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Exploring the links between the sustainability of consumption and resource security

(Guidance report)

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Summary

Resource security is important, as the continuous provision of commodities such as food, water and materials are essential for human safety and survival. Sustainable consumption is crucial to resource security; the very definition of consuming sustainably is consuming in a way that can be sustained in future down the generations. Intensive agriculture has been degrading many ecosystems because its rate of use of resources (e.g. soils, water) is beyond their capacity to regenerate on human timescales, so continuing with the levels and types of production and consumption we have been used to may not be sustainable into the future.

This review, therefore, aims to identify the effects that current consumption is having on future resource security, and how to consume in a way that will be most likely to allow us to continue production while conserving and supporting ecosystem services. It does this by focusing on three ecosystem services (soil health, clean air and freshwater supply) as examples. For each, the review identifies their importance to production, the ways in which they are affected by consumption, and what solutions people are developing to help ensure that consumer needs can be met whilst maintaining this ecosystem service.

An estimated 95% of the global food supply is produced, directly or indirectly, on soils. Healthy soils are therefore key to ensuring ongoing resource security. However, unsustainable consumption and intensification of production can lead to poor soil health through factors such as compaction, nutrient depletion, erosion, and contamination. Production and consumption systems could be made more sustainable using processes such as byproduct recycling, the use of plant growth-promoting microorganisms, crop rotation, no-tillage systems, and agroforestry.

Clean air is important for resource security, as air pollution impacts growth and yields of a range of plants, including agricultural crops. Unsustainable production and consumption can lead to the emission of a range of air pollutants, such as methane, nitrogen oxides, carbon monoxide and volatile organic compounds. The implementation of solutions such as consuming locally (where appropriate), clean energy production systems, agroforestry, and deforestation-free commitments in supply chains could help to ensure that consumer needs can continue to be met whilst reducing impacts on both the environment and future resource security through air pollution.

Water supply is vital for sustaining agriculture, and so is also a key requirement for resource security. However, farming practices to support consumption are responsible for approximately 70% of global freshwater withdrawals. This is especially a problem in areas where water for irrigation is being withdrawn from underground aquifer supplies with a long recharge time. Improved infrastructure, farming techniques, crop choice and governance can all contribute to ensuring water supply remains available for both nature and the next generation of producers and consumers.

Overall, sustainable consumption is a key factor in ensuring resource security, highlighting the need for action in this space not just for environmental reasons, but also for human-centred reasons (Figure 1). Many solutions are already available or in development to allow us to produce and consume more sustainably, and continuing to develop and implement such solutions will be important to improve the sustainability of consumption, and therefore resource security, going forwards (Figure 2).

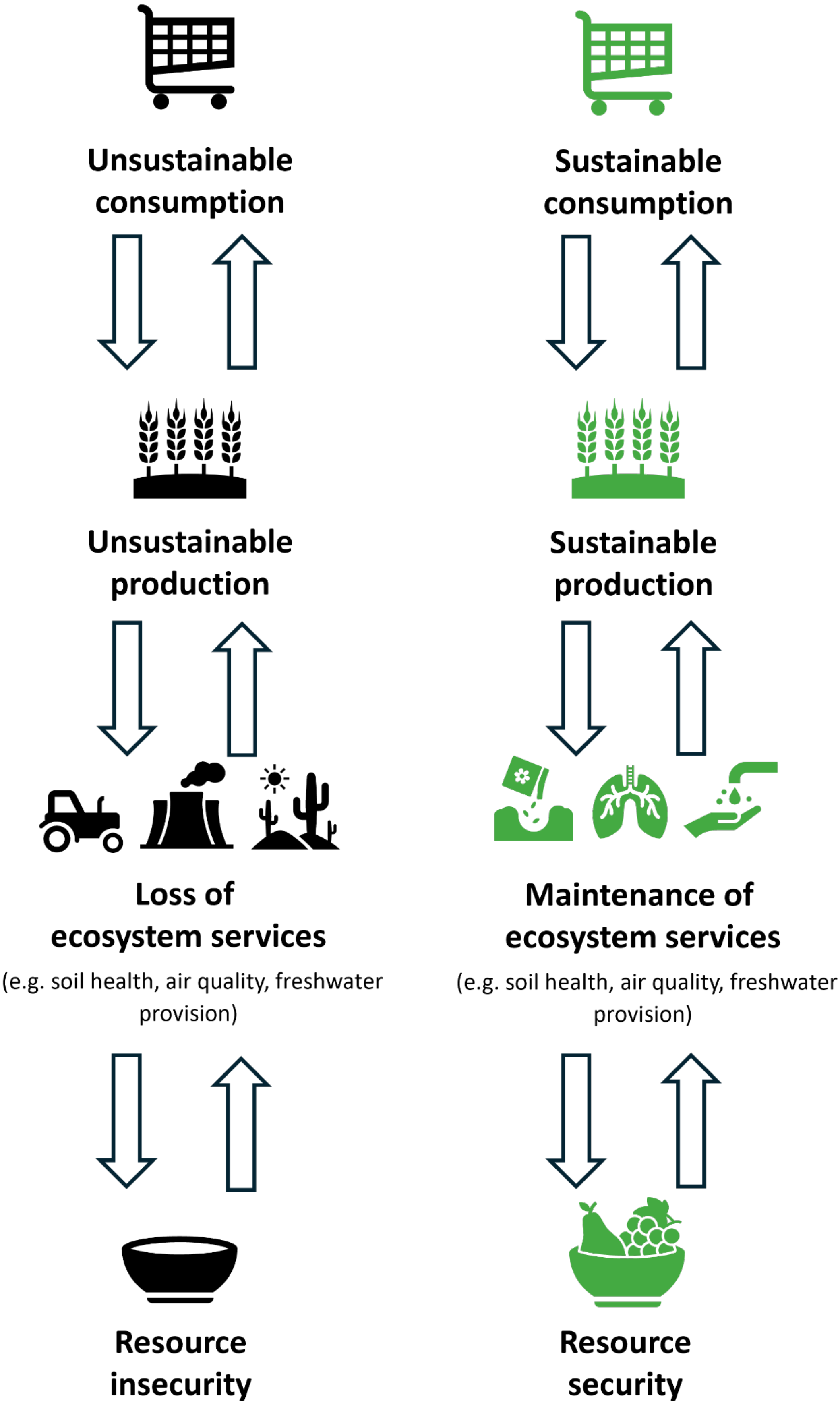

Figure 1. The effects of sustainable and unsustainable consumption on resource security.

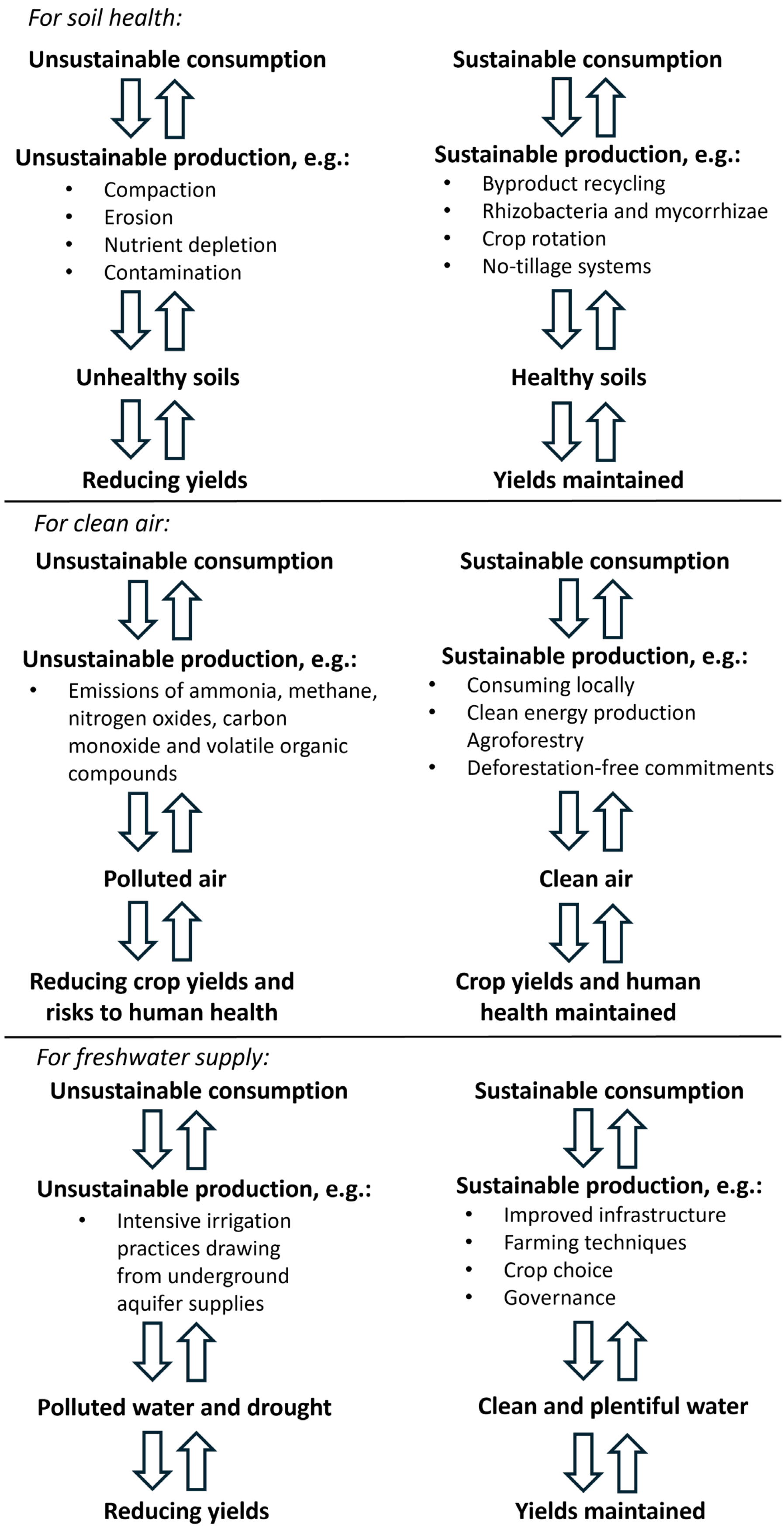

Figure 2. Effects of sustainable and unsustainable consumption and production practices on an example set of ecosystem services.

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1. Introduction

1.1. Context

Security of non-renewable or semi-renewable resources is important, as the continuous provision of commodities such as food, water and materials are essential for human safety and survival. Resource security is achieved when all people always have access to the resources required to live a healthy life, with these resources being produced and consumed in ways that can be sustained into the future (BBSRC 2024; International Food Policy Research Institute 2024).

Global population and affluence continue to increase, putting pressure on resource supply. The UN predicts that the population, which currently sits at 8 billion, will increase by nearly 2 billion by 2050 (UN, n.d.). Current resource security issues will only get worse if more sustainable methods of production and consumption are not widely implemented.

Resource and food security are particularly relevant at present due to their inclusion in numerous policies and strategic goals, both nationally and internationally. Goal 2 of the UN Sustainable Development Goals is Zero Hunger, with target 2.4 reading: "By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality." In the UK, Chapter 1 of the government's strategy for international development states: "With our network of allies and partners and through our efforts across the globe, we will focus on […] preventing and anticipating future shocks and building resilience in long-running crises by tackling the underlying drivers of crises, instability and extreme food insecurity." (Foreign, Commonwealth and Development Office 2023).

There are a number of environmental and socioeconomic threats to resource security. Climate change poses a significant threat to resource security. More frequent and intense extreme weather events, such as droughts or flooding, will result in more common crop failure (El Bilali *et al.* 2020; Gregory *et al*. 2005). Increasing global temperatures will also impact resource production. In an investigation of the impact of increasing global mean temperatures on crop yields, Zhao *et al.* (2017) found that each degree-Celsius increase in temperature would reduce average global yields of maize by 7.4%, wheat by 6.0%, rice by 3.2%, and soybean by 3.1%.

Invasive crop pest species are another threat, particularly to food security, and are related to climate change. Increasing global temperatures lead to increases in the range and activity of species such as *Diabrotica virgifera*, a major pest of corn (Schneider *et al*. 2022). Increasing mean temperatures can lead to species previously confined to warmer, tropical ecosystems moving into more temperate regions. Warmer temperatures can also increase the development, survival, and population sizes of a range of insect species, and can lead to more frequent pest outbreaks (Schneider *et al*. 2022).

Political unrest and war also impact resource security and have a significant impact on food security in affected countries. As of 2017, the FAO classified 19 countries as going through a "protracted (food) crisis", all of which were also experiencing conflict (Holleman *et al*. 2017). Conflict can physically damage infrastructure and agricultural land, impacting the production and storage of commodities (Holleman *et al*. 2017). Displacement of people due to conflict and violence impacts resource production and security, both in the areas from which they were displaced, and in the areas to which they have been displaced (Holleman *et al*. 2017). Countries experiencing war or political unrest may also have reduced imports and exports as well as within-country trade, which will impact both the country experiencing the conflict, and other countries that rely on commodities they produce (Holleman *et al*. 2017; Loft *et al.* 2022). All this also exacerbates income insecurity for smallholder farmers and businesses (International Security and Development Centre 2016).

Resource security is a problem that has different contexts around the world, with underconsumption and overconsumption leading to different effects in different places. In some areas, populations are growing quickly, and malnutrition is a problem, with food insecurity being exacerbated by increasingly frequent extreme weather (International Monetary Fund 2022). In other countries, there is recognition of the need to help countries that are suffering, while meeting the demand of increasingly varied consumption habits and dealing with their own issues of land degradation.

Food loss and waste also impact global resource security. The FAO estimates that approximately one third of our food is lost or wasted, with an estimated 13% being lost between harvest and retail, and a further 17% being wasted in retail, in food services, and in households (FAO 2023). Rates of food loss and waste vary geographically, with high levels of disparity between industrialised countries and developing countries. A study published by the FAO estimated that food waste in Europe and North America totals 95–115 kg/year per capita, compared to 6–11 kg/year per capita in Sub-Saharan Africa and South/Southeast Asia (FAO 2011a). Wastage of food not only loses the nutrition that could have been provided, but also wastes the resources, energy, and land used to produce the food (Jeswani *et al*. 2021).

Resource security is linked to sustainable consumption. Consuming sustainably is often portrayed as just an environmental issue, with campaigns encouraging us, for example, to eat less meat to reduce deforestation and greenhouse gas emissions. However, the very definition of consuming sustainably is consuming in a way that can be sustained in future down the generations. It is therefore crucial to resource security.

Intensive agriculture has been degrading many ecosystems, so continuing with the levels and types of production we have been used to may not be sustainable into the future. An estimated 60% of global ecosystem services are deemed to be degraded or consumed unsustainably (Lazarova *et al.* 2021). Whilst some may see resources such as food crops as a renewable resource, this is only the case if they are being produced in a system that retains the ecosystem services that the production relies on.

Consumers therefore have a responsibility not only to understand how what they are consuming affects the environment, but also how what they are consuming affects future resource security.

1.2. Aims

This review therefore aims to identify the effects that current consumption is having on future resource security, and how to consume in a way that will be most likely to allow us to continue production while conserving and supporting ecosystem services. Previous JNCC work has primarily focused on the impacts of consumption (for example through developing the GEIC indicator which estimates the deforestation, biodiversity loss and water impacts associated with consumption), rather than the implications of these impacts on ecosystem services and resource security. Whilst the impacts themselves are important to understand, the effects that they have on resource security provide another perspective that is crucial and broadens the relevance of this topic beyond those interested in protecting the environment to everyone who relies on the resources that the planet provides.

Ecosystem services can be defined as “the contributions of ecosystems to economic and other human activity” (Suwarno *et al*. 2016). Ecosystem services can be affected by the impacts of consumption and are also essential to support production. This report will therefore use the concept of ecosystem services to explore the aim stated above. A selection of specific ecosystem services will be reviewed, as examples, to identify their importance to production, the ways in which they are affected by consumption, and what solutions people are developing to help ensure that consumer needs can be met whilst maintaining each ecosystem service. The ecosystem services covered by this review are soil health, clean air, and freshwater supply. For each ecosystem service, the review explores its importance in general terms, its importance to resource security specifically, the effects that unsustainable consumption can have on this service, and solutions that are being developed to help ensure that consumer needs can be met whilst maintaining that service. Whilst explored in separate sections, it should be noted that there is a strong interdependency between different ecosystem services; each is essential to the health and function of the other (e.g. soil and water, Li *et al*. 2024).

1.3. Scope

The report is based on a review of both scientific and grey literature. The review was time-restricted to four weeks and so did not aim to be comprehensive or systematic. Whilst there are many ecosystem services that are affected by the impacts of consumption, the scope of the review was limited to the selection above due to time constraints. The report does not aim to give the full detail of all possible impacts on these ecosystem services, but rather aims to summarise key aspects to consider. Neither does it list all possible solutions, but rather includes several examples for each ecosystem service. The commodity scope of this report aligns with the commodities currently covered under the GEIC indicator, namely agricultural crops and timber. It therefore excludes marine commodities (fisheries and aquaculture) and metal/mineral commodities. Whilst the report explores the evidence base behind solutions that are being used to help ensure consumer needs can be met whilst maintaining ecosystem services, it does not aim to make specific recommendations about which solutions should be adopted. Rather, it aims to highlight the synergies between solutions focused on reducing the environmental impacts of consumption and solutions focused on increasing resource security.

2. Ecosystem services

2.1. Soil health

Soil health is defined by Lehmann *et al*. (2020) as “the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans,” and by Harris *et al*. (2023) as “the ability of soil to perform its functions and to deliver ecosystem goods and services... a ‘healthy’ soil is therefore one in which ecosystem services are provided at an acceptable level given inherent underlying constraints and the purpose of the land use.” Several factors contribute to soil health, including nutrient levels, water holding capacity, biodiversity, porosity, structure, respiration, pH, and organic matter content (Tahat *et al*. 2020; Harris *et al*. 2023).

2.1.1. Why is soil health important?

Soil is a finite resource. Healthy soils have a fundamentally important role in life and Earth systems and are key for the functioning of multiple ecosystem services, such as food production, water quality, biodiversity, carbon storage, flood management, nutrient cycling, and human health (Lehmann *et al*. 2020; Bagnall *et al.* 2021).

Soil health is important for water quality because it can absorb and degrade pollutants, making it an important part of water filtration (FAO 2015b). Storage and absorption of water is also a key part of erosion control and flood management. Healthy soils, with high porosity and low compaction, can absorb more water, reducing surface water and runoff (Keesstra *et al.* 2021). Higher water holding capacity is also a benefit for crop and vegetation growth, as more water is available for uptake by plant roots.

For biodiversity, healthy soils have a diverse soil biome and diverse mycorrhizae, and support plant growth which is essential for the rest of the food web (FAO 2015b).

Soils are a major global reservoir of carbon, stored mostly in the form of soil organic matter (FAO 2015b). Carbon stored in soil, known as soil organic carbon, is mostly added in the form of CO_2 fixation by plants, and plant residues such as leaf litter (FAO 2015b).

Nutrients from organic matter in soil being taken back into plants is a crucial aspect of nutrient cycling.

From a human health perspective, soil health is important for water quantity and quality, micronutrients, food production and wellbeing (Abrahams 2002; Friedrichsen *et al.* 2021).

2.1.2. Why is soil health important for resource security?

An estimated 95% of the global food supply is produced, directly or indirectly, on soils (FAO 2015a). As the global population continues to increase, so too will the demand for food and resources. To be able to meet growing demand, maintaining and restoring healthy and fertile soils is essential. Continuing unsustainable, damaging production processes is directly at odds with this and will increase soil degradation. An estimated 33% of soil globally is moderately to highly degraded (FAO 2015b).

Degradation of soil health has a range of impacts on resource production. When nutrients essential for plant growth are a limiting factor in soil, this has a direct impact on the growth of plants. Nutrient uptake in plants removes these nutrients in the soil, which, especially in already low-nutrient soils, can cause a nutrient imbalance if the nutrients removed are not replaced. This then diminishes the ability of the soil to sustain plant growth. Some soils are naturally low in nutrients, such as sandy soils, whereas others are low in nutrients due to degradation through unsustainable land use practices, such as soils that have had high levels of leaching occur (FAO 2015b). Crops grown in healthy soils typically see higher yields than crops grown in degraded soils. In a study investigating the relationship between soil quality and crop climate resilience, Qiao *et al*. (2022) found that crops grown in higher quality soils had both higher average yields (10.3 ± 6.7%) and reduced yield variability (15.6 ± 14.4%). Soil erosion is considered to have significant negative effects on agriculture (FAO 2015b), and healthy soils will suffer lower rates of erosion.

2.1.2.1. Soil health and climate change

The impact of climate change on resource security is a widely recognised problem. One of the ways in which our changing climate affects resource security is through its impact on soil health. Severe weather events are predicted to become more frequent with climate change, with increased rainfall and flooding causing the erosion and degradation of soils, which can lead to reduced yields, crop failures, and increased uprooting of trees, whilst decreased rainfall reduces the water content of soils, and in severe drought conditions can cause desertification.

Temperature also impacts the formation of soils, as well as plant growth. Extreme soil temperatures can cause damage to plant roots and affect the uptake of essential nutrients. Extreme temperatures also affect the soil biota, impacting microorganisms and the decomposition of organic matter. High soil temperatures increase CO_2 emissions from soil by increasing respiration (FAO 2015b).

Healthy soils also play a role in tackling climate change through carbon storage. Carbon stored in soil in the form of soil organic matter is the largest stock of carbon in many terrestrial ecosystems, containing more carbon than both the atmosphere and terrestrial plants (FAO 2015b; Lal 2009). Managing soils to increase soil organic carbon sequestration helps to prevent the release of carbon into the atmosphere (FAO 2015b).

2.1.3. How does unsustainable consumption affect soil health?

As global consumption continues to increase, implementation of intensive agricultural practices also increases to meet consumer needs.

Intensive agricultural practices lead to reduced organic matter and microorganism biodiversity in soil, and therefore have negative impacts on soil health. Monoculture crop production can result in soil degradation and depletion of nutrients necessary for plant growth, and therefore crop production (Jarecki *et al*. 2018).

Long-term use of heavy machinery and management practices such as tillage can cause soil compaction (Lehmann *et al*. 2020). Compaction results in decreased soil permeability and porosity, which affects crop growth, as roots are less able to penetrate the soil which in turn reduces nutrient and water uptake. Soil compaction also decreases water intake and increases surface runoff, which contributes to soil erosion and nutrient runoff, and reduces the functioning of soil in flood management and water filtration (Zalidis *et al*. 2002; Udeigwe *et al*. 2015).

A consequence of the increase in intensive agricultural practices has been the overuse of fertiliser. Between 1961 and 2002, global production of mineral nitrogen fertilisers increased by approximately 350% (FAO 2011b). While the impact of fertiliser use on crop production has been significant – it is estimated that 40% of the food production increase between 1970 and 2010 is due to mineral fertiliser use (FAO 2011b) – the detrimental environmental impacts are also significant. Use of mineral fertilisers and manure increases the levels of nitrogen and phosphorus in the soil, which promotes plant growth, but can also impact other ecosystem services such as water quality; when the quantity of fertilisers used is higher than that which the soil is able to retain, leaching of nitrates and phosphates into surface and groundwater can occur (Zalidis *et al*. 2002; Udeigwe *et al*. 2015). Pollution of waterways from fertiliser leaching is known to cause eutrophication and algal blooms, which impact drinking water as well as freshwater ecosystems (Lehmann *et al*. 2020). The issue of fertiliser overapplication is significant. A study by Miao, Stewart and Zhang (2011) found that in intensively farmed regions, nitrogen uptake in rice, wheat and maize was between 26.1% and 28.3%, and less than 20% in vegetable crops and fruit trees. Eutrophication due to agricultural fertiliser use is also widespread in Europe; a report on the 2008 European Database on Spatially Specific Critical Loads and Dynamic Modelling Parameters calculated that in 2000, approximately 77% of ecosystems within EU countries were at risk of eutrophication (Hettelingh *et al.* 2009). While mineral fertilisers enhance crop yields, inefficient application is unsustainable.

Other soil contaminants associated with intensive agriculture include heavy metals, pesticides, radioactivity, pathogens, and parasites, all of which have ecological and human health impacts. When present in agricultural soil, contaminants can accumulate in crops and livestock and are ingested by consumers (Udeigwe *et al*. 2015; Lehmann *et al*. 2020). Heavy metals are naturally occurring in ecosystems, and some metals such as copper and iron are required for plant growth. However, agricultural activities, along with other activities such as mining and industrial processes, can increase the amounts of heavy metals found in soil, causing contamination. Contamination of soil with toxic heavy metals such as lead, cadmium, mercury, and arsenic can reduce plant growth, as the metal ions taken up into plants disrupt enzyme activity, resulting in reduced growth, damaged roots, reduced levels of photosynthesis, and more. Application of pesticides, in particular insecticides, can impact the composition of the soil biome, affecting the abundance and lifecycles of microbes, springtails and earthworms (FAO 2015b).

As well as increasing the intensity of existing land, higher levels of consumption are leading to expanding areas of land required for production, and therefore habitat conversion. For example, deforestation for lumber production and expanding agriculture reduces the root structure in the soil, decreasing protection from soil erosion (Fahad *et al.* 2022).

Another form of habitat destruction often associated with agricultural expansion is the draining of wetlands. Wetland soils contain high levels of organic matter and nutrients due to the accumulation of plant material over time. When wetlands are drained, the increase in oxygen available to previously submerged soils impacts the chemical processes occurring in the soils, increasing the decomposition of soil organic matter, resulting in sequestered carbon being emitted into the atmosphere (Wright 2019). In addition to the loss of wetlands as carbon sinks, drained wetland soils may not be particularly fertile or productive for arable farming. Soils commonly subside after drainage, and water loss can cause soil compaction and increase soil hydrophobicity (Wright 2019). This decreased permeability reduces the ability of the soil to hold water, which in turn increases surface run off. Increased oxidation and decomposition of organic matter also increases nutrient release. While these nutrients may be taken up by crops planted in the area, with increased surface run off this can cause leaching and eutrophication (Wright 2019).

If current levels and patterns of consumption continue, it is predicted that soil health will continue to decline, undermining resource security (FAO 2015b). We need sustainable solutions to maintain soil health while supporting consumption, and ways to measure the impacts of consumption to better understand and protect resource security.

2.1.4. What solutions are being developed to help ensure that consumer needs can be met whilst maintaining soil health?

2.1.4.1. Byproduct recycling as part of a circular economy

Byproduct recycling is the reuse of materials used or created in the production of commodities, that are not a part of the consumable product and would otherwise go to waste. Byproduct recycling is key to reducing the amount of waste created during commodity production that would otherwise go to landfill or be incinerated. A common and well-known type of byproduct recycling is the use of livestock manure as fertiliser, but this is just one waste product that can be put back into the production process.

Another type of byproduct recycling is composting. Composting organic waste reduces the need for chemical fertiliser use by increasing the organic matter content of soil (Lehmann *et al*. 2020; Bekchanov & Mirzabaev 2018). In an experiment spanning 6 years, farm compost was applied to a crop rotation and a range of soil properties were measured. They found that organic carbon and nitrogen content increased significantly, as well as earthworm and nematode presence and microbial biomass. Crop yields also increased in the areas where farm compost was applied. Another study investigated the impacts of composting on soil health and waste pollution in Sri Lanka. The authors estimate that implementing widespread composting could reduce the costs of waste management and fertiliser use in Sri Lanka by US$191 million, and that an established compost trade between provinces could reduce costs by US$357 million (Bekchanov & Mirzabaev 2018).

Waste sheep wool can also be used as a fertiliser (Lal *et al.* 2020). Waste wool contains high levels of carbon and nitrogen (50% and 14.6% respectively), as well as small amounts of other elements including sulphur, iron, and zinc, all of which are important nutrients for plant growth, and the slow rate of decomposition of wool leads to the release of these nutrients over a long period of time, acting as a slow-release fertiliser (Lal *et al.* 2020). Wool has been used as an organic fertiliser alternative, and multiple studies have found it to improve both soil health and crop yields (Lal *et al.* 2020). In a study comparing the use of waste wool as a fertiliser with sheep manure and other crop residues, it was found to improve soil water holding capacity, neutralise soil pH, and increased soil fertility and levels of organic carbon, nitrogen and phosphorus (Lal *et al.* 2020).

Sugarcane is a major global crop, grown in over 100 countries, using almost 27 million hectares of land (Dotaniya *et al.* 2016). Sugarcane requires a high level of soil nutrient content to grow, namely nitrogen, potassium and phosphorus. This means that large amounts of fertiliser are typically used to enhance yields. Use of high levels of chemical fertilisers has detrimental impacts on soil health and other ecosystem services, as discussed above. In India and Pakistan, use of sugarcane byproducts as replacements for industrial fertilisers is becoming a commoner practice. Two byproducts are press mud and bagasse, both of which have significant storage and waste management requirements. Press mud and bagasse can be recycled and used as fertiliser, enhancing soil health, and promoting root growth and increased sugarcane yield. Press mud contains nutrients that are good for both plant growth and for soil microbes and has a high organic carbon content (21%). As well as increasing the organic matter and nutrient content of soil, it has also been found to improve porosity, aeration and water holding capacity (Chatta *et al.* 2019). This makes it a good fertiliser replacement. Use of press mud on arable land is increasingly common in India and Pakistan, due to the positive effects on soil health and sugarcane crop growth and yields (Dotaniya *et al.* 2016). The study looking at the use of press mud cake to fertilise wheat crop in Pakistan found that using a combination of mineral fertiliser and press mud resulted in the optimal wheat growth and yield, despite the total nutrient content being lower than when applying solely mineral fertiliser (Chatta *et al.* 2019).

It is worth noting, however, that while waste products provide a more readily available and sustainable alternative to chemical fertilisers, they can be an unpredictable source of nutrients, and the content of key elements will vary year to year (Siddiqui *et al.* 2008). In addition, even the application of recycled sources of nitrogen and phosphorus can lead to a surplus accumulating in soils and groundwater, leading to contamination, leaching, and eutrophication of bodies of water (Siddiqui *et al.* 2008). Careful calculation of the levels of nutrients to add to agricultural land is important, but with waste products containing unpredictable levels of nutrients this may be more difficult.

2.1.4.2. Plant growth-promoting microorganisms

Rhizobacteria are a group of bacteria that live in soil, in and around root systems. Plant growth-promoting rhizobacteria (PGPR) are a particular group of rhizobacteria that have a positive impact on plant growth (Parewa *et al.* 2018). One of the ways in which PGPR enhance plant growth is by enhancing the uptake of soil nutrients. Use of PGPR in crop management could reduce the need for industrial fertiliser application and therefore improve soil health, through the enhancement of nutrient uptake.

Mycorrhizal fungi are found in and around plant root systems in soil and form symbiotic relationships with plants through their roots. Arbuscular mycorrhizae (AM) are one of the most widespread types of mycorrhizal fungi, forming associations with upwards of 80% of all species of vascular plant (Siddiqui *et al.* 2008). AM fungi exchange nutrients with their plant hosts, with the fungi taking in carbon from the plants and facilitating the uptake of minerals such as nitrogen and phosphorus into the plants (Bücking *et al.* 2015). Inoculating crop plants with AM has been found to be particularly effective in improving the yield of crops grown in low-phosphorus soils. The presence of AM on plant roots effectively increases the roots' surface area, increasing access to soil nutrients and water, which can improve plant growth. This increase in nutrient uptake can reduce the need for application of mineral fertilisers. Additionally, AM occur all around the world, in a wide variety of climatic and environmental conditions, making them applicable to a range of crops across geographic regions (Siddiqui *et al.* 2008).

Rhizobacteria and mycorrhizae interact in ways that are beneficial for both. Increased plant uptake of phosphorus because of the mycorrhizal symbiote increases the activity of the enzyme in some rhizobacteria responsible for nitrogen fixation, further increasing plant nitrogen uptake, which in turn improves the development of the roots and the mycorrhizae (Bücking *et al.* 2015). Effective management of mycorrhizae and rhizobacteria could not only increase growth and yield, but can also facilitate decreased use of fertilisers, as there will be reduced need for increasing the nutrient content of the soil.

Mycorrhizae can also be used to treat contaminated soils, such as toxic metal pollution (Riaz *et al.* 2021). However, the effectiveness of this depends on the type of AM. AM from non-polluted environments are less tolerant to heavy metals than AM from soils polluted by heavy metals, so choice of specific AM isolate is essential when using mycorrhizae to treat contaminated soils. AM can also increase the tolerance of crop plants to stressful conditions, such as drought and salinisation, partly by increasing nutrient and water uptake, but also by improving soil quality (Wu & Zou, 2017; Begum *et al.* 2019). Arbuscular mycorrhizae provide some protection for plants against soil pathogens and parasites, reducing damage to plants from organisms such as nematodes and other fungi (Veresegolou & Rillig 2011). As such, crops with established symbiotic relationships to AM may have reduced need for pesticide application.

Ectomycorrhizal (ECM) fungi are another widespread type of mycorrhizae and are important in forestry (Siddiqui *et al.* 2008). As with AM, ECM form symbiotic relationships with trees through their roots, which increases root surface area and nutrient and water uptake. ECM capture and mobilise soil nutrients, such as nitrogen, sulphur, zinc and phosphorus, and in turn receive assimilated carbon from the trees. Tree plantations have been observed to fail to establish in soils lacking ECM (Siddiqui *et al.* 2008). Inoculation of mycorrhizae onto seedlings in forest nurseries is one way of ensuring they are present, and it is possible to establish nurseries of micro-propagated seedlings.

However, positive impacts of mycorrhizae are not universal. In some conditions, nutrient uptake and growth of the fungi has been lower and may be impacted by abiotic factors such as sunlight, precipitation, soil pH, and mineral levels, as well as fungal genetic variation (Siddiqui *et al.* 2008). Similarly, the protective effects of mycorrhizae against plant pathogens also varies between plant species, AM species and environmental conditions, and not all pathogens are protected against (Siddiqui *et al.* 2008). Therefore, mycorrhizae and rhizobacteria cannot be used as a blanket source of crop fertilisation and protection but need to have tailored application that considers plant type, fungi and bacteria type, and environmental conditions.

2.1.4.3. Crop rotation and no-tillage systems

Crop rotation involves planting different crops one after the other in the same place to improve soil health, improve soil nutrients, and address issues such as pests and weeds. Crop rotations have been found to increase crop yields, improve soil health indicators such as soil organic carbon and biomass, reduce incidence of plant-specific pests and diseases, and increase biodiversity (Jarecki *et al.* 2018; Rodale Institute 2024). Plants involved in rotations include alfalfa, winter wheat, legumes (which increase soil nitrogen), clover, mustard, radish, and more (Rodale Institute 2024).

Tillage is the use of machines to agitate the soil in preparation for planting. Tillage disrupts mycorrhizal fungal networks within the soil, affecting the symbiotic relationships between mycorrhizae and plants, reducing the positive contributions to plant growth and soil health detailed above. Tillage has also been found to have negative effects on soil fauna (Kladivko 2001).

The use of management practices such as crop rotation and no-tillage systems could therefore be useful in contributing to production and supporting consumption reduced impacts on soil health as an ecosystem service. For example, a 2021 report details the findings of a study on the impacts of crop rotation and no-tillage system on corn and soybean crops at two test sites (Chahal *et al.* 2021). The crops, which had previously been grown as monocultures, were rotated with cover crops, perennials, and cereals, and these rotations were found to increase soil health indicators by 32% at one test site and by 49% at the other. Corn yields at both sites increased with crop rotation, with 10.4% increase in yield with the addition of red clover to rotations compared to monoculture corn, and an increase of 25% with the addition of alfalfa in comparison with monoculture corn. No-tillage practices produced less conclusive results, with increases in soil CO_2 and NH_3 (indicators of soil microbial activity) only observed at one of the two sites.

2.1.4.4. Agroforestry

Agroforestry is the practice of integrating trees into areas of agricultural crop and livestock production. The aim of agroforestry is to produce agricultural and forestry-related commodities whilst sustaining and diversifying environmental and economic resources (The Woodland Trust 2022; Agroforestry Research Trust, n.d.).

Planting trees on agricultural land has numerous impacts on soil health, such as increasing soil organic matter, increasing nutrient cycling, and improving soil structure. Trees also create a barrier against weather-related soil erosion, and root systems improve water infiltration, which both increases the water holding capacity of the soil and reduces surface runoff (The Woodland Trust 2022). Contour buffer strips are used to reduce erosion on slopes (Agroforestry Research Trust, n.d.).

Soil fauna is important for soil health. Falling leaves and exudates from tree roots are a source of nutrients and energy for microorganisms in and on the soil, as well as providing habitat for insects (Fahad *et al.* 2022).

The benefits of agroforestry on soil health can be seen in practice through the FAO's International Poplar Commission (IPC). Poplars are fast-growing trees, which makes them a good choice both for roundwood plantations and for agri-environmental purposes (He *et al*. 2018). Planting of native poplars through the IPC in Siyang County, China, has reduced flooding and soil erosion, and increased soil biomass from the trees has created more fertile soils, allowing for the cultivation of a wider range of crops, including wheat, maize, and mushrooms (FAO 2015a).

There is currently not much uptake of agroforestry in the UK, occupying an estimated 3.3% of agricultural land (The Woodland Trust 2022). Barriers to more widespread implementation of agroforestry include tenancy restrictions, lack of knowledge of agroforestry among farmers, and lack of specific support for farmers and landowners (Tosh 2021).

When implementing agroforestry-based solutions, it is important to incorporate a diversity of species when planting trees, and to consider species suitability (for example whether they are native, suited to the local ecology/climate, susceptible to disease, or toxic to livestock). Increasing tree cover using agroecology may in certain circumstances be good from a carbon storage and climate resilience perspective.

2.1.5. Conclusion

Overall, soil health provides a good example of a factor that humans are affecting through our consumption patterns, but that we are also dependent on for resource security. Making use of solutions such as by-product recycling, crop rotation, no-tillage systems and agroforestry could help us to reduce these effects.

2.2. Clean air

Clean air is characterised as air that is free from or low in pollutants, relative to the amounts that would cause damage to people and nature. Pollutants include hazardous chemicals, gases and suspended particles, such as sulphur dioxide, nitrogen dioxides, carbon monoxide, heavy metals, ozone, volatile organic compounds, and respirable particulate matter (PM2.5 and PM10) (Kampa & Castanas 2008; JNCC 2023).

2.2.1. Why is clean air important?

According to the World Health Organisation (WHO), 99% of the global population are exposed to air pollution levels greater than the WHO guideline limits (WHO 2024).

The most widely discussed impacts of air pollution are the effects on human health. The Health Effects Institute (2019) estimate that air pollution is the fifth highest risk factor for global mortality. Prolonged inhalation of pollutants is known to have damaging effects on the respiratory and cardiovascular systems (Kampa & Castanas 2008; Zhu & Zeng 2018), with particulate matter exposure being linked to increased risk of stroke, heart failure, bronchitis, and lung cancer (Zhou *et al.* 2020). Both outdoor and indoor air pollution are linked to an estimated 7 million premature deaths each year (WHO 2024).

Air pollution can also cause depositions of pollutants (for example in the case of acid rain or nutrient nitrogen deposition) which affect soil and water quality, harming vegetation and aquatic life, as well as animals relying on those habitats for feeding and breeding.

One study, assessing the net costs and benefits of reducing nitrogen emissions across six ecosystem services, estimated a net benefit of £65 million per year, based on the amount that emissions reduced between 1987 and 2007 (Jones *et al*. 2014). Another, aiming to value the impacts of nitrogen pollution on biodiversity estimated that these declines in emissions had led to benefits of £32.7 million per year (Jones *et al*. 2018).

2.2.2. Why is clean air important for resource security?

Air pollution impacts growth and yields of a range of plants, including agricultural crops (Wahia *et al*. 1995). For example, one study looked at the impacts of both long-lived and short-lived pollutants on wheat and rice crops in India and found that reductions in crop yields were mostly caused by short-lived pollutants (methane, ozone, black carbon, HFCs) (Burney & Ramanathan 2014).

Ozone (O_3) is a major global pollutant and is the most harmful air pollutant to plants (Avnery *et al.* 2011; Liu & Desai 2021). Surface ozone is toxic to plants and reduces photosynthesis by affecting chlorophyll and carbon allocation and alters the susceptibility of plants to different conditions and stresses, leading to reduced growth, quality and yield of crops (Hu *et al*. 2020; Avnery *et al.* 2011). It is estimated that increasing levels of ground-level ozone will cause increased economic and crop losses in the coming years, with a 2011 study predicting yield losses due to ozone for the major crops of wheat, soybean and maize of up to 26% in 2030 (Avnery *et al.* 2011). The authors acknowledge that their predictions may be conservative, being based on observational data. Indeed, another study published in 2020, studying the effects of ozone on wheat in the North China Plain, concluded that wheat yield losses due to ozone in 2014–2017 were 18.5–30.8%, with economic losses of US$12.4 million in 2017 alone (Hu *et al*. 2020). In the UK, ozone pollution reduces yields of wheat, oilseed rape and potato by approximately 5% each year (Defra 2019).

Ozone levels are expected to rise most rapidly in developing countries due to industrialisation, putting more pressure on nations that are already impacted the most by resource insecurity (Avnery *et al.* 2011). In addition, depositions of sulphur, nitrogen and other pollutants can cause issues such as eutrophication and acidification, which can have negative impacts on crop and tree growth and affect resource security of commodities such as fish in freshwater ecosystems (FAO 2015b).

Nutrient nitrogen deposition, ammonia concentrations, sulphur dioxide and nitrogen dioxides are other key air pollutants that are produced from agricultural or industrial processes. In 2020, acid deposition exceeded critical load in 45% of sensitive terrestrial habitats, and nitrogen deposition exceeded critical load in 86% of sensitive habitats (UK Biodiversity Indicator B5a).

2.2.3. How does overconsumption affect clean air?

Commodity production can lead to emissions of ammonia, methane, nitrogen oxides, carbon monoxide and volatile organic compounds (compounds which can react together in the troposphere, causing the production of ozone or acidification and fertilising effects), which leads to increased levels of ground-level ozone, which impacts crops as detailed above, as well as human health and the climate (Hu *et al*. 2020; Avnery *et al.* 2011).

Emissions related to the energy required for agriculture and forestry (vehicles, machinery, transport of goods, biomass burning, slash and burn land clearing, etc.) also contribute to air pollution. Resource production and consumption require energy (fuel, electricity), the production of which contributes to air pollution (e.g. power stations releasing byproducts into the atmosphere). An example of this is the energy required for fertiliser production (FAO 2015b; Udeigwe *et al*. 2015).

Large off-road vehicles which are often used in intensive agricultural production systems, such as tractors, use a lot of energy and produce a lot of emissions. The internal combustion engines used in these vehicles emit carbon monoxide, nitrogen oxides, particulate matter (and secondary particulate matter, such as ammonium nitrates and ammonium sulphates) and volatile organic compounds, all of which are hazardous pollutants that can have detrimental impacts on human health, ecosystem health, and agriculture (Gonzalez-de-Soto *et al*. 2016).

Deforestation caused by expanding agricultural land to support demand from consumers results in less carbon sequestration and less absorption or trapping of pollutants from the air. Some trees, such as conifers, also release phenols when cut down. Other kinds of habitat destruction to support production and consumption systems, such as draining of wetlands, similarly reduce environmental protections against air pollution. Changes to ecosystems and landscapes to enable greater resource production can reduce the ability of these systems to filter pollutants from the air.

Intensive farming has a higher concentration of agricultural products and animals, more machinery, fewer non-crop plants and trees, more off-gassing from fertilised fields or emissions from manure and slurry spreading, and more arable monoculture, resulting in higher emissions of methane, ammonia and nitrogen oxides. Higher energy needs also lead to more sulphur dioxide produced by energy generation.

2.2.4. What solutions are people developing to help ensure that consumer needs can be met whilst maintaining clean air?

2.2.4.1. Buying local produce, where appropriate

One simple and direct action that consumers can take themselves is to try and source locally produced products, where appropriate. This would help to reduce emissions of pollutants during transportation. However, it should be noted that this is not a blanket solution – in certain energy intensive production systems, the emissions from the production stage might outweigh the emissions savings from the transport stage. For example, one study found that whilst potatoes, beef and apples led to lower carbon emissions in the UK compared to when imported, that this was not the case for tomatoes, strawberry, poultry and lamb (even when considering carbon emitted during transport), when comparing to a selection of alternative producer countries (Webb *et al*. 2013).

2.2.4.2. Clean energy production systems

Transport is not the only stage of the supply chain at which pollutants are emitted. Ensuring that energy required at the point of production, for example to drive tractors and operate farm machinery, is kept as low and as green as possible, is another solution that could contribute towards reducing the pollutants emitted by the consumption system. For example, one study looking at a hybrid tractor, which had a usual combustion engine with an electrical energy system and found that in their best case scenario emissions were reduced by almost 50% (Gonzalez-de-Soto *et al*. 2016).

2.2.4.3. Agri-environment management practices

Sourcing from production systems undertaking agri-environment management practices such as tree planting could be another way to reduce pollutant emissions related to the consumption system. This is because trees and other vegetation can reduce the levels of particulate matter in the atmosphere as particles accumulate on leaves (Yan *et al*. 2018; McDonald *et al.* 2007). Other relevant management practices include those that reduce ammonia emissions, such as storing and covering organic manures (Defra 2024).

2.2.4.4. Deforestation-free commitments in supply chains

For the same reasons as in the previous section (the importance of trees and vegetation in reducing pollutants in the atmosphere), ensuring that commodities are sourced from supply-chains with zero deforestation commitments could also contribute to reducing the impacts of consumption on this important ecosystem service. Many companies are implementing deforestation-free commitments, and some countries are beginning to enforce legislation related to this, such as the EU's and the UK's upcoming Due Diligence legislation.

2.2.4.5. Reducing waste

As well as meaning that any emissions released during production and transport are not going towards a used final product, wasting resources generates emissions through disposal routes (e.g. NOx through incineration or methane and ammonia in landfill from food stuffs). Reducing waste, for example through improved storage facilities and buying patterns, as well as circular economy strategies such as composting food waste for use in vegetable patches, is therefore also an important solution.

2.2.4.6. Wider solutions

As well as solutions directly relating to agricultural production and consumption systems, a range of other solutions to reduce air pollution could be undertaken which would improve resource security. This could include policies on reducing air pollution (e.g. clean air zones), switching to less polluting and more sustainable energy sources, and urban tree planting (Liu *et al*. 2016).

2.2.5. Conclusions

Overall, clean air is another clear illustration of an ecosystem service that our consumption is impacting, but that it also relies on. Reducing the amount of fossil fuel-based energy required to support consumption and ensuring to support solutions that encourage the maintenance or planting of trees and vegetation are examples of ways we can help to reduce these impacts.

2.3. Freshwater supply

Having sufficient fresh, clean water is vital for human life, industry and biodiversity. As we simultaneously tackle demands from rising populations, wealth and climate change, water use has, and is set to continue, to increase. Therefore, understanding our impact on both the quantity and the quality of water is necessary to maintain a sustainable supply.

2.3.1. Why is freshwater supply important?

Water is essential for all living processes and beings. However, its supply is finite. Most fundamentally, all living things – including humans and their livestock – rely on access to fresh, clean drinking water. The quality of this water has one of the greatest effects on human health (Li & Wu, 2019). Despite this, more than a billion people lack reliable and safe water supplies (Gleick 2002). Water is also important for industrial processes, such as in cooling systems. These processes can account for 10% of a country's freshwater use (Joseph *et al*. 2019) and a shortage of water can result in factory and plant closures. Globally, the demand for domestic and industrial water used has increased significantly over the last century as populations and prosperity has, and is set to continue, to increase (Flörke *et al*. 2013). Water is also important for mental health and recreation. There is a growing body of evidence that water insecurity is an important driver of poor mental health (Wutich *et al*. 2020) and that people are more likely to enjoy recreational activities in local blue spaces, such as swimming and fishing, if water quality is high (Vesterinen *et al*. 2010). The public's appreciation of blue spaces is determined by both the quality and amount of water present, making both key aspects to freshwater supply (Crase & Gillespie 2008). Poor freshwater supply and quality is also detrimental to ecosystems that depend on bodies of water. Species that wholly or partially rely on bodies of freshwater suffer when wetlands are drained and freshwater supply is limited, resulting in community shifts (Thibodeau & Nickerson 1985), reduced abundances or local extinctions (Elo *et al*. 2015). Finally, freshwater supply is important for agricultural processes. Approximately 70% of global freshwater withdrawals are currently used for agriculture, primarily for irrigation (FAO 2019). Thus, freshwater supply is vital for many aspects of human life and ecological systems, ultimately affecting industrial processes, mental and physical health, and drinking water and food security, making its sustained supply invaluable to society.

2.3.2. Why is freshwater supply important for resource security?

Freshwater supply is vital for sustaining agriculture. Steduto *et al*. (2007) and Perry *et al*. (2009) show that the yield of most field crops is a near-linear function of crop water consumption. Ensuring that that there is sufficient water for the additional crops needed to feed a global population of 10 billion therefore is one of the great challenges of this century (Easterling 2007). The amount of water required by crops varies markedly by crop type. For example, in 2018, the United Kingdom used 1.44x10^9 m^3 of water for wheat, but only 1.61 x 10^8 m^3 for potatoes (Commodity Footprint Dashboard). A lack of water in agriculture causes drought stress in crops which is one of the most limiting factors in agriculture (Seleiman *et al*. 2021). Water makes up 80–95% of plants' body biomass, thus a reduced freshwater supply in the rhizosphere has significant effects on the plants' physiology, morphology and biochemistry, reducing their nutrient uptake, growth and ultimately yield (Battaglia *et al*. 2018; Brodersen *et al*. 2019; Elemike *et al*. 2019; Iqbal *et al*. 2020). The severity of the impacts of limited freshwater supply on crops varies depending on a mix of factors, including drought severity, previous drought experience, other stresses that are present, the crop species, and the age and growth phase of the crop when it experiences drought (Hafez *et al*. 2015; Gray *et al*. 2016; Humplík *et al*. 2017). In all cases, a limited freshwater supply will affect the crops to some extent by invoking stress responses and reducing overall yields with consequences for food security.

Different crops are sensitive to reduced water supplies. For example, Ray *et al*. (2018) showed that winter wheat and corn were more sensitive to the effects of drought than cotton and sorghum whilst, in the Mississippi region, rice received nearly three times as much irrigation as corn and soybean (Massey *et al*. 2017). Within vegetable crops, root crops are relatively tolerant of drought stress, whilst leafy crops are particularly vulnerable. Different cultivars of a species may also have different drought tolerances; the field bean Gobo and field pea Solara are more drought resistant than field bean Victor and field pea Bareness (Grzesiak *et al*. 1997). These differences are due to plant adaptations for drought stress, which vary from the molecular to plant levels (Xoconostle-Cazares *et al*. 2010). Thus, increasing limitations to freshwater supply will affect crops differently, with increased crop failures in some species and cultivars compared to others.

Crops are affected by the quality, as well as the quantity of water supplied to them. If agriculture uses contaminated or otherwise poor-quality water, the soil quality significantly changes, increasing plants' uptake of synthetic nanomaterials (Malakar *et al*. 2019) and trace elements (Hass *et al*. 2010) and reducing overall crop yield (Arshad & Shakoor 2017). Additionally, if wastewater that has not been properly processed is used for irrigation, it may act as a source of pathogens with potentially deleterious health effects if the crops are consumed (Allende & Monaghan 2015). These consequences are particularly of concern in developing countries where the use of contaminated and poor-quality water is high, with approximately 80–90% of wastewater remaining untreated (WWAP 2017). Therefore, it is important that agriculture has access to not only plentiful, but clean water to maintain high yields of safe crops and prevent exacerbation of food security issues.

2.3.3. How does overconsumption affect freshwater supply?

Farming practices are responsible for approximately 70% of global freshwater withdrawals (FAO 2019). As described above, the amount of water required varies dramatically by crop and region (and the amount of water available also varies significantly by region), but water demands can be extremely high; it takes 1–3 tonnes of water to produce just 1 kg of rice (FAO 2019). As we race to feed a growing population with increased wealth and consumption, irrigation use is growing to maintain or increase crop yields in areas that are becoming drier and expand agriculture into less-suitable regions. This water can come from renewable rainfed sources or from non-renewable groundwater reserves. An increased reliance on irrigation affects the sustainability of water supplies by changing waterway hydrology, overexploiting non-renewable water sources, and polluting water bodies.

Although using rainfed water reserves for crop irrigation is generally renewable, the increased rates of water removal has had some deleterious effects. Excessive water withdrawal causes increased periods of dried riverbeds and river diversions to feed crops. These changes alter the hydrology and ecology of rivers and wetlands, reshaping biotic communities and removing vital water supplies for human use. More than half of global river systems now experience intermittent drying, which is caused by high irrigation use and is exacerbated by climate change (Datry *et al*. 2007). This drying may also be linked to salinization. Countries can be water stressed if they are withdrawing more than 20% of their renewable water supplies each year, meaning that by 1998 23% of countries were already water stressed, and 20 countries were in a critical state of using 40% of their renewable water for withdrawals (FAO 2019). Thus, even renewable sources of water can be overexploited and cause freshwater supply concerns when water is withdrawn at too high of a rate and natural waterways are modified to meet human needs for overconsumption in the short term.

The use of non-renewable water has had serious effects on current water supplies worldwide. Groundwater aquifers are potentially very large bodies of fossilised water stored under the ground for thousands of years. The rate of recharge is extremely slow and so the water is effectively non-renewable, meaning that their freshwater supply can be overexploited and dried up. In the mid-1980s, Saudi Arabia underwent a large agricultural expansion using fossilised water from the Pleistocene to irrigate crops in the barren Wadi As-Sirhan basin. This area receives just 100–200 millimetres of rainfall a year, meaning that aquifers do not recharge and are thus non-renewable (USGS 2016). Despite this, up to 2.1×10^{10} m^3 of water have been pumped to the surface for agricultural use each year (Halverson 2015), causing a collapse of the agricultural industry as aquifers dry up. Depletion of these groundwater reserves can be due to overexploitation in a limited area, with consequences on freshwater supply for much larger areas; approximately a third of the water depletion occurring in the high plains and central basin of the US occurred in just 4% of the land area (Scanlon *et al*. 2012). As a result of this, it is predicted that over the next 30 years, 35% of the land area will not be able to sustain irrigation from this water reserve

(Scanlon *et al*. 2012). As 60% of irrigation comes from this fossilised water, its overexploitation has significant implications on freshwater supply to a much larger area than that where the overexploitation is occurring (Scanlon *et al*. 2012). These patterns of overexploiting groundwater supplies have been seen around the world, leaving many areas in severe water crises (e.g. Al-Zyoud *et al*. 2015; Chatterjee *et al*. 2018). Overuse of these water sources in arid areas leaves agriculture with few alternatives and thus vastly reduced crop yields or even results in a collapse of the industry, having significant effects for food security needs.

As well as affecting the quantity of water, agriculture has a large effect on the quality of the wider freshwater supply. Agriculture is a significant contributor to pollution of waterways, responsible for approximately 60% of nitrate, 25% of phosphate, and 75% of sediment that enters rivers in England and Wales (Defra 2019). This is due to large amounts of nutrients being added to farmlands as fertiliser, a large proportion of which washes off during rain events into the surrounding waterways (Chakraborty *et al*. 2017). An excess of nutrients in freshwater bodies degrades water quality and causes detrimental shifts in water ecology (Kahiluoto *et al*. 2021) by promoting harmful algal blooms and anoxia (Carpenter *et al*. 1998). Agriculture can also result in contamination of freshwater supply by chemicals from pesticides and herbicides which similarly degrade water used for human and ecological purposes (Hayhow *et al*. 2019). Additionally, when excess irrigation is used, there is a threat that this contaminated water may leach into otherwise clean groundwater sources, exacerbating the issue (Nolan & Weber 2015). The implications of pollution on making the freshwater supply unsafe to use can be large and widespread, making it important that this aspect of freshwater supply is not overlooked.

Even in areas which are not typically drought prone, such as the United Kingdom, these factors are important. To understand the full extent of the environmental impacts of consumption within a country, it is important to consider the effects of commodities that are consumed by the country but produced overseas. In a 2016 study by de Ruiter *et al*. it was found that 70% of the cropland associated with the food and feed consumed in the UK was located overseas. Therefore, consumption in the UK directly contributes towards the resource impacts in other, potentially more water stressed, countries. In 2021, for example, 2.23×10^9 m^3 and 1.99×10^9 m^3 of the blue water use associated with UK consumption came from commodities produced in Pakistan and India, respectively (Commodity Footprint Dashboard). In comparison, 6.77×10^7 m^3 of the blue water use associated with UK consumption came from within the UK itself (Commodity Footprint Dashboard). India is now expected to experience a water demand supply gap of 7.5×10^{11} m^3. in the agricultural industry by 2030 (Aayog 2019). Export of products accounts for a significant amount of this, with the export of Basmati rice in 2014–15 costing India 1×10^{10} m^3 of water alone (Aayog 2019). These complexities and ‘offshoring’ of environmental impacts should not be forgotten when evaluating the impact of overconsumption within a country, as this would lead to significant understatements of the true effect of agriculture on freshwater supply.

2.3.4. What solutions are being developed?

There has been a growing focus on developing solutions for agricultural demand on water. Broadly, these solutions can be discussed in the following categories: improved irrigation, farm practices and crop choice; nature-based solutions; and improved infrastructure and governance.

2.3.4.1. Improved Irrigation, Farming Practices and Crop Choice

Engineering irrigation methods that are more water efficient could result in reduced water use and limit agriculture’s stress on freshwater supply. A predicted 60% of the additional food that will be needed to feed the growing population will come from irrigated crops

(Plusquellec 2002); thus, it is important that water is used as efficiently as possible in irrigation to prevent wasting water that is not taken up by the plants. Using well managed sprinkler irrigation in place of surface irrigation in the Ebro River basin, Spain can improve the irrigation efficiency from 53% in areas with poor soil quality and 79% in areas with good soil quality to 94% (Causapé *et al*. 2006). However, the general effectiveness of water conserving irrigation methods have been debated, with arguments that irrigation should not aim to conserve water but to maximise farmers' income and productivity (Pérez-Blanco *et al*. 2020). Using more efficient irrigation methods may limit return flows and aquifer recharges, in some cases increasing freshwater supply stress (Ward & Pulido-Velazquez, 2008). Additionally, when water is saved, this 'saved' water is often used to expand agriculture meaning that there is no overall reduction in water use (Molle *et al*. 2018). Thus, there is potential to use more efficient irrigation methods to reduce water use and lessen the strain on freshwater supply. However, its effectiveness varies and may be overemphasised. It is important that the best irrigation method is considered on a case-by-case basis.

Proper agricultural techniques can also reduce the industry's impact on the freshwater supply crisis. Farming practices such as tillage, fallow fields and draining removes soil moisture. Moving away from these practices will therefore increase the retention of soil moisture and prevent soils drying out – keeping a water resource for the crops and reducing the requirement for additional irrigation. Mulching also prevents water evaporation and improves plants' water use efficiency. This means that comparable yields can be attained with reduced irrigation but with mulching as when there is conventional irrigation but no mulching, whilst also potentially having benefits of recycling plant nutrients (Ramakrishna *et al*. 2006; Chakraborty *et al*. 2008). Additionally, it is important that farmers grow appropriate crop breeds and cultivars for their region. In regions that typically receive a lot of rainfall, growing water demanding crops such as wheat will create high yields, whereas drought sensitive crops may have a higher metabolic demand to maintain drought tolerance, at the expense of its yield. However, growing the same crop in arid places leads to a rapid loss of freshwater supply, as described above in the arid Wadi As-Sirhan basin which led to diminished ground water supplies. There are thus a range of choices and simple changes that farmers can make to conserve water and limit the amount of water they need, and thus the effect that they have on the wider freshwater supply.

Riparian buffer strips have the potential to lessen pollution of waterways. Buffer strips between farmland and waterways reduce polluted water running off farms directly into freshwater systems and polluting water sources. On top of this, buffer strips have economic, societal and carbon-sequestration co-benefits (Uggeldahl & Olsen 2019; Dlamini *et al*. 2022). Although buffer strips have grown in popularity as a nature-based way to tackle freshwater pollution, an extensive review of the literature shows that their benefit is highly variable, and the literature is potentially not representative of how farmers will implement them (Hickey & Doran 2004). Hickey and Doran (2004) showed that most studies investigated buffer strips that are at least 30 meters wide and argued that it is important to study the impacts of buffer strips closer to the widths that farmers are likely to give up, in the region of 1–10 metres. The vegetation composition can also be important in affecting the effectiveness of these strips; Dunn *et al*. (2022) showed that willow buffer strips led to a greater reduction in runoff, compared to having no buffer, than other vegetation communities including grass. These experiments followed the effect of buffer strips for the first three years of establishment; the effects of more established vegetation communities may differ. Hence, encouraging farmers to implement riparian buffer strips can lessen the pollution pressures that freshwater bodies face, however, it is important that they are implemented correctly, with the optimal width and vegetation communities to see the benefits.

One way that people are trying to address this problem is through breeding or engineering increased drought tolerance into crops so that they require less water and are less affected by freshwater supply issues while still allowing farmers to grow crops that are in demand

(Tao *et al*. 2017). Plants are very plastic, allowing many desirable traits to be genetically chosen and bred for. Tao *et al*. (2017) used an ensemble of eight simulation models to investigate the response of different barley ideotypes to increased drought climates. The results identified several genotypes that are more resistant to modelled future climate scenarios. Knowing which ideotypes are best suited to drought conditions allows targeted breeding to achieve these desired traits. Additionally, advances in genomics and phenomics have allowed the discovery of drought resistant genes in crops' wild relatives and the transfer of these genes into crop strains to increase their yields in drought scenarios (Rosero *et al*. 2020). An example of using interspecific gene transfer to create a desired trait is in rice where *Oryza glaberrima* was used in backcrossing to increase *Oryza sativa*'s drought resistance (Ndjiondjop *et al*. 2010). These innovative techniques allow farmers to continue growing crops that are high in demand but can sustain a higher yield under drought condition, limiting the water use and restrictions on crop variety.

2.3.4.2. Habitat restoration

Restoration of natural environments and processes, such as wetland areas can also improve freshwater supply by preventing the loss of fresh, clean water through pollution. When fresh rainwater runs over agricultural fields, it causes the runoff of pollutants and soil particles into rivers and streams. If these rivers and streams are fast moving along their whole length, the suspended particles get washed into lakes and reservoirs, thus polluting large bodies of water and making them unsuitable supplies of water. However, if water stands still for long periods of time in wetlands, water is given a natural way to be cleaned – soil particles have time to settle and sediment out and pollutants can be removed through denitrification by microbes and absorption by vegetation, protecting downstream waterways. Hansen *et al*. (2018) show that wetlands can be five times as powerful in reducing nitrate concentrations in rivers than land-based activities. Smaller wetlands may play a disproportionately large role in processing and cleaning water; Cheng and Basu (2017) showed that as much as 50% of nitrogen removal happens in wetlands that are 102.5 m^2 or smaller in their study. Additionally, wetlands that are geographically isolated and not directly connected to water systems may also have a large role in water processing, due to water standing still in them for longer periods of time (Martínez-Espinosa *et al*. 2022). Cheng *et al*. (2020) showed that a targeted increase of wetlands by 10% could reduce the nitrogen loads in the Gulf of Mexico by as much as 40%. Although there is ample evidence that wetlands reduce water pollution, there is limited empirical evidence of this at a watershed-scale, potentially due to a range of land-cover types masking the effect of a single variable (Hansen 2018). Thus, it is important to protect and restore wetlands to provide a natural solution to preventing the pollution of water supplies, as well as providing co-benefits to carbon sequestration and biodiversity (Thorslund *et al*. 2017). Effort should be paid to small, disconnected wetlands to bring the biggest benefits.

2.3.4.3. Improved infrastructure and governance

Grey water can be used to supplement water sources, increasing freshwater supply. Grey water is water that has already been used before being treated and reused. It may therefore include some impurities. Grey water does not need to be excessively treated to remove all these impurities as a healthy soil system will filter out many harmful impurities. Some of the impurities in grey water may even be of benefit by providing additional nutrients to the field, both increasing crop yield and preventing them from entering waterways (Soil Science Society of America 2022). There is evidence that grey water can lead to high yields of crops (Salukazana *et al*. 2005) with no significant increase in contaminants in the crop compared to if it were irrigated with unused water (Finley *et al*. 2009). However, overcoming public opinion of using wastewater to irrigate crops can be a significant challenge, although has been overcome through outreach and education (Sheikh *et al*. 2018). Once public opinion is won over and infrastructure is established to allow the collection, treatment and redistribution of grey water, it unlocks a large reservoir of water that can be used without affecting blue water supply.

Ambitious engineering may elevate freshwater supply issues by moving excess surface water to areas that have depleted their source of groundwater. To minimise further depletion of aquifers, the Arkansas Water Plan will collect excess water from the Arkansas and White Rivers and divert and deliver it to water-scarce farms and for storage in on-site reservoirs-tailwater recovery systems for use in irrigation. Modelling work suggests that the two diversions planned will reach 73 and 100% of the water needs which are currently satisfied through groundwater exploitation (Clark & Hart 2011). Although potentially beneficial, the redistribution of costs and benefits of projects like this may create monopolies on freshwater supply and leave some communities marginalised (Zacatecas *et al*. 2018). Therefore, although they appear promising, there must be careful consideration of the potential social, as well as financial and environmental effects before implementation.

Freshwater supply strains can be lessened through efficient and inclusive governance and policy of water use. The 2000 Global Framework for Action (Global Water Partnership 2000) highlighted how the issues surrounding freshwater supply is usually down to poor governance and that improving this should be a high priority. Multiple case studies indicate that many states have failed in their attempts to regulate groundwater for many reasons including a lack of expertise, resources and willingness to face potential political consequences of imposing restrictions onto rural communities (Rogers & Hall 2003). Considering the complexities of water use in society, it is vital that water is allocated fairly and sustainably with stakeholder involvement to ensure the provision of basic human rights and societal co-operation (Rogers & Hall 2003).

2.3.5. Conclusion

In summary, having a sustainable fresh, clean water supply is vitally important to many key aspects of human life, industry, and biodiversity. Its scarcity and poor-quality are major limitations to agriculture and thus food security by causing metabolic and physiological effects in crops, ultimately reducing their yields. The degree to which water scarcity affects crops varies significantly based on environmental factors as well as the crop species, cultivar and life stage. Overconsumption creates a larger demand on agriculture and pressure to expand where food is grown and the yields of crops, thus requiring a substantial amount of water for irrigation. To meet these demands, excessive water is withdrawn from places that cannot sustain it and waterways are altered and polluted, creating freshwater supply crises around the world. There are several possible solutions being developed to limit the effect of agriculture and consumption on freshwater supply. Improved irrigation efficiency is a popular, often-cited way to reduce water use, however, it comes with some caveats and its tangible difference is variable. Other changes to agricultural systems such as mulching, buffer strips and growing the correct crops – which can be aided by crop breeding for improved drought tolerance – are simple yet effective ways to limit the water demands of agriculture. Restoration of wetlands have been shown to make a significant difference to reducing the pollution of waterways, whilst also having many co-benefits to society, carbon-sequestration and biodiversity. Although it has previously faced public concern, the use of grey water has been proven to be safe and a vital way to increase the water available for irrigation. More ambitious projects may move water from areas with excess water to areas with a shortage, however this must be done carefully so as not to marginalize communities. Each of these solutions have many benefits that, if implemented correctly and carefully, can make a significant difference to the water demands and usage in agriculture. However, these solutions need to be underpinned by widespread changes in governance and policy.

3. Conclusions

This report illustrates just some of the inextricable links between consumption and resource security, highlighting why anyone with an interest in resource security should also have an interest in improving the sustainability of consumption. It demonstrates a need for greater interaction and collaboration between those working in these two important areas, which are often dealt with in siloes from each other, despite the many examples of synergies where action taken towards achieving one of these aims will contribute to achieving the other. The evidence provided in this report supports the need to align efforts related to these two agendas.

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