing plant cover and increasing the soils susceptibility to water and wind erosion. Trees and other foliage protect the soil: i) by adding SOC to the soil (for example by degradation of dead organic matter, or via rhizodeposition (Thirkell et al., 2020); ii) roots provide stability to the soil and provide surface erosion protection (Giadrossich et al., 2019); iii) forests maintain the hydrological cycle, preventing flooding and droughts and thus protecting the soil from wind, water and gully erosion; and iv) by preventing splash erosion via the interception of rainwater (L. Wang et al., 2023). Flooding as a result of deforestation have occurred since at least 602BCE, where records first began, which has resulted in the deaths of millions of people (Yan et al., 2022) as well as being a significant contributor to soil erosion.

There have been many studies documenting the effects of deforestation upon soil erosion (Chatterjee et al., 2018). For example, in Bera Lake, Malaysia, there has been severe LUC, where 340km^2 out of

600km^2 of forest has been converted into oil palm and rubber plantations, or cleared for monoculture (Gharibreza et al., 2013). This has resulted in soil erosion of 915 t ha^{-1} yr^{-1}, 117 t ha^{-1} yr^{-1}, 75 t ha^{-1} yr^{-1} in cleared, developing and developed land respectively, which corresponds to soil loss in these regions of 74%, 63% and 55% (Gharibreza et al., 2013). In naturally forested areas in this region, soil erosion is 7 t ha-1 yr^{-1}, and soil loss is 5% (Gharibreza et al., 2013). Carbon stocks have been reduced in the soil by 75%, 59% and 28% in cleared, developing and developed land when compared to natural forest, respectively (Gharibreza et al., 2013). Carbon stocks, particularly SOC stocks, are an important indicator of soil quality and health and thus soil erosion.

Another study reports SOC losses of 29% following forest conversion to vineyard in Western Iran (Khodadadi et al., 2023), mostly due to erosion but also emissions. Soil percolation stability has been reduced by ≈50% in this region (Khodadadi et al., 2023). Percolation stability (PS) is a method that assesses aggregate stability; a higher PS and thus a higher aggregate stability is an important factor in resistance to soil erosion. Mbagwu & Auerswald (1999) concluded that land use has more influence on the PS than the type of soil; forest soils, bush fallows, mulched, minimally tilled plots and pasture lands have high PS; conventionally tilled plots, bare fallows and continuously cultivated plots have a low PS. Other studies have reported soil carbon losses of up to 80% (de Blécourt et al., 2019), 30%-60% (Villarino et al., 2017), and ≈80% (Eleftheriadis et al., 2018) following forest conversion to agricultural land.

In the Amazonia of French Guiana, deforestation reduced SOC in soil by 18.6% after five years of conversion to annual crop (Fujisaki et al., 2017), which is associated with soil erosion. This is less of a decrease when compared to other regions of deforestation around the world (de Blécourt et al., 2019; Eleftheriadis et al., 2018; Gharibreza et al., 2013; Khodadadi et al., 2023; Villarino et al., 2017), and can be attributed to the fact that large woody debris as a result of deforestation contributes to the SOC. Soil erosion rates reported for different studies may also vary depending on the length of the study, the exact nature of the land use change, and the length of time since land use transitions.

2.4 Problem Analysis Conclusion

This problem analysis has delved into some of the environmental issues associated with deforestation and subsequent application of industrial agriculture, and has described the agricultural causes and effects of climate change, biodiversity loss and soil erosion at a global scale, which are summarized in Figure 1. If we continue with our current methods of agriculture, topsoil will continue to be eroded, GHGs will continue to be emitted into the atmosphere at an unsustainable rate, and we will continue to accelerate towards a sixth mass extinction event, threating global food security and human health. Our current agricultural systems are particularly vulnerable to the effects of climate change as their low biodiversity and eroded soils provide little resilience against the extreme weather patterns that are on the rise as climate change continues.

It should be notes that this paper has not provided a full problem analysis of industrial agriculture. Additional aspects that may be considered include: i) the environmental effects of certain management practices, for example tilling and monoculture, which reduce biodiversity and soil quality and contribute to GHG emissions; and ii) many societal problems. For instance, industrial agriculture promotes the development of human diseases via zoonosis (Hayek, 2022; Morse et al., 2012), and overuse of antibiotics in livestock farming is promoting the evolution of antibiotic resistant microorganisms. Industrial agriculture has dominated landscapes, forcing many small-scale farmers out of business and driving urbanization (Capra & Luisi, 2012), and has resulted in the ownership of 85% of the global food industry by the top ten agrochemical companies (Simms, 1999). These issues are large and complex and fall outside of the scope of this essay; this essay instead aims to bring a larger focus to the important aspects of agroforestry and deforestation.

The following section will now delve into agroforestry as a framework for addressing some of the problems outlined above, and how one can improve upon agricultural practices to fit more in line with ecological principles. Here, we will show GHG emissions can be slowed via the carbon sequestration ability of terrestrial ecosystems, that biodiversity can be improved to promote more climate resilient food systems, and how AF can be used to restore soil fertility and health.

Section 3: Agroforestry as a Mitigation against Climate Change, Biodiversity Loss and Soil Erosion

Agroforestry (AF) is the intentional incorporation of trees and shrubs into farming systems, either in cropland or pasture. In a literature review of agroecology, Aguilera et al. (2020), found that AF has largely positive effects upon: a farms resistance and adaptability; microclimates; GHG mitigation; SOM; erosion control; water use; reduced nutrient surplus; reduced chemical pollution; pest, disease and weed regulation; total farm productivity; biodiversity; employment and other positive socio-cultural effects (Figure 4), when compared to deforestation followed by intensive agriculture. Types of agroforestry systems can be seen in Table 1. It is worth noting, that the scenario where forest is allowed to exist, provides these benefits better than AF. However, since agriculture is necessary, and deforestation has already impacted vast regions of the world, AF can be thought of as an applicable compromise between natural forest and providing sufficient food, to provide, to a lesser extent, the benefits of forests at an environmental level. The following section will outline the potential benefits of AF systems when compared to industrial agriculture, unless otherwise stated.

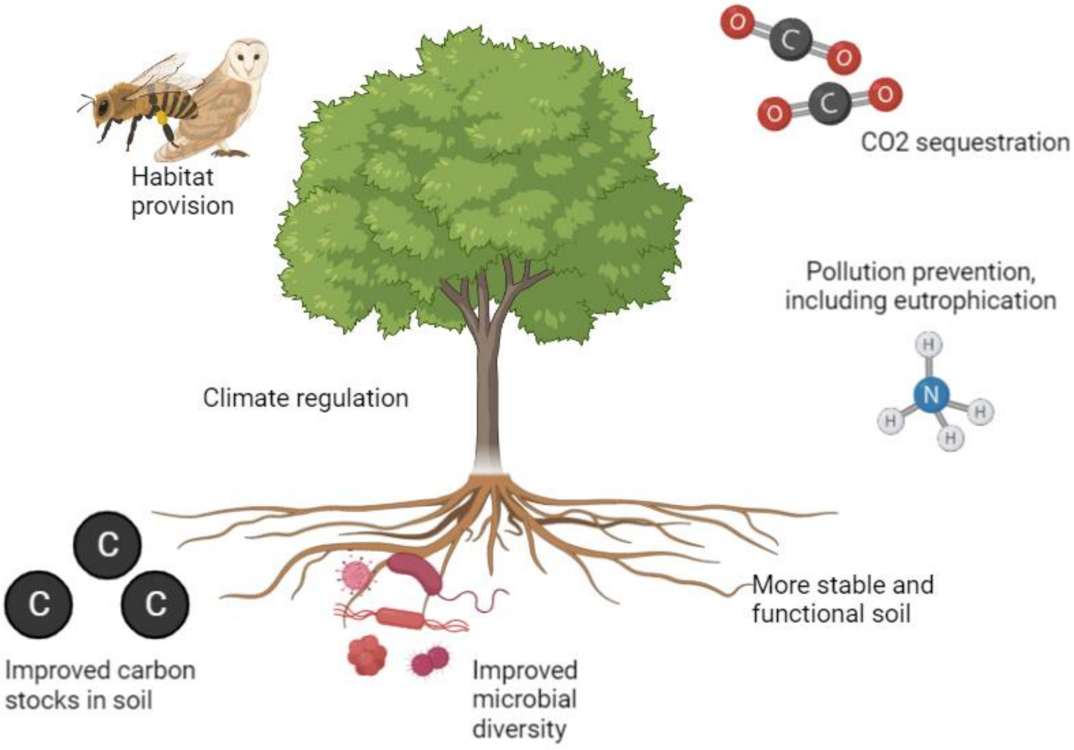

Figure 4: Environmental benefits of AF systems, when compared to industrial agriculture.

Table 1: A summary of some of the different agroforestry practices

Agroforestry Practice	Description	Reference(s)
Silvopasture	The integration of trees, forage and grazing livestock on the same piece of land. Livestock provide nutrients via manure, and trees provide shade for the livestock.	(Baker et al., 2023; Smith et al., 2022)
Silvoarable systems	The cultivation of arable crops and trees is combined, for example by planting trees alongside rows of crops.	(Kletty et al., 2023; Reisner et al., 2007)
Forest farming	The cultivation of shade-tolerant crops under a forest canopy. It is especially useful in the growing of medicinal herbs, ornamental plant, and certain foods, such as mushrooms.	(Baker & Saha, 2018; Bruhn & Mihail, 2009)
Riparian buffer strips	The incorporation of trees and vegetation adjacent to streams and rivers, bordering agricultural fields or pasture. They can be used to mitigate the effects of N leaching and eutrophication, and also prevent flooding and drought via water retention.	(Cole et al., 2020; Dlamini et al., 2022)
Improved fallow	The deliberate planting of fast-growing plants, such as legumes, for replenishment of soil fertility, for instance via accumulation of N in soil. It differs from forest farming, as fallow implies that the land is resting from cultivation.	(Kaonga & Coleman, 2008; Sanchez, 1999)
Multipurpose trees	Trees that are cultivated for more than one purpose/use. For example, fruit and other trees can be planted together to provide fruit, fuelwood, fodder and timber, among other services.	(Herrero-Jáuregui et al., 2013; Lelamo, 2021; Nair et al., 2021)
Food forests	The diverse planting of edible plants that aim to mimic natural forests and its ecosystem(s). Their aims are to be climate resilient, biologically sustainable and efficient.	(Albrecht & Wiek, 2021; Lehmann et al., 2019; Riolo, 2019)
Peri-urban food forest	A food forest that is placed in the transitional zone between urban and rural areas.	(Lehmann et al., 2019)

3.1 Agroforestry and Climate Change Mitigation

AF is a useful tool in GHG mitigation via its potential in carbon sequestration: both aboveground by converting CO_2 into biomass, and belowground via litter or its root system and relationships with microorganisms (Thirkell et al., 2020).

57% of agricultural land has less than 10% tree cover, and yet trees contribute 75% of the carbon stored in agriculture (Zomer et al., 2016). From 2000 to 2010, tree cover increased by 3.7%, which resulted in an increase in carbon storage in agriculture by 4.7% (Zomer et al., 2016), demonstrating the potential of agroforestry in carbon sequestration and GHG mitigation. Trees remove carbon from the atmosphere via the action of photosynthesis, which is then used to add biomass, both aboveground and belowground, in their roots. Silvopasture, the integration of livestock with trees, is the agroforestry practise that has the highest potential for CO_2 mitigation in the Himalayas (Sharma et al., 2023). This is supported by Mosquera-Losada et al., (2016), who also identified silvoarable and silvopasture to be the most effective AF practices for carbon sequestration in the EU.

Forest has higher potential in GHG mitigation than agroforestry (Chatterjee et al., 2018), however this is not a feasible option, since agricultural land is necessary. Agroforestry may then be thought of as a compromise between the most effective GHG mitigation tool (forest) and providing sufficient food.

Agroforestry systems can also provide resilience against climate change in agriculture, via maintenance of carbon, nutrient and hydrological cycles, and providing cooling effects via the provision of shade (Ellison et al., 2017) or transpiration (J. Huang et al., 2022) This can help buffer crops during times of climate extremes, by increasing the adaptive capacity of a farm (Quandt et al., 2023) and moderating microclimates (Mosquera-Losada et al., 2023). It has been demonstrated that in silvoarable systems, such as the implementation of hedgerows, that air temperatures that are lower and steadier than that of surrounding areas, even in the field at underground and soil surface levels (Sánchez et al., 2010), and that adding tree canopy to pastureland can improve pasture yield of up to 19% (Moreno, 2008). Agroforestry can be used as both a drought and a flood mitigation strategy, by improving the soil hydraulic properties such as infiltration capacity (Ilstedt et al., 2007), and preferential flow, which positively influences groundwater recharge (Bargués Tobella et al., 2014).

Thus, agroforestry is a promising technique that can be implemented in agricultural systems, that can mitigate the effects of climate change via CO_2 sequestration, as well as providing a more resilient agricultural system against climate change, particularly in regions of water scarcity and hot temperatures, and regions that will be most affected by climate change.

3.2 Agroforestry and Biodiversity

Agroforestry enhances both functional and overall biodiversity within landscapes (Santos et al., 2022), and impacts biodiversity both directly by providing habitat and corridors for species, and indirectly by promoting SOC formation and preventing eutrophication.

Many studies have demonstrated a higher abundance and richness of species in agroforestry systems (Barrios et al., 2018; Bohan et al., 2022; Centeno-Alvarado et al., 2023; Jarrett et al., 2021; Klein et al., 2003; Santos et al., 2022; Weiner et al., 2014). AF promotes the stability and quality of ES (Bohan et al., 2013), improves the quality and connectivity of the agricultural matrix, and enhances plant-animal interactions (Klein et al., 2003). Especially worth noting, is the positive impact on earthworm (Barrios et al., 2018) and pollinator populations (Centeno-Alvarado et al., 2023). Earthworms promote litter decomposition and improve the nutrient availability of the soil, improve soil drainage and maintain a stable soil structure, and can help promote higher yields (Singh, 2018). For instance, in coffee agriculture, a loss of native earthworms as a result of the absence of trees, resulted in 76% lower soil microporosity (Barrios, 2007). Earthworms also show promise in vermiremediation, and they can act as biofilters and biotransformers of toxic pollutants such as microplastics and heavy metals in soil (Gudeta et al., 2023).

Agroforestry promotes and maintains pollination services by diversifying agricultural landscapes (Centeno-Alvarado et al., 2023). As well as providing habitat, agroforestry provides additional sources of food for pollinators, for example by supporting the growth of flowers (Weiner et al., 2014). By increasing the plant diversity on farms, this can increase the taxonomic range and functional diversity of pollinators and plants (Weiner et al., 2014). Levels of pollination ES are higher in agroforestry systems that in conventional agricultural systems (Centeno-Alvarado et al., 2023), which can improve crop quality and yields (Maccagnani et al., 2020), and enhance fruit nutritional composition (Centeno-

Alvarado et al., 2023). In agricultural systems that have already implemented agroforestry, pollination services can be maximized by increasing shade-tree cover, decreasing the distance between agroforestry fragments, and increasing local floral resources (Centeno-Alvarado et al., 2023).

Agroforestry practices may be beneficial in pest, disease and weed management (Pumariño et al., 2015), for example by providing habitat for natural enemies of pests (Chaplin-Kramer et al., 2011). For example, AF and natural forest systems provide habitat for bats that feed on both forest and crop pests (Ancillotto et al., 2022). Landscape complexity has a strong positive response to natural enemies (Chaplin-Kramer et al., 2011), which control the populations of animal pests and weeds, for example by eating seeds and preying on the pests (Boinot et al., 2020). Additionally, shade from trees may provide insurance against pest outbreaks in the field (Tscharntke et al., 2011). However, this is context dependent, and one must also consider that agroforestry may also provide habitat to the natural pests themselves, particularly in conventional agriculture, where the use of pesticides reduces natural predator populations (Boinot et al., 2020). Agroforestry has also been associated with a reduction in plant disease (Beule et al., 2019; Cerda et al., 2020; Durand-Bessart et al., 2020); this may be due to a number of factors, for example the provision of shade (Durand-Bessart et al., 2020), or the promotion of disease suppressive soils via the promotion of beneficial microbes (Moreira et al., 2019). Thus, agroforestry can be a useful tool in weed, disease and pest suppression.

While agroforestry promotes biodiversity aboveground, it also plays a role in the maintenance of microbial diversity and abundance, which has potential in the restoration and improvement of soil functionality. Agroforestry increases SOC in the soil by the presence of its deep roots (Chatterjee et al., 2018), and the presence of diverse plants positively affects soil biodiversity (Wooliver et al., 2022). Furthermore, the action of rhizodeposition promotes SOC formation and can cause a 10-100-fold increase in the microbial density in the soil (Bakker et al., 2013). This promotes the proliferation of beneficial microorganisms, such as plant-growth promoting rhizobacteria (PGPR) and plant-growth promoting fungi (PGPF) (Pieterse et al., 2014). Beneficial bacteria can provide: enhanced mineral uptake by the plant, nitrogen fixation, growth promotion and protection from pathogens (Pieterse et al., 2014). The implementation of silvopasture further promotes SOC formation and supports soil diversity via the addition of manure to the soil (Baker et al., 2023). Furthermore, AF promotes the formation of arbuscular mycorrhizal fungi (AMF) (Qiao et al., 2022). AMF may also provide enhanced adaptability to plants under stressful conditions, such as heat (Mathur et al., 2021), salinity (Dastogeer et al., 2020), drought (Mathur et al., 2019), heavy metals (Dhalaria et al., 2020) and other biotic and abiotic factors. It may achieve this via the up-regulation of tolerance mechanisms and by preventing the down-regulation of key metabolic pathways (Begum et al., 2019), as well as by improving plant health status via the acquisition of nutrients.

The incorporation of agroforestry in agriculture also shows great potential in mitigating pollution, via the prevention of nitrogen and phosphate leaching (Aguilera et al., 2020; Dlamini et al., 2022; Kuusemets et al., 2001). For example, silvopasture reduces nutrient loss from the soil surface when compared to open pasture (Rigueiro-Rodríguez et al., 2009). In heavily polluted areas, riparian buffer strips can reduce nitrogen and phosphorus fluxes by up to 90% (Zhao et al., 2009) and 84% (Kuusemets et al., 2001), respectively. Riparian buffer strips reduce N fluxes by a denitrification process, whereby denitrifying bacteria convert nitrate into N_2O and N_2; this is most effective in the top 10cm of soil (Lowrance, 1992). Riparian buffer strips stabilize the soil, which may also slow down the addition of nitrates into aquatic system by acting as a ‘safety net’ (Allen et al., 2004), and provide enough time for denitrifying microbes to reduce nitrates. Trees may also utilize the nitrates to support their own growth (Allen et al., 2004). Thus, riparian buffer strips play an essential role in preventing eutrophication and preventing aquatic biodiversity losses. However, the denitrifying process releases N_2O; there have been increased N_2O fluxes in riparian system of areas of high N pollution, compared to conventional agriculture (Dlamini et al., 2022). Based on the potential of agroforestry in carbon sequestration, enhancing biodiversity and soil quality, and reducing nitrogen leaching, an increase in N_2O emissions may be a worthwhile tradeoff.

A limitation of agroforestry is that crop yields have been shown in some cases to decrease as a result of resource competition, and yields are lowest when in close proximity to the forest (Pardon et al., 2018; Reynolds et al., 2007; Swieter et al., 2019; Wanvestraut et al., 2004). However, as silvoarable systems establish themselves, there is evidence to suggest that yields are comparable to monoculture (Swieter et al., 2019), and agroforestry does not negatively influence quality of the crop (Beule et al., 2019).

3.3 Agroforestry and Soil Restoration

Agroforestry has long been recognized in its ability to mitigate land degradation and assist in its recovery (Marques et al., 2022). Agroforestry promotes carbon sequestration in soil to improve soil quality, which has already been discussed (see section 3.1). Furthermore, the increased presence of worms and saprotrophs in woody areas also improves soil quality, for example by improving aeration and decomposing organic matter into nutrients (Barrios et al., 2018). The capacity of deep roots in absorbing water reduces both water and wind erosion and stabilizes the soil, thereby improving soil quality. Agroforestry also promotes soil enzyme functioning (Ghosh et al., 2021).

Via symbiotic relationships with microorganisms, plants may also deposit carbon in the soil, in a process known as rhizodeposition, whereby microorganisms in the rhizosphere may receive 20% (Thirkell et al., 2020) to 40% (Bais et al., 2006) of the plants photosynthetically derived carbon. This promotes a higher C:N ratio and improves SOC stocks in the soil, which prevents soil erosion, improves carbon sequestration thus mitigating GHGs (see section 3.1) and promotes microbial diversity (see section 3.2). The presence of deep roots further promotes SOC deposition, which can be up to 27% higher in agroforestry systems than in other agricultural systems (Chatterjee et al., 2018). This aligns with the goals of the 4 per 1000 initiative, that aims to enhance carbon uptake and SOC stocks in soil as a GHG mitigation strategy and to improve soil health (4 per 1000 initiative, 2022).

3.4 Implementation of Agroforestry

Agroforestry has been identified as an economically viable practice in agricultural systems, which is also recognized by the EU (Albrecht & Wiek, 2021). For example, field experiments in three European countries demonstrated that AF can increase overall yields by up to 40%, relative to monoculture and arable systems (Graves et al., 2007). Other studies have reported increased yields as a result of agroforestry (Carsan et al., 2014; Cerda et al., 2020). However, agroforestry may provide lower yields than fertilized fields (Ajayi et al., 2010) (see section 3.3); thus there are mixed research outcomes on whether AF improves or decreases yields. It is recommended that one takes into account the potential outcome, and here the community sharing of knowledge may be a beneficial tool to determine best practices. Overall, agroforestry has been identified as an economically viable option, that results in improved yield and yield stability, a reduction in agrochemicals, and higher profitability, in a meta-analysis of farming systems (Rosa-Schleich et al., 2019). AF may also provide increased profits indirectly. Since AF contributes to soil fertility and a reduction in pest species, synthetic fertilizer and pesticide usage can be reduced, which benefits both the environment and the socio-economic status of the farm.

One may consider developing an AF system as a provisioning service, for example the implementation of food forests. Food forests are the diverse planting of edible plants that aim to mimic natural forests and ecosystems, and in order to maximize profit should incorporate 3-7 types of provisioning plants, as can be seen in Figure 5 (Albrecht & Wiek, 2021). By incorporating different types of plants, each plant fills its own ecological niche, to provide enhanced environmental effects upon biodiversity and soil quality. Higher biodiversity has also been linked to improved carbon sequestration and enhanced productivity (Chen et al., 2018), and food forests can provide farms with additional profits. In order to ensure food forests are economically viable, one must first design a business plan, and incorporate as many of the different plant types as possible, that will support the local environment (Albrecht & Wiek, 2021).

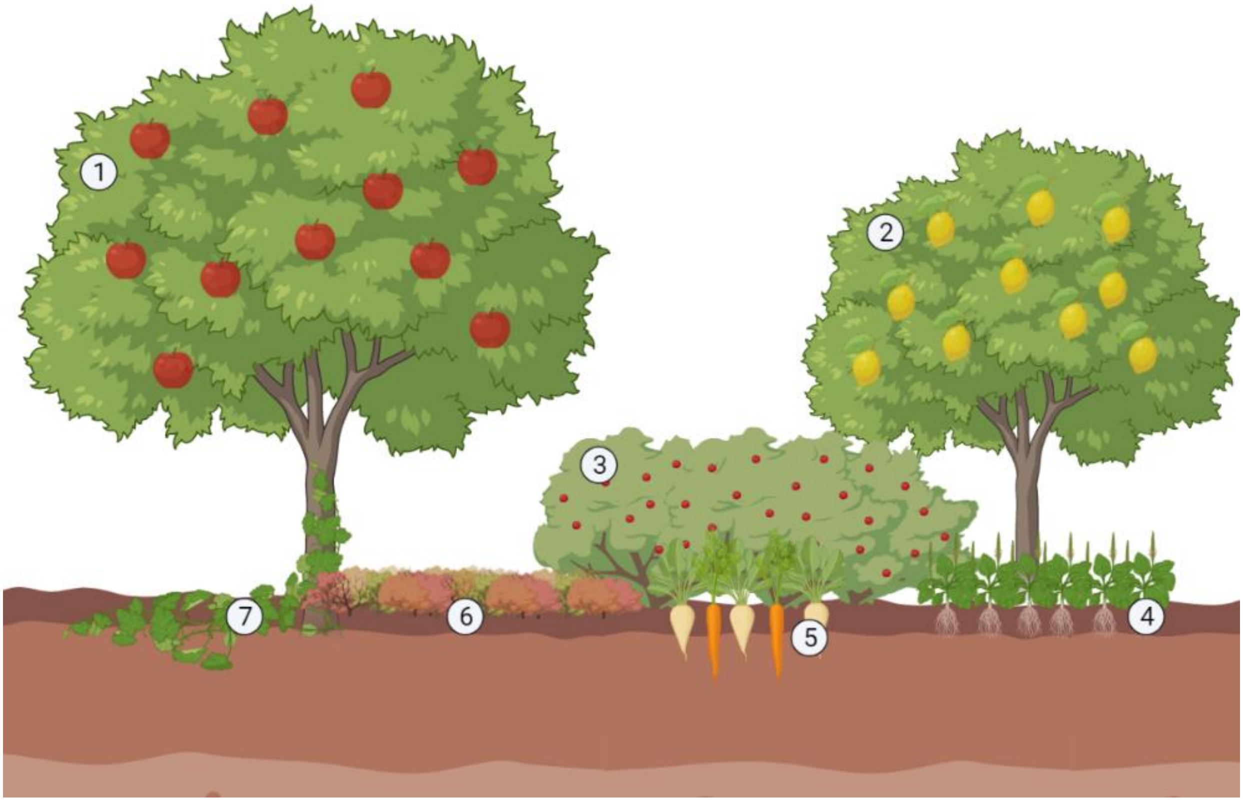

Figure 5: The different components required for a functional food forest: 1) Canopy, for example large fruit and nut trees; 2) low tree layers, for example dwarf fruit trees; 3) Shrub layer, for example currants and berries; 4) Herbaceous layer, for example beets and herbs; 5) Root vegetables, for example carrots and potatoes, to support the rhizosphere; 6) Soil surface layer as ground cover, for example strawberries; 7) Vertical layer, for example climbers and vines. In an ideal system, all components would be intermixed with one another, in a 'stacking' manner, and not separated as is depicted in the figure. Adapted from (Burnett, 2008)*. Image designed in BioRender.*

Section 4: Discussion and Conclusions

Agroforestry can be incorporated into agricultural systems to minimize their negative environmental effects, either directly or indirectly. AF systems provide direct environmental benefits by improving carbon sequestration, increasing biodiversity and improving soil quality, when compared to industrial agriculture that does not incorporate AF. AF also provides indirect benefits, for example by reducing the quantity of pesticides and synthetic fertilizers required. AF provides benefits for: a farm's resilience and adaptability; microclimates; GHG mitigation; SOM; erosion control; water use; reduced nutrient surplus; reduced chemical pollution; pest, disease and weed regulation; total farm productivity; biodiversity; and employment (Aguilera et al., 2020). The implementation of agroforestry may also include economic benefits: directly via increased yields, and indirectly by reduced inputs, such as labor, fertilizers and pesticides.

AF should not be used as a replacement for natural forests, nor as a justification for further deforestation: whilst AF systems can be implemented to mitigate the effects of industrial agriculture upon climate change, biodiversity loss, and soil erosion, one must consider that AF does not achieve this as well as natural forests. For example, AF systems may not provide as much benefit to biodiversity as natural forests, since age of forest is directly correlated to an increase in functional diversity (Bongers et al., 2021). In addition, natural and older forests have also been associated with increased levels of SOC and total nitrogen (TN) (Y. Guo et al., 2021), indicating higher soil quality, as well as showing reduced levels of soil erosion (Sun et al., 2023), when compared to younger forests. Older trees may also sequester carbon more effectively than younger trees (Köhl et al., 2017). Thus, one should not use the implementation of an AF system in industrial agriculture as a justification for further deforestation, since natural forests promote higher levels of biodiversity, ecosystem functioning and soil quality, and have a higher potential in carbon sequestration. However, since high levels of deforestation have already occurred to make space for agriculture, it is recommended that AF systems can be implemented in these areas to help restore and promote biodiversity, soil quality and GHG mitigation.

While in some cases, agroforestry may reduce yields, overall AF improves yields. Since 44% of crops are wasted annually (Alexander et al., 2017), a small reduction in yields may be a viable option. In this case then, one should instead focus on the socio-economic factors that surround food justice and inequality and here, society must ensure a fairer and more equitable spreading of food resources, which is outside of the scope of this review. Furthermore, one must also consider the economic costs that AF may mitigate. For example, AF may reduce eutrophication and soil erosion, which normally costs billions of dollars annually to remediate (FAO, 2016; McDowell et al., 2020; Pimentel et al., 1995).

While there may be some long term economic benefits associated with AF, economic and social barriers have been identified by Abdul-Salam et al. (2022) as: i) high upfront costs of conversion; ii) uncertainty of returns from forestry relative to agriculture; iii) long production cycle and perceived irreversibility of land management; and, iv) in some cases, reduced yields when compared to monoculture. Furthermore, a lack of awareness of AF, both at a policy level and a farm level, may also hinder the adoption of AF in agriculture (Mosquera-Losada et al., 2023). AF is also not well designed for large-scale implementation and automation, which may be achieved with technological advances, for example those acknowledged by the Scaling Up Initiative (FAO, 2018). To further promote AF in agriculture, the Scaling Up Initiative identified three areas of work and actions (FAO, 2018):

1. Knowledge and innovation:
    a. Strengthening the role of family farmers to safeguard, utilize and access natural resources.
    b. Foster experience and knowledge sharing, innovations and collaborations.
2. Policy processes:
    a. Promoting markets for products based on agroecological principles, for health, sustainability and nutrition.
    b. Review policy, legal and financial frameworks to promote AF transitions.
3. Building connections:
    a. Take agroforestry to scale through integrated and participatory processes.

While agroforestry shows promise for the future of farming, it cannot be the whole solution. One must also consider other agroecological practices, such as: the reduction of tilling; a recircularization of farms to combine cropland and animal husbandry; organic farming, etc. While these techniques may provide significant steps towards a sustainable future in agriculture, this is also not the whole picture. One must also return to local methods of production, and a reduction in animal husbandry is also recommended. Here, policy change is crucial, and sufficient support must be provided to farmers, both at a financial and an educational level, for example by educating farmers of the benefits of AF, and how it may be implemented. Furthermore, there have been a lack of studies comparing different AF practices, and the correct AF practice must be determined at a local scale. Farmers must decide based on their own local knowledge the most appropriate practice to adopt for their farm. This local knowledge may be combined, for example, with a modelling approach and/or capital budgeting analyses (Abdul-Salam et al., 2022). Modelling approaches can be used to determine the optimal placement of trees, to find the best compromise between yield and environmental benefits, as well as comparing financial and economic benefits (Mosquera-Losada et al., 2023).

To conclude, agroforestry is shown to be a promising practice that can be incorporated into farming systems, that shows both environmental and economic benefits, and that can be used to help mitigate the effects of climate change, biodiversity loss, and soil erosion, whilst also providing sufficient food and providing farms with improved climate resilience. To execute this, political and governmental support is required, both at regional and global scales, and education and policy change are required. The action and support of NGOs, such as the 4 per 1000 initiative, may also speed up implementation. When implemented correctly, with proper planning, guidance and financial support, agroforestry is a viable practice that can be integrated into farms to reduce their environmental impact, whilst also providing social benefits, such as employment and improved living conditions. Agroforestry can be used in combination with other agroecological practices, to further promote environmental benefits, and help guide us into a new era of economically viable food production.

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