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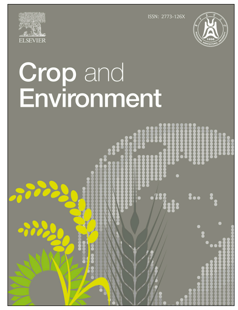

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PII: S2773-126X(22)00022-3

DOI: https://doi.org/10.1016/j.crope.2022.05.001

Reference: CROPE 13

To appear in: *Crop and Environment*

Received Date: 3 March 2022

Revised Date: 21 April 2022

Accepted Date: 2 May 2022

Review

The deployment of intercropping and agroforestry as adaptation to climate change

Running title: Agricultural practices for climate adaptation

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Keywords
Adaptation, Agroforestry, Alternative Cropping, Climate Change, Intercropping

Abstract

Food security is threatened by the combined pressures of increasing populations and climate change. Agricultural land is vulnerable to overexploitation and environmental change. Within this review, we identify the role of multiple cropping systems as an adaptation method towards climate change. Intercropping, the relay or simultaneous cultivation of two or more crops, and agroforestry, the incorporation of trees on at least 10% of agricultural land, provides an alternative cropping practice which can provide many advantages over industrial sole cropping. Examples from these systems are given to indicate how multiple cropping can provide increased yield, stability, ecosystem services and societal benefits when adopted. We also discuss instances where multiple cropping systems may be maladaptive or instances where desired benefits may not be achieved. Finally, we highlight the important considerations or constraints limiting the adoption of alternate systems and indicate how modelling approaches can be used to reduce the uncertainty of altering agricultural systems. This review challenges the traditional concept of how to increase industrial crop yields whilst maintaining sustainability. Future research should be aimed at overcoming the constraints limiting adoption of alternative cropping systems to revolutionise global crop production.

1. Introduction

Improving crop productivity is a key aim of agricultural production. With a changing environment this must be achieved through sustainable approaches, minimising the effect of climate change on crop growth, whilst restricting further negative impacts of agriculture on the environment (Rosenzweig and Hillel, 2008). Approximately 50% of habitable land has been converted to agriculture including croplands, pastures and rangelands (Ritchie and Roser, 2019). In the tropics, 80% of this expansion has occurred into forested areas (Foley et al., 2005; 2011), with approximately 92 million hectares of forest lost between 1990 and 2010 in Latin America and the Caribean alone (Willaarts et al., 2014). This has increased the vulnerability of the systems to changes in abiotic and biotic factors.

As climate variability increases, the strain on systems is likely to exceed existing adaptive capacity (Lin et al., 2015). The term “adaptive capacity” is defined here as the ability for the ecosystem to absorb climatic change with minimal impact on function (resistance) or evolve to climatic disturbances through altering structure or composition (resilience). Ecologically-based management alternatives that combine multiple components in one system may provide a robust path to increase the productivity, sustainability and resilience of agricultural production (Altieri, 2002). These diversified agricultural systems provide examples by which structural complexity can help to adapt to a change in climate to stabilise and improve crop yields (Lin, 2011). Two examples of these systems include intercropping and agroforestry.

Intercropping refers to the cultivation of two or more crop species, or genotypes, simultaneously for a period of time (Andrews and Kassam, 1976; Vandermeer, 1989). This can either be for the full crop life cycle or for only a part, termed relay intercropping. Intercropping can be designed to achieve spatial and/or temporal complementarity. There are several basic spatial, temporal or functional arrangements utilised in intercropping and most practical systems are variations of these arrangements (Table 1). Similarly, the proportion of each component relative to sole cropping geometry can be altered. In additive intercrops, the ‘base crop’ is sown at 100% of the population of a sole crop and the second component, termed the ‘intercrop’ is sown around the base crop, usually at less than the optimal population size if sown as a sole crop (Maitra et al., 2021). In comparison, in a replacement intercrop, both component crops are sown at less than their optimised population size. Often a set proportion of one crop is sacrificed and the second component is sown within this space. Dependent on competitive ability and resource requirements, the optimum plant density of an intercrop may be greater than that of sole crops, as seen in pea-barley systems (Hauggaard-Nielsen et al., 2006). This is due to the altered phenology of components permitting a reduced competitive pressure plus a suppression of weed infestation within the system.

Agroforestry refers to the cultivation of trees on at least 10% of the agricultural land for timber, firewood or other products, with crops or livestock systems (Montagnini and Nair, 2004). Agroforestry includes the incorporation of trees with livestock and/ or crops in different spatial arrangements, however the rest of this review will focus on examples from tree and crop systems only (Table 2). Agroforestry systems can be generated via two routes; either through the conversion of existing farmland or pasture to an agroforestry system by incorporating trees, or through thinning of existing woodland or rainforest to enable agricultural production. This latter example enables the area of agricultural land to be expanded, whilst simultaneously attempting to preserve the ecosystem services provided by tree cover. In areas of northeast USA, up to 65% of agricultural land is classified as woodland and recent research has focussed on the conversion of this land into agricultural uses, primarily silvopasture, to meet the increasing consumer demand of the region (Coble et al., 2020; Orefice et al., 2019; USDA-NASS, 2014).

The practices of intercropping and agroforestry are widespread in many areas of world, with visibility of these multiple cropping systems increasing at the national and international levels. These systems are especially prevalent in regions such as the tropics, where they can be the dominant form of agriculture (Beets, 1982; Francis, 1986; Kass, 1978; Vandermeer, 1989). Globally, most intercropping and agroforestry occurs on a small-scale in resource-poor environments (Ghosh-Jerath et al., 2021; Lithourgidis et al., 2011), although adoption is increasing in developed countries such as the USA and areas of Europe (Blackshaw et al., 2007; Coble et al., 2020; Hauggaard-Nielsen et al., 2009; Jensen et al., 2005). Whilst prevalent in small-scale production, such systems are currently underutilised in terms of industrial production, where nutrient cycles are predominantly externally regulated (Bybee-Finley and Ryan, 2018).

1.2. Climatic variables influencing crop productivity

Climate change will substantially contribute to food insecurity affecting both crop production and food prices. The Intergovernmental Panel for Climate Change (IPCC) indicated that substantial climate change has already occurred since the 1950’s, and global mean surface temperatures are projected to rise by <3.1°C by the end of the century (IPCC, 2014, 2019, 2022). This temperature change, and the associated changes to precipitation, will influence crop yields, with comparatively narrow thresholds required for optimum yields (Gregory and Ingram, 2000; Hatfield et al. 2011; Luo, 2011; Passioura, 2007). The increase in frequency of extreme events will be further deleterious to production across the globe (Beillouin et al., 2020; Chavez et al., 2015; Elahi et al., 2021). The effects of climate change on agricultural production will differ depending on region. In higher latitudes, climatic trends indicate potential positive increases in productivity associated with increased carbon dioxide (CO_2) levels, warmer temperatures and lengthened growing seasons (Alcamo et al., 2007;

Meng et al., 2014; Peltonen-Sainio et al., 2016). In contrast, regions closer to the equator are expected to experience negative effects of climate change with reduced yield, higher yield variability and a reduction in suitable cultivation areas (Berg et al., 2013; Olesen and Bindi, 2002; Shi and Tao, 2014). However, the specific effect on crop performance will depend on geographical location as well as local environmental conditions or constraints, such as nutrient and water availability, crop type, and phenology.

Climate change is also projected to increase the frequency and severity of extreme climatic events (Moriondo et al., 2011). Such events are often associated with crop damage and yield loss due to extreme changes in temperature, precipitation, including both droughts and floods, and/or high wind speeds (Lesk et al., 2016). Extreme events or a higher variability in climate conditions will have a greater effect on yield production than changes in mean climate alone (Moriondo et al., 2011; Porter and Semenov, 2005;). In many regions, variability in rainfall or severity of extreme weather events are greatly exacerbated by other factors such as land use change and local biogeographical features (Lesk et al., 2016; Verchot et al., 2005;). For example, practices such as deforestation, overgrazing and continuous cropping can contribute to land degradation and the vulnerability of specific ecosystems. Greater effects are felt in developing countries, whereby a quarter of damage and losses attributed to climate-related disasters are associated with the agricultural sector in these regions (FAO, 2015). For instance, Goettsch et al. (2021), found that 14% of crop wild relatives of Mesoamerican taxa are threatened by climate change. In contrast, for developed parts of the world such as the US corn belt, agriculture relies heavily on mechanisation. Therefore one of the main effects of climate change felt relate to the timings of farm operations, with rainfall variability and uncertainty limiting the number of viable planting or harvesting days (Tomasek et al., 2015, 2017).

With the anticipated increase in climate variability, the range of available adaptation options decreases while the cost and complexity of implementing these options increases (Guan et al., 2017; Kassie et al., 2015). Agricultural vulnerability points to the need to develop resilient systems that can buffer crops from climatic variability and extreme climatic events, especially during crucial developmental periods. The following sections will discuss how intercropping and agroforestry can be used to adapt to these changes.

2 Adopting multiple cropping systems as an adaptation method

Multiple cropping systems may contribute to many of the sustainable development goals (SDGs, UN 2015a, b) including: SDG2, to eradicate hunger; SDG13, climate action and SDG15, to improve life on land particularly through restoring degraded land and soil including areas subject to desertification, droughts and floods. Complementarity is a general term used to describe the positive effects occurring in diverse ecosystems (Cardinale et al., 2007; Loreau and Hector, 2001; Tilman et al. 2012). Primarily, two mechanisms can contribute to complementarity, and both can be achieved using multiple cropping. The first is resource partitioning, in which two or more components can more efficiently utilise resources than a single component on its own (Loreau and Hector, 2001; Tilman and Snell-Rood, 2014). The second is facilitation, whereby one component reduces a limitation of a resource that improves the environmental conditions for another component (Bybee-Finley and Ryan 2018; Loreau and Hector, 2001; Saharan et al., 2018; Singh et al., 2020). An overview of the key changes in microclimate and social variables during conversion from a single to multiple cropping system is given in Figure 1.

2.1 Increased yield and stabilisation

Per equivalent component crop area, the production of a greater yield on a given piece of land is the most commonly perceived advantage of multiple cropping systems (Dhima et al. 2007; Lithourgidis et al., 2011; Malézieux et al. 2009; Mucheru-Muna et al. 2010). This can be determined as a land equivalence ratio (LER) where values above 1.0 indicate a higher yield production through multiple cropping over monoculture (Mead and Willey, 1980). Productive systems enable growth resources such as light, water and nutrients to be more efficiently exploited as a results of difference in growth or competitive ability of the component crops (Burgess et al., 2017; Midmore, 1993; Tsubo et al., 2001). Architectural traits can be selected which enable exploitation of a greater volume such as combining deep roots with shallow roots or a tall component crop with erect leaf structure with a short component with horizontal leaf structure (e.g. Burgess et al., 2017; Li et al., 2021; Makumba et al., 2009). This form of spatial differentiation can also be achieved through plasticity of the component crops selected, whereby cultivation in an intercrop modifies the arrangement of plant material to avoid severe competition or alters functional traits–for example increasing the reliance of N fixation for a legume (Hauggaard-Nielsen et al., 2006; Schiffers et al., 2011; Zhang et al., 2020a). Alternatively, the timing of peak resource requirements can be staggered to reduce competition through either selecting components with different maturation rates or by staggering sowing, as achieved in relay intercropping (Dowling et al., 2021; Engbersen et al., 2021; Maitra et al., 2021; Tilman and Snell-Rood, 2014). This is particularly beneficial in regions of restricted water availability (see below) or limited time for crop management as the second crop is generally seeded once the first has passed a major growth stage (Baldé et al., 2011).

Increased yields allow either an increase in production on the same or a reduced land area. In intercropping scenarios, cereal-legume systems are commonly adopted to create a synergistic system, with N-fixing provided by the legume component (Dhima et al., 2007; Ofori and Stern, 1987). In agroforestry systems, the crop component generally performs better if it has higher shade requirements or early in agroforestry establishment as competition for light is one of the predominant yield limiting factors in such systems (Ong et al., 2015). The tree canopy can therefore provide an optimised microclimate as well as other ecosystem services (section 2.3), and provide other additional sources of income from timber, fruit or fodder products.

Whilst intercropping is traditionally considered as species diversity, a system containing functional diversity could also be considered. Planting multiple varieties of the same species increases the genetic diversity present. Using the examples of wheat, oats and corn the associated benefits include: extending the growing season, mitigating transfer of disease and overall increase in productivity (Borg et al., 2017; Tooker and Frank, 2012; Reiss and Drinkwater, 2018).

Multiple cropping systems have been shown to decrease the risk of crop failure by improving yield stability (Raseduzzaman and Jensen, 2017). This can occur temporally, through improved yield stability over years at the same location, or through improvements in the production consistency throughout the year. Yield stability can also be achieved spatially, by reducing the variability in production within and between different fields. In addition, agroforestry systems have also been shown to reduce human impacts on natural forests, which in turn are essential to counter climate change (Mbow et al., 2014).

In some instances, multiple cropping systems results in undesirable outputs, mainly as a result of component crop selection or geographical region (see also Section 3). Reduction in crop yield, either per plant or on a land area basis, can arise due to inter- and intra-specific competition within intercropping systems. Architectural traits may limit the uptake of resources to one or both components. For example, in annual intercropping, a taller component crop may cast shade on a shorter component restricting photosynthesis or encouraging lodging, or similarities in root structure may lead to competition for nutrients or water in the same soil volume (Celette et al., 2009; Chui and Shibles, 1984; Fukai and Trenbath, 1993; Mushagalusa et al., 2008; Raza et al., 2020). In agroforestry systems, light is likely to be the limiting resource for understorey crops in many regions, with reductions in yield associated with increase in shade (Artru et al., 2017; Charbonnier et al. 2013). To some extent this may be compensated by adaptive of tolerance mechanisms of the component species, through spatial arrangements of the system or through management practices such as pruning. For example, in a coffee agroforestry system in Costa Rica, net primary production was relatively stable across different levels of shade despite up to a 60% reduction in irradiance. This was attributed to an increase in light use efficiency of 50% associated with changes in carbon allocation between organs (Charbonnier et al., 2017). Alternatively boundary planting or alley cropping (Table 2) enable light competition to be minimised, with optimised row orientations dependent upon latitude (Dupraz et al., 2018). However, light limitation will restrict yields in many temperate regions or for high-light requiring species such as rice, maize or other C4 species (Artru et al., 2017; Lin et al. 2015; Peng et al., 2009).

2.2 Diversified farm economics

As well as increased yield and stabilisation, multiple cropping systems can optimise farm economics. This may partly arise through diversifying the crop or tree products but also through optimised resource capture, reducing the need for additional applications of fertilisers or pesticides, and through more efficient use of equipment or labour. In some instances, producers are able to spread the production costs and fixed costs of equipment and land, or seasonal labour costs over multiple components (; Antle and Ray, 2020; de Roest et al., 2018; Khanal et al., 2021; Palmer et al., 1993). Although this must be balanced against potential damage associated with soil compaction in mechanised agriculture or timings of farm operations with relation to viable planting or harvesting days (Tomasek et al., 2015, 2017).

Alternatively, intercropping may provide a means to cultivate certain crops over a wider geographical range than previously. For example, a higher profitability of organic lentil-wheat intercrops compared to sole crops was found in Europe despite the additional costs associated with grain sorting (Loïc et al., 2018). This is due to the reduction in lodging in lentils when intercropped, which increased the mechanical harvest efficiency by 50% relative to sole cropped lentils, despite a reduction in actual yield production. Combined with the additional wheat harvest, this resulted in an overall increase in the mean marketable gross margin of the intercrops compared to sole cropped lentils. Similarly, in agroforestry systems, farmers may maximise farm income and productivity by cultivating around trees, utilising woody perennials for livestock browsing and producing construction materials and firewood from trees. Other agroforestry products include food, fuel, gums and resins (Graß et al., 2020). The contribution of these different components towards food security and farm stability will depend upon tree and crop density, rainfall, labour availability and market prices of each of the components (Rinaudo, 2014).

2.3 Ecosystem services

Not only does mixed cropping provide diversity of crops in time and space, but it may also provide a set of ecosystem services that are not possible under monocropping. Many of these factors influence the microclimate and energy balance of the system (Figure 1).

2.3.1 Climate regulation–wind and temperature

Introducing spatially contrasting components to a cropping system can help to regulate climatic variables. For example, incorporating a tall component can reduce the impacts of drought and heat stress on a shorter component crop through partial shading and a reduction in wind speed. This can be achieved through altered phenology and growth in a relay intercrop, or through species selection in both intercrop and agroforestry systems. However, this comes at the expense of light and could lead to adverse results such as lodging, effecting possible yield gains (Mushagalusa et al., 2008; Raza et al., 2020).

The effect of altered wind movement is particularly evident in agroforestry systems. Trees and understorey plants are able to deflect some of the moving air upwards via stream flow or downwards via tunnelling as well as modifying the lateral flow of wind (Ong et al., 2015). Geometry, crown size and planting density will determine the relative ratio of each of these flows. Thus the structural and biomechanical components of the system will determine the degree of wind protection that trees are able to provide (Onyewotu et al., 2004; Stigter et al., 2002). Through these modifications, agroforestry can reduce air pollution and reduce extremes in temperature (Ellison et al., 2017; Montagnini et al., 2013).

2.3.2 Water relations

Multiple cropping systems can alter the water available to component crops. Altered canopy structure can modify rainfall interception causing spatial redistribution through canopy drip and stem flow. A potentially successful way to increase water use efficiency of systems is to reduce the amount of water lost through soil evaporation and transpiration. The rate of transpiration is generally related to leaf area of the canopies however, changes can be induced through structural modification of above-ground matter. Crops grown in highly shaded areas receive less direct solar radiation, reduced air temperatures and higher humidity than those in exposed areas (Coble et al., 2020; Gutierrez et al., 1994). This is partly due to a reduction in the vapour pressure deficit and soil evaporation rates (Grossiord et al., 2020; Lott et al., 2009; Ong et al., 2015) and is particularly beneficial during the reproductive phase where grain production and quality are two factors greatly influenced by quantity of precipitation (Ndjiondjop et al., 2010; 2018).

Differential growth of two components can maximise water use efficiency and reduce the risk associated with crop loss through drought (Nelson et al., 2021). Where maturity is reached at different time points (typically <40 days apart in intercrops), or when sowing is staggered as in relay intercropping, components are likely to reach peak water requirements at different times. This is especially valuable in water-limited environments, providing temporal complementarity as a result of improved resource capture (Gebru, 2015; Wang et al., 2018). Conversely, reduction in performance may occur where component species have similar life cycles, and thus require specific resources at the same time. In such instances, the dominant (most competitive) component is likely to outperform the other (Fukai and Trenbath, 1993; Mushagalusa et al., 2008).

Spatial complementarity in water use (and nutrient uptake) can be achieved by combining components that exploit different soil volumes through selection of root traits including root length and density (Ren et al., 2017), or through selection components that enable the transfer of water or nutrients to the other component species (Bayala and Prieto 2020; Bogie et al., 2018; Saharan et al., 2018; Singh et al., 2020). For example, the water availability and nutrient uptake of finger millet can be improved by the presence of pigeon pea through redistribution of resources in processes called bioirrigation (i.e. water transfer trough hydraulic lift) and biofertilisation (i.e. mobilisation of nutrients available in soils), respectively (Saharan et al., 2018; Singh et al., 2020).

As in annual intercropping, combining architectural traits can aid resource capture in agroforestry systems. This is particularly the case for root systems, whereby resource use and more complete soil exploitation can be achieved through root stratification of tree and crop roots (Bayala and Prieto, 2020; Borden et al., 2017; Cannell et al., 1996). It is generally desirable to have tree components containing deep-rooted, vertically stratified root systems to exploit soil volume; access leached nutrients below crops and contribute to soil carbon storage through input of organic matter although the optimised traits will depend upon the component crops present (Bambrick et al., 2010; Bergeron et al., 2011; Upson and Burgess, 2013). In some instances, root systems can exploit water from up to 20 m depth. Trees can also provide bioirrigation or biofertilisation effects dependent on species selection (Bayala and Prieto, 2020; Bogie et al. 2018; Rosenstock et al., 2014s;).

Within agroforestry systems, water security can be enhanced through improved infiltration to soils and groundwater (Bargués Tobella et al., 2014). Management practices such as pruning can also be used to reduce competition for water (Nicodemo et al., 2016). At the landscape scale, this may alter regional water cycles, through recycling rainwater, reducing stormflow and recharging aquifers. However, dependent on species and planting density, agroforestry can deplete groundwater thus altering the risks and impacts of droughts and floods (Van Noordwijk et al., 2014). In eastern Zambia and Zimbabwe, conversion of monocropped maize to rotations containing leguminous trees led to a 42–600% increase in steady state infiltration rates, a 40–133% increase in time for water run-off and an 88–900% improvement in drainage (Sileshi et al., 2014). Together with fertilisation effects of the incorporated trees, this led to an increase in maize yield of between 89–318%.

There may be significant trade-offs associated with high tree cover within various specific land use types, farming systems, or with changing climatic conditions, and the extent of microclimate modifications will depend on previous land use. Several studies indicate a higher water use from the tree layer compared to monocropping systems thus future provision of water or susceptibility to drought stress must be considered prior to promoting tree species diversity (Schume et al., 2004; Yang et al., 2021; Zhang et al., 2016). For example, conversion of forest land to silvopasture through tree thinning will be affected differently than the conversion of monoculture to multiple cropping. Coble et al. (2020) found that conversion of forest to silvopasture in north-eastern USA led to a 35% reduction in transpiration rates, which accounted for a greater overall water saving despite an increase in soil evaporation. In contrast, Awessou et al., (2017) found that agroforestry systems in the African Sudanian belt were less efficient than the previous forest stands at recycling local rainfall due to altered species composition and a reduced tree density.

Below-ground competition for water and nutrients may also provide another barrier to success implementation of a multiple cropping system. This will be dependent on rooting traits including occupied soil space, rooting depth, morphological and physical plasticity as well as temporal and spatial variation in the soil substrate (Gao et al. 2013; Mao and Zeng, 2009). Competition for water is also likely to limit yields of agroforestry systems, particularly in low rainfall areas or where root systems are unable to reach deep water reserves (Ong et al., 2014).

Recent work has shown that introducing alternative cropping systems as an adaptive measure can also help increase the awareness of climate change events. For example, introducing agroforestry practices in Kenya has been shown to alter the perception of floods and droughts (Quandt et al., 2017). Households that practiced agroforestry largely reported a reduction in the frequency of droughts whereas many of the households not practicing agroforestry reported the opposite thus suggesting that households were more conscious of local environmental conditions if they adopted agroforestry on their land. This reflects previous work whereby trees incorporated into agriculture are considered to be more intimately linked to the local society than trees found in forestry settings (Ong et al., 2015). They are important in supporting both national and international economies and have an important role in efforts towards improving sustainability.

2.3.3 Soil improvement and carbon sequestration

Human-induced soil degradation is currently projected to affect approximately 25% of the Earth's ice-free land area, with a large proportion located in the tropics (IPCC, 2019). The organic matter found within soils (SOM) contains approximately three times more carbon than in the atmosphere, functioning as a carbon sink (Jobbágy and Jackson, 2000). However, land degradation, climate and soil properties can convert this sink into a source; releasing vast quantities of carbon back into the atmosphere (IPCC, 2019).

Approximately 23% of the total greenhouse gas (GHG) emissions come from agriculture, forestry and land degradation, with further emissions associated with deforestation, fertiliser use, waste management and other related activities (IPCC, 2019). Farming practices such as mechanisation, pesticide or fertiliser application and livestock farming generate large quantities of GHGs (Chen et al., 2014b;Daly and Hernandez-Ramirez, 2020; Wang et al., 2019). However, multiple cropping practices such as agroforestry can remove significant amounts of GHGs through increased carbon storage above and below ground in plant material and soil organic carbon (SOC) (Ramachandran Nair et al., 2009; IPCC, 2019). Globally, tree cover is highest (>45%) in humid regions of Southeast Asia, Central, eastern and South America plus central and coastal West Africa; moderate (10-30%) in South Asia, Africa, Central and Western Europe and; low (<10%) in Eastern China, Northwest India, Western Asia, North America and Southwest Australia (Zomer et al., 2016). Given the amount of land suitable for increased tree cover, the potential for increasing agroforestry to maximise carbon sequestration is a suitable and potentially rapid route towards mitigating GHG emissions (Baah-Acheamfour et al. 2016;Bastin et al. 2019; Zomer et al., 2016).

Land use type as well as system design influence the SOC storage efficiency within agroforestry systems (Dollinger and Jose, 2018). Via a meta-analysis approach, De Stefano and Jacobson (2018) found that shift from a system without any trees (including monocrop, pasture or un-cultivated land) to agroforestry resulted to an increase of SOC by <40 %. Conversely, shifting from a primary- or managed-forest to agroforestry generally results in a decrease in SOC storage by <26 %. Remote sensing data indicated that in 2010, 43% of global agricultural land contained at least 10% tree cover, accounting for carbon storage of approximately 45.3 Pg C, 75% of which can be attributed to the trees (Zomer et al., 2016). This represents a 3.7% increase in global tree cover from 2000, corresponding to a 4.6%, or 0.2 Pg C yr^{-1} increase in carbon storage as biomass. Conversely, above ground loss due to tropical land conversion equates to 0.6-1.2 Pg C yr^{-1} loss.

The benefits derived from SOC may be mitigated by high emissions of nitrous oxide (N_2O) or methane (CH_4) from soil under certain management practices or environmental conditions (Amadi et al., 2018; Priano et al., 2018). In Argentina, systems containing trees were found to have a higher SOC storage and reduced emissions of CH_4 relative to prairie land (Priano et al., 2018). However, Amadi et al., (2018) found that this was dependent upon water regimes in Canadian shelterbelts, whereby greater emissions of CH_4 and N_2O were found under irrigated conditions compared to rainfed and riparian forests emitting more GHGs than other land uses. Similar results were found by Moore et al., (2018) whereby soil water content and fertiliser input altered the carbon sequestration capacity plus N_2O and CH_4 emissions from an agroforestry orchard.

Annual intercropping systems have also been explored as a means to mitigate GHG emissions and thus provide clean agricultural production (Abagandura et al., 2020; Wang et al., 2016, 2021; Zhuang et al., 2019). In particular, intercrop mixtures containing a legume component have been shown to increase the number of N-fixing bacteria in soil and improve the crops ability to absorb N, thus reducing the requirements for additional fertiliser application (Hauggaard-Nielsen et al., 2016;

Solanki et al., 2019; Yu et al., 2019). In South China, excessive fertiliser application (360–500 kg N ha^{-1}) plus up to three harvests per year is a common practice for the cultivation of sweet maize (*Zea mays* L. *saccharata*) (Liang et al., 2009). Incorporation of soybean into sweet maize cultivation has been shown to increase crop productivity per unit land area (Wang et al., 2021). N fixation by the legume contributed to the improved sweet maize yield and a reduction in GHG emissions at a fertiliser input of 300 kg N ha^{-1} combined with an increase in SOC sequestration, although the yield of soybean was reduced. However, under complete elimination of N fertilisation, the N_2O emissions were reduced but the CO_2 emissions significantly increased because of soil respiration, resulting in the overall highest GHG emissions. This phenomenon is proposed to be a result of N mineralisation; whereby soil microorganisms decompose a greater amount of SOM under N-limiting conditions (Moorhead and Sinsabaugh, 2006; Wang et al., 2014).

Soil conditions such as moisture content, temperature and nutrition have large effects on the abundance and action of the soil microbiome, including N-fixing bacteria (St. Clair and Lynch, 2010). Therefore, introducing multiple crop or tree components can help boost this action through soil improvement, including the incorporation of N-fixing species or promotion of microbial activity and decomposition in the soil. Intercropping systems containing grass-legume mixtures can self-regulate based on soil N levels. This is important for reducing the amount of reactive N, thus reducing nitrate leaching and denitrification, which are major contributors to fresh-water pollution and GHG emissions, respectively (Mariotti et al., 2015; Whitmore and Schröder, 2007). In addition, there was a reduction of agrochemical inputs due to a mix of deterrent pest crops, pathogen resistant varieties (Ratnadass et al., 2012) or N-fixing species might help mitigate GHG emissions by reducing the amount of inorganic agrochemicals produced (Jensen et al., 2012).

Improved soil nutrition is particularly prevalent in agroforestry systems whereby tree presence is relatively permanent, leading to improvement and retention of SOC over the long-term (Li et al., 2015; Lorenz & Lal, 2014). The process of litter decomposition and mineralisation can greatly improve the nutrient capacity of soils (Dollinger and Jose, 2018). This is further complemented by throughfall and stemflow which facilitate the nutrient transfer from above-ground plants parts to the forest floor (Dawoe et al., 2018). Not only do agroforestry systems improve nutrient accumulation but also nutrient availability. Salim et al. (2018) found that home gardens present greater soil fertility than primary or secondary forests in Brazil despite a reduced SOM accumulation, because nutrient availability was improved. As soil fertility and organic content is related to temperature and moisture status, benefits can be seen through modifications to the microclimate and ecosystem stabilisation (Zomer et al., 2016).

Under certain instances and with careful selection of species, multi-cropping can restore soils contaminated with inorganic and/or organic compounds in the process of phytoremediation (Kidd et al., 2015). For example, monocropping or intercropping of alfalfa (*Medicago sativa*) and poplar (*Populus x canadensis*) has been shown to be effective and improving soil health in degraded peri-urban areas (Gómez-Sagasti et al., 2021) with previous applications in phytoremediation of soils contaminated with metals and hydrocarbons (Bonfranceschi et al.,, 2009; Lingua et al., 2008; Marchand et al., 2016; Panchenko et al., 2017). Intercropping wheat with *Sedum plumbizincicola* or incorporating multipurpose tree species has been effective in improving remediation of soils contamination with heavy metals including cadmium (Cd) and zinc (Zn) (Kaur et al., 2018; Zou et al., 2021). Dependent on the location and contaminants present, multiple cropping has been proposed as an integrated approach to provide phytoremediation, post processing energy conversion and high-value element recovery (i.e. phytomining) (Jiang et al., 2015). In the UK and Australia, this has shown to be a viable approach towards recovering Nickel, Arsenic and Platinum group metals (Jiang et al., 2015; Rosenkranz et al., 2019).

2.3.4 Biodiversity, weeds, pollination, disease and pest control

Alternative cropping systems that include multiple components can provide high species diversity within a small area of land (Leakey, 1999). The actual increase in biodiversity will depend upon maturation as well as the number of components involved in the system; with a greater number of crops or tree species generally leading to a higher biodiversity. Additional benefits may also arise through the increased habitat or landscape connectivity through the generation of wildlife corridors. For example, tropical home gardens, a type of mutltistrata agroforestry, contain the highest biodiversity of all human-created ecosystems. Home gardens in Indonesia contain 60–70% of animal species found in the surrounding rainforest (Kumar & Nair, 2004; Leakey, 2012). Whilst increasing species richness provides a form of ecological insurance in relation to abiotic or biotic buffering, mixed cultivation may not always be suitable as an adaptation method (Brang et al., 2014).

The ability for multiple cropping systems to provide a buffer for crops and farmers to adapt to changing climate parameters highlights the utility of this type of agriculture to maintain production levels through variable future scenarios. Increased temperatures have been shown to shorten the developmental cycles of disease and pest organisms, favouring their altitudinal and latitudinal expansion as well as increased virulence (Battisti et al., 2005; Hlásny and Turčáni, 2009). Weed and pest prevalence is likely to differ between monocrops versus mixed cropping and in many cases, there is a reduction in the incidence of insect pests and weeds under multiple cropping. More generally, pest and diseases can be limited through three methods: by reducing the number of susceptible hosts (dilution effect), by incorporating resistant plants that function as a physical barrier to susceptible plants (barrier effect), and by compensating for a species that is more susceptible or by reducing the speed of pest or disease adaptation through disruptive selection (Borg et al., 2017). In certain multiple cropping systems, exudates of one component may inhibit a pest or pathogen which is prevalent on another component as seen in maize-soybean intercropping (Zhang et al., 2020b). Other factors affecting disease or weed dynamics include changes in vector dispersal; modification to the microclimate; changes in host or system physiology and morphology; or direct pathogen and weed inhibition (Boudreau, 2013). In the latter scenario, this is often achieved through maximising resource partitioning between the components in the system, resulting in a reduction in the resources available to the weeds (Hauggaard-Nielsen et al., 2001, 2006; Liebman and Dyck, 1993). Maturity date of component species is an important trait benefitting weed suppression, as seen in legume intercropping systems (Rodino et al., 2007; Vollmann et al., 2010).

In some systems, the component species may release phytotoxic components limiting the germination and growth of the second component species or understory plants in the case of agroforestry. For example, teak (*Tectona grandis* L.f.) releases phenolics, benzofurans, quinones, terpenes, apocarotenoids and phenylpropanoids from the decomposition of leaf litter which suppresses weed and growth of certain crop species (Kato-Noguchi, 2021). Similar phytotoxic effects are evident in agroforestry systems containing species of alder (*Alnus nepalensis*), jackfruit (*Artocarpus heterophyllus*) and the Indian gooseberry (*Emblica officinalis*) (Kumar et al., 2006). Thus careful selection of component species is important to minimise weed or pest competition without restricting crop growth.

2.4. Livelihood and societal benefits

Multiple cropping systems can improve livelihoods through diversified income and cash crop systems (e.g. coffee, cocoa and nuts). This is particularly important for smallholder farmers and helps to improve access to nutritious foods and education (Agroforestry Network, 2018; Kiptot et al., 2014; Rigal et al., 2018). Furthermore, agroforestry systems also provide the benefits of tree-products for either sale or home use. Pruning of trees for firewood can retain all ecosystem service benefits of tree cover whilst simultaneously preventing deforestation in regions where wood is the primary cooking fuel. A comparison of farmers in Kenya who adopted agroforestry practices versus those who did not showed that agroforestry was able to enhance standards of living by increasing income, productivity and environmental conditions (Thorlakson and Neufeldt, 2012). Incorporating climate resilient practices such as multiple cropping can also help reduce the economic recovery time following natural disasters or extreme weather events (Simelton et al., 2015). However, potential productivity may be limited by a lack of education, access to finances, industrial equipment, or market chains (see Section 5 for more details; Agroforestry Network, 2018).

In many developing regions, women constitute the majority of farm labour whilst their male counterparts are usually travelling for work (Leder et al., 2016). Female farmers generally have less access to resources or opportunities and thus diversified cropping could provide a suitable system to improve natural resource access (Agroforestry Network 2018; Kiptot et al., 2014; Rigal et al., 2018).

3. Constraints limiting the adoption of alternative cropping practices

An overview of factors relevant to adoption and deployment of alternative cropping practices is presented in Table 3.

3.1 Financial Constraint

There are several barriers preventing the broad-scale implementation of multiple cropping practices such as inefficient markets, limited access to knowledge or finance and unclear land-rights (Agroforestry Network, 2018). Widescale adoption of alternative cropping practices will only occur through appropriate support from policies, institutions and market demand that influence both farmer and consumer behaviour (Alam et al., 2014; Dhandapani et al., 2020; Isaacs et al., 2016). Markets for agroforestry and intercropping products must be present on a sufficient scale to have meaningful environmental, economic and social impacts (Gyau et al., 2014). In general, economic incentives are the main element encouraging the transition to alternative cropping practices. Historically, policy makers have focused almost exclusively on forest and wood production and the goods and services provided by trees in the forestry setting. However increasing interest in the social and environmental services provided by trees, including their role in adaptation to climate change, provides an incentive for a greater practical consideration of trees in agricultural settings and elsewhere (Stigter, 2010). Although the benefits outweigh the costs of implementing agroforestry, uptake is often restricted by legal constraints, adverse policies and lack of coordination between governmental departments. These restrictions include policies which segregate forest from agriculture and therefore miss benefits at the landscape scale (FAO 2013; Mbow et al., 2014). Possible ways to promote alternative cropping systems could include incentives such as subsidies, financial support or cost-share programmes. In the context of agroforestry, measures to improve adoption of agroforestry practices include improving farmer access to markets and value chains for products, supporting financial models which acknowledge the long-term returns on agroforestry systems, and improving participatory and inclusive research (Agroforestry Network, 2018). In some regions, efforts are being made to alter policy and provide such incentives, such as the acknowledgement of agroforestry systems as eligible for the basic payment scheme (BPS) by farmers in the UK (DEFRA, 2020).

Despite an international goal to increase the uptake of agroforestry practices, significant gaps exist between a countries' ambition and their capability of measurement, reporting and verification of uptake (Rosenstock et al., 2019). As of June 2018, a study carried out by the Consultative Group for International Agricultural Research (CGIAR) found that 59 of 147 developing countries proposed agroforestry as means to mitigate climate change under their nationally determined contributions (NDC) under the United Nations framework convention on climate change (UNFCCC) (Rosenstock et al., 2019). Agroforestry systems are most widely proposed in Africa (71%), with a lesser amount in the Americas (34%), Asia (21%) and Oceania (7%).

3.2 Agronomic constraints

Multiple cropping systems can be designed in an almost infinite combination of species, temporal and spatial arrangements. The choice of component crops and their layouts may be tailored depending on any environmental or geographical constraints of the location. Similarly, consumer habits and dietary information may influence the quantities of crops required (Brooker et al., 2015). This may also determine whether a mixed cropping system is adopted. For example, many intercropped grain-crop mixtures with similar maturation timings cannot be machine harvested to produce a marketable commodity unless appropriately spaced or with appropriate methods for separation. For example, flax and wheat can be mechanically harvested and separated, however the mechanised separation of other mixtures may be prohibited. In such instances, multiple cropping systems may be restricted to regions of cheap and plentiful manual labour or designated for animal feed.

The choice of component species for multiple cropping as well as their spatial arrangement is critical in determining the level of competition between components as well as the potential perceived benefits. Thus, designing the optimal combination of components can be difficult, often requiring a greater number of skills and knowledge than monoculture. Additional skills are also required for the careful timing of field operations, alterations in cultivation practices or the use of external inputs such as fertiliser or mulches and changes to the series of crop rotation to ensure sufficient separation of plant families over time (Mohler and Johnson, 2020).

Traits that may confer optimal performance within one setting may be different to those that benefit another system, i.e. the crop varieties chosen for a monoculture are likely to differ from those which will perform better in a multiple cropping system (Zhu et al., 2015, 2016), thus requiring either additional knowledge or trial and error when selecting optimal combinations. Similarly, the often-high initial investment costs and low initial returns, particularly during the slow establishment of an agroforestry system, may be prohibitive in many instances. Knowledge regarding the optimal management techniques is also important in receiving the greatest returns from multiple cropping systems. In the case of agroforestry, management practices could include pruning or removal of trees.

For example, the choice of regeneration cut is a crucial factor contributing to changes in species richness or competition (Brang et al., 2014). Therefore selection for the optimal adaptive system requires not only conscious selection of the varieties, the species diversity present but also knowledge of the maintenance and management practices required as well as the cost and time requirements needed to maintain the system (Brang et al., 2014). Both the additional labour required or the added complexity of the management needed may therefore prohibit uptake (Fletcher et al., 2016).

Geographical variation in tree species is one of the fundamental issues determining the success of agroforestry or reforestation attempts (Ong et al., 2015). Evidence of poor selection can be found in failed plantations or poorly developed shelterbelts, indicating the importance of appropriate seed and species selection (Morgenstern, 1996). Many of the considerations governing the success of forestry management, such as close-to-nature silviculture (CNS), also apply to agroforestry (Brang et al., 2014). For CNS, six core principles have been identified to enhance the adaptive capacity of the system to climate change: 1) increased tree species richness, 2) increased structural diversity, 3) increased genetic variation within species, 4) increased resistance to abiotic and biotic stresses, 5) reduce the size of growing stocks and 6) replace high-risk stands. Domestication of agroforestry tree species emerged as a farmer-driven initiative in the last three decades, increasing the knowledge and suitability of tree species for co-cultivation with crops and/or livestock (Leakey et al., 2005). For example, indigenous fruit and nut trees have been progressively improved in villages of Nigeria and Cameroon, with vegetative propagation used to maintain desirable traits (Leakey et al., 2004). Indigenous crop varieties, seed conservation and access to forest foods and weeds are often adopted as an adaptation strategy in regions of India (Ghosh-Jerath et al., 2021). In addition, it is key to call attention to inclusion of local species that help enhance biodiversity, and that are well adapted to microclimate conditions and might have developed resilience to climate change or to extreme weather events (Ghosh-Jerath et al., 2021). Copper et al. (2020) demonstrate how indigenous grape varieties for wine production in Cypriot can tolerate the hot and dry conditions and, in comparison to commercial varieties, can be productive without additional irrigation inputs. Rendón-Sandoval et al. (2020) showed that traditional agroforestry systems in seasonally dry tropical forests in Mexico can keep on average 68% of the forest species from adjacent patches, highlighting the importance of considering native species and local knowledge in the design of agroforestry systems.

3.3 Varietal constraints

Despite perceived benefits of multiple-cropping systems, breeding and genetic improvement for system components has received very little attention, with varieties specifically targeting multiple cropping being unavailable (Brooker et al., 2015; Duc et al. 2015; Haug et al. 2021; Litrico and Violle 2015; Saxena et al. 2018). Thus, varieties currently used in intercropping or agroforestry were bred for monoculture and their performance in alternative systems is often left unevaluated (Brooker et al., 2015). This restricts many of the potential benefits of such systems due to a lack of adaptability (Duc et al., 2015; Saxena et al., 2018). Simulation studies indicate that intercrop breeding programmes which use genomic selection can produce faster genetic gain than programmes using phenotypic information only (Bančič et al., 2021). This can aid in reducing the generation interval of new varieties and increasing both the selection intensity and accuracy of breeding. However, breeding for multi-species assemblages requires more complex and integrated objectives for breeders (Duc et al., 2015). This requires selection for a combination of genotypes, plant species and associated symbionts, plus potential targets dependent on spatial arrangements of the system.

Breeding and genetic improvement for tree component of agroforestry systems is also a complex task. Genetic variation in forest trees is amongst the highest observed in all living organisms (Lal and Bhandari, 2020). Compared to agricultural crops, genetic improvement of tree species takes several years at a higher overall cost (Grattapaglia et al., 2018; Lebedev et al., 2020). This is partly a result of long-life cycles of tree species, meaning that phenotypic selection for traits is generally only possible at 30–50% of the rotation age for fast-growing species and 25% for long-duration trees (Durán et al. 2017; Harfouche et al. 2012; Lebedev et al. 2020; Muranty et al. 2014). Each tree breeding programme will depend on the overall aim, but generally includes improvement of traits of high economic and social importance whilst maintaining genetic diversity (Wanders et al., 2021). Geographical location of the native population of plant material is known as provenance, with significant genetic variation present between different provenances. In comparison, tree species with limited natural geographical range or isolated within a small population have comparatively low genetic diversity (Lal and Bhandari, 2020; Lowe et al., 2009). Therefore, the selection of progenitor individuals is critical in retaining genetic diversity with provenance testing essential for identification of the best performing populations (Makueti et al., 2015; Wanders et al., 2021). Where background genetic information is not available or optimal provenances cannot be identified, locally selected cultivars are expected to be better adapted to local environmental conditions compared to commercial varieties (Picucci et al., 2020; Rigal et al., 2018; Waruhiu et al., 2004). The timespan available for the adoption of multiple cropping systems is an important factor determining feasibility. This is particularly evident in agroforestry systems, whereby benefits are predominantly achieved if they are maintained for extended periods (Frenzel and Scherr, 2002; Mercer, 2004). For example, it is expected to take 3-6 years for the benefits of agroforestry to be fully realised (Lin et al., 2015).

4. Future research: optimising agriculture for climate change through modelling approaches

Understanding the plant response to the environment in which it is grown, including the cropping system or practices adopted, will be critical in optimising our agricultural systems. To optimise the system for climate change, Van Noordwijk and Minang, (2011) proposed that at least three representations must be considered for each location: 1) open-field agriculture, 2) medium tree cover or agroforestry and 3) full tree cover or forestry. For this review, this can also be extended to a fourth representation encompassing intercropping systems or multispecies assemblages, without tree presence. The differences between these systems as well as the relative response of each to changes in climate should form the basis for decisions on desirable component species chosen, their planting layouts and densities and other societal requirements per location. This long-scale meso-climatological approach emphasizes the need to take into account all climate and landscape factors in the adaptability of agroecosystems and provides a systematic criterion for disaster risk reduction (Van Leeuwen et al., 2014). This can encompass the generation of multiple designs of cultivation systems combining components to maximise outputs based on current subsistence requirements, markets and historical agricultural practices. Similar frameworks can also be applied to combatting other factors relating to land degradation or climatic factors (Onyewotu et al., 2004; Stigter et al., 2002).

Modelling approaches can be used to estimate productivity in multiple cropping systems. This can overcome some of the uncertainties relating to the selection of the optimal components, planting density or spatial arrangements. Simulation of the assessment of different combinations of crops can simultaneously be applied to different locations if climatic or weather data can be included. Such approaches could provide an initial screening for assessing crop combinations before more time-, labour- and space-incentives methods are used (Burgess et al., 2017; Evers et al., 2019). Additionally, coupling physical modelling with dynamic growth models could provide a means to link causative genomics with yield models, particularly where models are aimed primarily at optimising sustainable yields in complex multi-component systems. In functional structural plant (FSP) modelling, complementary and competitive interactions between individuals are assessed to determine overall crop performance and, as such, can be used to simulate interactions in multi-species mixtures (Evers et al., 2019).

For climate change impact assessment, crop growth models have been widely used to evaluate the development, growth and yield of crops by combining future climate conditions with the simulation of CO_2 physiological effects, such as using Free Air Concentration Enrichment experiments (FACE), (Ainsworth and Long, 2005). However, whilst FACE experiments have been extensively used for monocultures, multi species systems have received little attention (Calfapietra et al., 2010; Chen et al., 2014a; Esmail and Oelbermann, 2011; Yang et al. 2021b). Within agroforestry systems, this is partly a result of system constraints, with tree size, microclimate modifications and length of growth seasons limiting potential experimental design (Calfapietra et al., 2010). Similarly, ecosystem-scale warming experiments are seldom due to difficulties in manipulating air temperature outside of growth chambers (Rustad et al., 2001). Thus, optimised cropping designs need to also account for elevated CO_2 and temperature, requiring advanced methodologies to overcome current constraints with FACE or ecosystem-scale warming experiments.

Future conditions are generally obtained from General or Regional Circulation Models (GCMs and RCMs respectively), which incorporate the dynamics of physical component of the atmosphere and ocean circulation with future GHG projections. These often relate to several key environmental factors including elevated CO_2 concentration, temperature, tropospheric O_3 concentration plus variation in spectral composition including ultraviolet (UV) B radiation. However, simulating all environmental changes simultaneously within field experiments is not feasible due to geographical or diurnal variation and single-factor responses do not account for interactions between variables (Calfapietra et al., 2010). For realistic projections of the effect of climate change on crop production, there is a need to also include impacts to the entire production chain and market mechanisms, including socio-economic factors (Tubiello and Rosenzweig, 2008). Together these factors can be incorporated to determine the most vulnerable regions, which are generally developing countries with an often higher baseline temperature, increased exposure to extreme weather events and reduced capital to invest in adaptation measures.

5. Conclusions

With changes in climate and increased incidence of extreme weather events, many of our current agricultural systems will be ill equipped to buffer against damage. However, transition towards more biodiverse systems could provide a solution, with implementation of intercropping and/ or agroforestry providing an adaptive measure towards climate change. These systems can provide numerous benefits both at the farm and ecosystem levels, encompassing biotic, abiotic, economic and social advantages. However, whether such benefits are achieved is dependent upon the system implemented including geographical location and the careful selection of components plus their spatial arrangement. There are numerous constraints limiting the adoption of alternative cropping practices however, advances in modelling provide one solution to aid identification of potentially productive systems.

Tables

Table 1. Basic spatial or functional arrangements used during intercropping

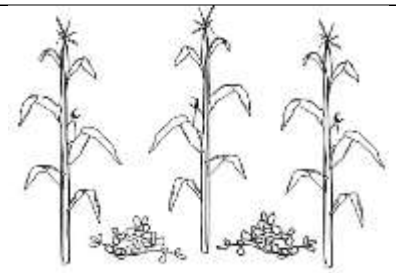
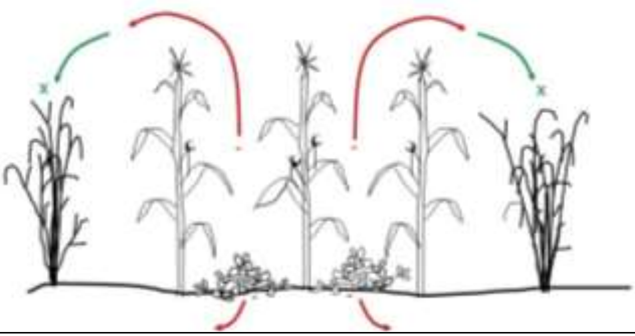
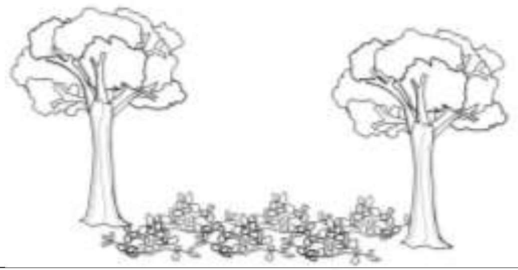
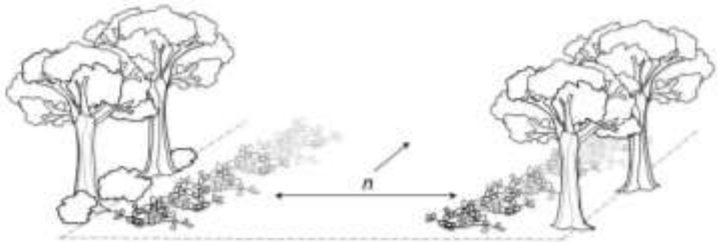
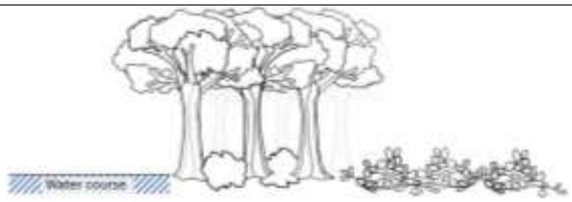
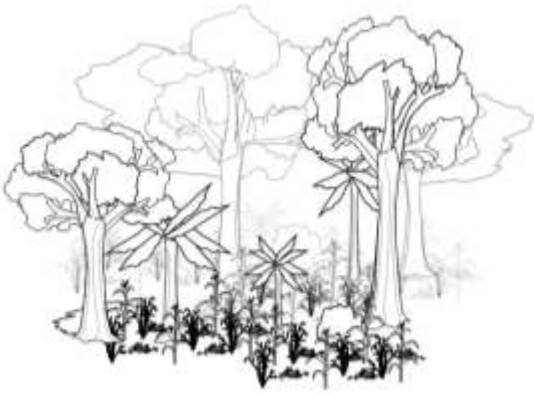
Schematic	Description	Examples
	Row intercropping: The cultivation of two or more crops at the same time with at least one crop planted in rows.	(Ren et al., 2017; Schulz et al., 2020)
	Strip intercropping: The cultivation of two or more crops together, wide enough such that they permit access to separate machinery but close enough for the crops to interact.	(Iqbal et al., 2019; Li et al., 2001; van Oort et al., 2020)
	Mixed intercropping: The cultivation of two or more crops together in no distinct row arrangement.	(Agegnehu et al., 2008; Senbayram et al., 2015)
	Relay intercropping: Planting a second crop into a standing crop part way through its development but prior to harvesting.	(Amossé et al., 2014; Zhang et al., 2008)
	Push-pull intercropping: A specific system adopted for pest management whereby a 'trap/pull' crop attracts pests away from the main crop and a 'push' crop aids to repel pests.	(Hailu et al., 2018; Khan et al., 2016; Xu et al., 2018)

Table 2. Overview of different types of agroforestry system

Schematic	Description
	Silvopastoral: Combining forestry and grazing of domesticated animals on pastures, rangelands or on-farm.
	Agrosilvopastoral: Combining trees crops and animals in the same area.
	Agrisilvicultural: Combining crops and trees in the same area: this can come under different spatial arrangements detailed below.
	Random planting: Trees are randomly distributed throughout the field.
	Boundary planting: Trees are planted around the edge of the field to form a boundary.
	Riparian buffer: Linear bands of permanent vegetation, such as trees, shrubs etc, are grown adjacent to an aquatic ecosystem to maintain or improve water quality

	Alley planting: Trees are grown in rows with wide alleys in between for crop cultivation.
	Polyculture: Combining multiple trees and crops in the same space, usually with no distinct arrangement.

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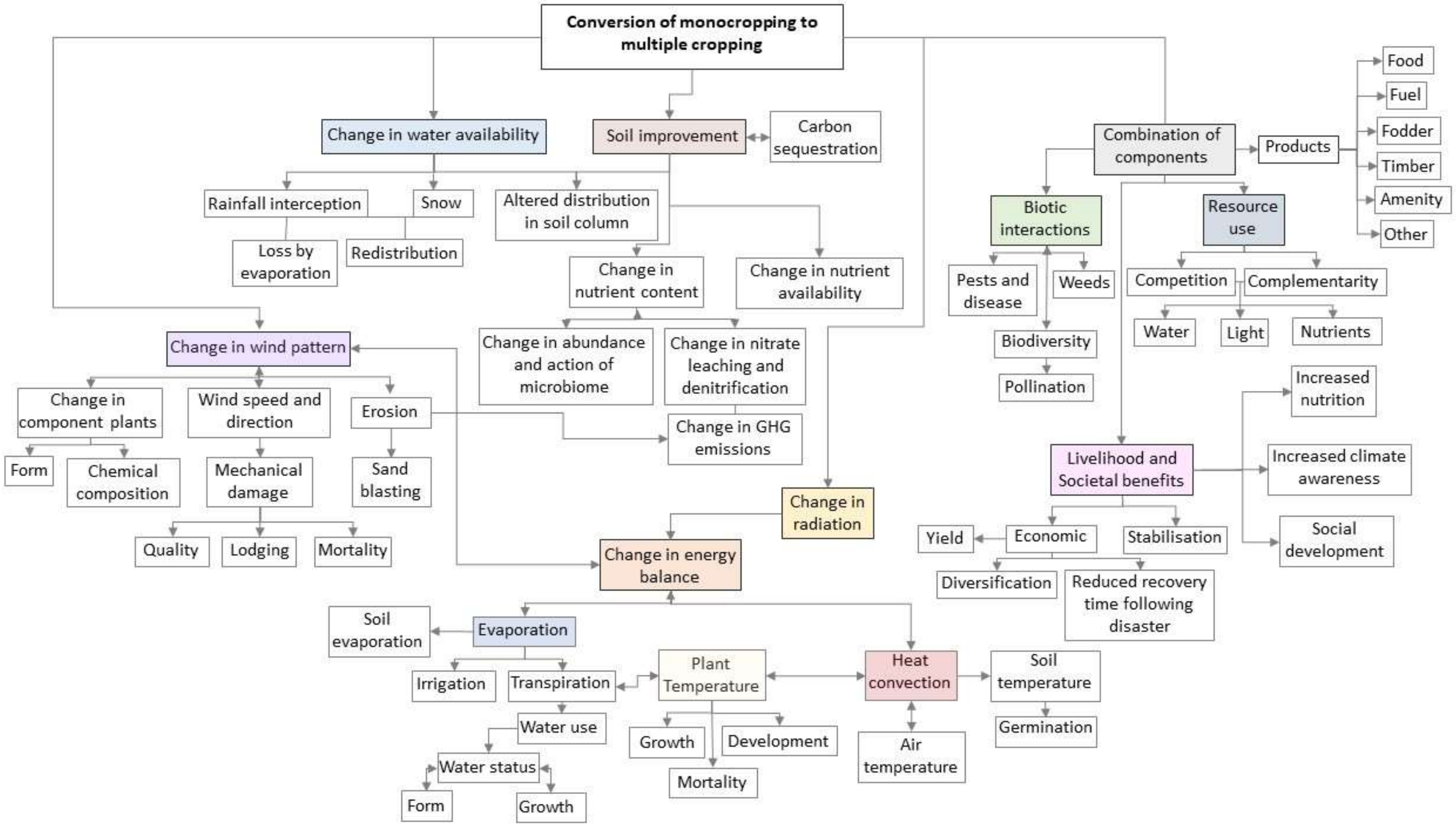
685 ***Table 3. Considerations for the feasibility of adopting alternative cropping practices including intercropping and***
686 ***agroforestry (adapted from Romanillos et al., 2010).***

Factor	Details
Geographical	Consideration of soil type, land relief, climate, growth season and other biophysical factors
Environmental	Can the system improve microclimatic conditions? Can the system alter ecosystem services? Will the system help ease the effects of climate change on plant diversity, soil conditions, water, soil and energy conservation and nutrient cycling
Technical	Is the alternative cropping system complementary to the existing land area, capital, management approaches and labour? Are there support systems to promote the system such as government regulations, marketing or technical assistance? Are management practices known that can be implemented to improve the system and is the infrastructure in place to do so? Are the chosen components suitable for a multiple cropping system?
Economic	Will the system be profitable both in the short- and long- term?
Social	Does the system match the current socio-economic environment? including factors such as food or crop preferences, market demand, land tenure and security.
Political	Is there political or institutional support for adoption of multiple cropping systems?
Other	What is the timespan of adopting the alternative system? Does this agree with all the factors given above?

687

688 **Figures**



689 Figure 1: Changes in key microclimate and social variables during conversion from a single to multiple cropping system. Adapted from (Ong et al.,
690 2015).

Declarations

Funding

This work was supported by the Biotechnology and Biological Sciences Research Council [grant number BB/R004633/1]. AJB is supported by the Leverhulme Trust as an early career fellow. BP is the recipient of the Ekpe Research Impact Fellowship in the Department of Mechanical, Aerospace and Civil Engineering at the University of Manchester. MC was funded by the UK Natural Environment Research Council (NERC) and the Chilean National Agency for Research and Development (ANID/CONICIT)-FONDEF/Concurso de investigación conjunta PICARTE "NEXUS" NEWTON RCUK-CONICYT BROADENING IMPACT CALL 2017 through the NEXT-AG project (Nexus thinking for sustainable agricultural development in Andean countries; NE/R015759/1).

Conflict of Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Approval

No ethical approval was required for the work presented in this paper.

Consent to participate and for publication

No consent was required for the work reported in this paper.

Availability of data/ material/ code

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Author contributions

All authors contributed to the review conception and design. Material preparation, literature search and data collection were performed by A.J.B. M.E.C.C and B.P. The first draft of the manuscript was predominantly written by A.J.B, with assistance of all authors. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: