



## RESEARCH ARTICLE

# REVISSED Effects of environmental change on agriculture, nutrition and health: A framework with a focus on fruits and vegetables

## [version 2; referees: 2 approved]

Previously titled: Effects of environmental change on population nutrition and health: A comprehensive framework with a focus on fruits and vegetables

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### Abstract

Environmental changes are likely to affect agricultural production over the next decades. The interactions between environmental change, agricultural yields and crop quality, and the critical pathways to future diets and health outcomes are largely undefined. There are currently no quantitative models to test the impact of multiple environmental changes on nutrition and health outcomes. Using an interdisciplinary approach, we developed a framework to link the multiple interactions between environmental change, agricultural productivity and crop quality, population-level food availability, dietary intake and health outcomes, with a specific focus on fruits and vegetables. The main components of the framework consist of: i) socio-economic and societal factors, ii) environmental change stressors, iii) interventions and policies, iv) food system activities, v) food and nutrition security, and vi) health and well-being outcomes. The framework, based on currently available evidence, provides an overview of the multidimensional and complex interactions with feedback between environmental change, production of fruits and vegetables, diets and health, and forms the analytical basis for future modelling and scenario testing.

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**REVISED Amendments from Version 1**

With the helpful comments of our reviewers we have improved our manuscript. In this updated version we have further clarified and justified our focus on fruits and vegetables and changed the title, introduction and discussion to be consistent with this focus. Furthermore, we expanded the climate change, water quality and water availability sections and added a new section on adaptation and mitigation options.

In Figure 3 “heat stroke” was changed to “heat stress” to better reflect the many gradations of heat impact on producers health and labour productivity.

Furthermore, we adapted the conclusions to point out the various possible applications of the framework.

**See referee reports**

## 1. Introduction

In the next decades, the world population will continue to be confronted with environmental changes that pose increasing challenges to our food systems, health and well-being. These changes – such as climate change, increased ground-level ozone, changes in water availability, carbon dioxide fertilisation, soil degradation, deforestation and land use change – can directly and substantially influence agricultural production. In addition, variability in abundance and spread of pests, pathogens and pollinators – which are also related to environmental change – could form an additional, indirect impact on agriculture. Without successful and widespread implementation of adaptation and mitigation strategies aiming to overcome and/or reverse these environmental changes and their consequences, global food security, health and well-being could be significantly affected (IPCC, 2014).

The scale of impacts of environmental change on food systems and health will depend on a variety of environmental, behavioural and economic factors. Firstly, the magnitude of environmental change will depend on the current level and trends of different environmental stressors and the *mitigation* actions taken by both individual countries and the global society as a whole. For example, several countries are taking individual action to ban nicotinoid pesticides to protect insect pollinators, and the Paris agreement (UN, 2015) has committed the global community to mitigating future climate change. Secondly, the effects of environmental change will depend on the *adaptation* mechanisms developed and adopted. This could include changing agricultural production methods and altering the types of crop grown in certain areas that are less sensitive to certain environmental stressors. Thirdly, markets play a key role in distributing food between production and consumption locations. Globalised agricultural systems may be better placed to respond to changes in environmental conditions for food production, whereas food systems in areas that are strongly dependent on local markets may be more vulnerable to environmental change. Fourthly, food prices have an influence on consumer behaviour – consumption of some foods is much more sensitive to price changes than other foods. Finally, the effect of changing food availability on nutrition and health is likely to differ between countries and population groups, due to both price responsiveness and differences in pre-existing dietary patterns. Therefore, predicting the impacts of environmental changes on diets and health requires a detailed

understanding of the various interactions and feedback loops between numerous actors and processes, as well as information on environmental, social and economic contexts.

Past research has been largely one-directional and limited to single steps in the pathways linking environment, food and health, e.g. concentrating on the impacts of environmental change on crops or the impacts of different diets on health. Research related to the impacts of environmental change on food production has mainly focused on the effects of climate change on staple crops (Challinor *et al.*, 2014; Knox *et al.*, 2012; Porter *et al.*, 2014), whereas the impacts on other foods and impacts from other environmental stressors have been less studied.

A few studies have integrated environmental change, agriculture, markets, nutrition and health (Myers *et al.*, 2017; Smith *et al.*, 2015; Springmann *et al.*, 2016a) focussing mostly on important staple crops and/or meat. These studies have provided better insight into the potential scale of the impact of environmental change on the food system but the nutritionally-important fruit and vegetable food-groups remain largely understudied. With their unique nutritional features, significance for public health and relatively low environmental footprint (Clune *et al.*, 2017), fruits and vegetables have the potential to play a crucial role in healthy population diets of the future.

The association between low consumption of fruits and vegetables and risk of non-communicable diseases (NCDs) including cardiovascular diseases and certain types of cancer (Forouzanfar *et al.*, 2016; Miller *et al.*, 2017) is well established. Furthermore, recent research has shown that even beyond the WHO recommendation of 400 grams a day, higher intake of fruits and vegetables continues to reduce risk of cardiovascular disease, cancer and all-cause mortality (Aune *et al.*, 2017). The consumption of fruits and vegetables per person has been shown to be linked with socioeconomic status: low income countries have lower consumption per capita than high income countries (Miller *et al.*, 2016a), and within countries consumption has been found to be lower in poor neighbourhoods than in wealthier ones (Dubowitz *et al.*, 2008; Pessoa *et al.*, 2015). However, many fruit and vegetable crops prove to be relatively sensitive to environmental changes (Backlund *et al.*, 2008) raising the prospect of reduced fruit and vegetable availability in the future with contingent public health concerns.

We focus in this paper specifically on fruits and vegetables due to their nutritional importance. The aim of this paper is to illustrate a set of pathways that connect environmental changes, production of fruits and vegetables, nutrition and health in a comprehensive framework. The framework provides a basis for the identification and detailed modelling of the key pathways that link environmental change – through agriculture and nutrition – with population health. Even though this paper focuses on fruits and vegetables, we acknowledge the importance of also considering staple crop and livestock production in a comprehensive analysis. Furthermore, the framework considers only pathways that impact health through nutrition, whereas direct health impacts of environmental changes (for example through air pollution, extreme weather events or infectious diseases) are not included in this paper.

## 2. Methods

The framework was constructed based on an extensive literature search, including both peer-reviewed and grey literature. First, the literature was searched for existing frameworks covering several parts of the environmental change, agriculture, nutrition and health nexus. The identified existing frameworks, such as [Ingram \(2011\)](#) and [McMichael \(2003\)](#), informed the selection of main components for the new framework and facilitated hypothesis formulation around impact pathways. Subsequently, evidence was gathered (preferably in the form of systematic reviews) to establish the main pathways linking environmental change (through agriculture) with nutrition and health. This exercise included consultations with experts working in the fields of environment, agriculture, trade, nutrition and health including those studying the temporal trends and impact of specific environmental stressors.

The framework is graphically presented in three stages: i) a schematic overview of the links between environmental change, food systems, nutrition and health (Section 3, [Figure 1](#)); ii) illustration of the interactions between different environmental stressors (Section 4, [Figure 2](#)); and iii) the links between environmental stressors and production of fruits and vegetables (Section 4, [Figure 3](#)). The following section presents an overview of mechanisms through which the most important interactions between environmental change and production of fruits and vegetables operate (Section 4). The potential consequences of environmental change on food security (through changes in the availability of fruits and vegetables), nutrition and health outcomes are discussed in Section 5. The feedback loops from dietary choices to agricultural production and the impacts of agriculture on environmental change are discussed in Section 6 and the adaptation and mitigation strategies in Section 7. It was outside of the scope of this article to provide a systematic review of each interaction in the framework, neither was it possible to quantify and rank each individual stressor in terms of the strength of the evidence. We intend, however, to contribute to this evidence base through our future work.

## 3. Overall framework

Within the overall framework ([Figure 1](#)), we refer to the boxes and the arrows in the figure with the symbols ■ and ▲, respectively, followed by a corresponding letter or number) six main components are distinguished to map the interactions between environmental change, agriculture, and nutrition: i) socio-economic and societal factors (■ A); ii) environmental changes (■ B); iii) interventions and policies (■ C); iv) food system activities (■ D); v) food and nutrition security (■ E); and vi) nutritional health and well-being (■ F) ([Figure 1](#)). The socio-economic factors, such as culture, religion, wealth distribution and population structure provide the context for environmental change, interventions and policies, food system activities, level of food and nutrition security and nutrition related health and well-being. The environmental changes include stressors that directly affect food systems (▲1, [Section 4](#)). The interventions component includes research and innovation, technological development and government policies that provide the boundaries, opportunities and restrictions to the interactions between environmental changes, food system activities, food and nutrition security, health and well-being (▲2, 3, 12). The food system activities component covers the interlinked food system

functions, including production of inputs and infrastructure, agricultural processes, food processing, trade, consumption and waste management (▲4–11). In the framework, food and nutrition security are identified as a fifth component group, which are important determinants of the burden of disease and well-being. The framework presents a static conceptualisation of the interactions, although we recognise that the interactions are dynamic and operate over different time scales. For example, changes in food prices can have an immediate impact on food consumption, whereas the impacts of some environmental changes on health outcomes may be seen only after a few decades.

## 4. Impacts of environmental change on production of fruits and vegetables

### 4.1. Climate change

Climate change has been predicted to impact agricultural production through multiple direct and indirect pathways ([Porter et al., 2014](#); [Smith et al., 2014](#)). Changes in temperature and water availability combined with increased variation in weather conditions and more frequent episodic weather events will have a direct impact on crop yields ([Lobell & Gourdji, 2012](#)). Increased temperature results in faster crop growth, and therefore, shorter cropping seasons and lower yields. Temperature also impacts on photosynthesis rates and respiration. C4 crops (maize, sorghum, sugarcane, etc.) have higher optimum temperature for photosynthesis than C3 crops (cereals and most vegetables and fruits).

Climate change can have also some positive impacts as on crop production as increased carbon dioxide concentrations in the atmosphere can boost photosynthesis of C3 crops and water use efficiency in both C3 and C4 crops, and improve crop growth ([Long et al., 2006](#)). At the same time, however, this can lead to a reduction in protein, vitamin and mineral concentrations in the edible part of the crop, possibly due to reduced canopy transpiration or changes in metabolite or enzyme concentration ([McGrath & Lobell, 2013](#)). This phenomenon was studied by Myers and colleagues who modelled the impact of CO<sub>2</sub> on staple and legume crops and found that the impact of CO<sub>2</sub> was very different for C3 plants compared to C4 plants ([Myers et al., 2014](#); [Myers et al., 2015](#)). Nearly all fruits and vegetables in the human diet are C3 crops and hence are likely to be relatively vulnerable to these climatic changes. While research on drought and heat resistant staple crops has taken off greatly in the last decades, adaptive capacities in fruits and vegetables are less studied.

Besides the direct effects, increased temperatures may indirectly affect fruit and vegetables yields due to decreased labour productivity of farmers, affecting agricultural productivity ([Kjellstrom et al., 2016](#)). Many fruit and vegetable crops require high labour inputs, especially for planting and harvesting and hence climate change induced heat stress may disproportionately affect this sector.

Climate change affects many other environmental drivers, both directly and indirectly ([Figure 2](#)). For example, rising temperatures increase tropospheric (i.e. ground-level) ozone formation, and increased ozone levels cause oxidative stress for plants, which reduces photosynthesis and plant growth ([Ainsworth et al., 2012](#)). Furthermore, climate change has impacts on animal species, and a

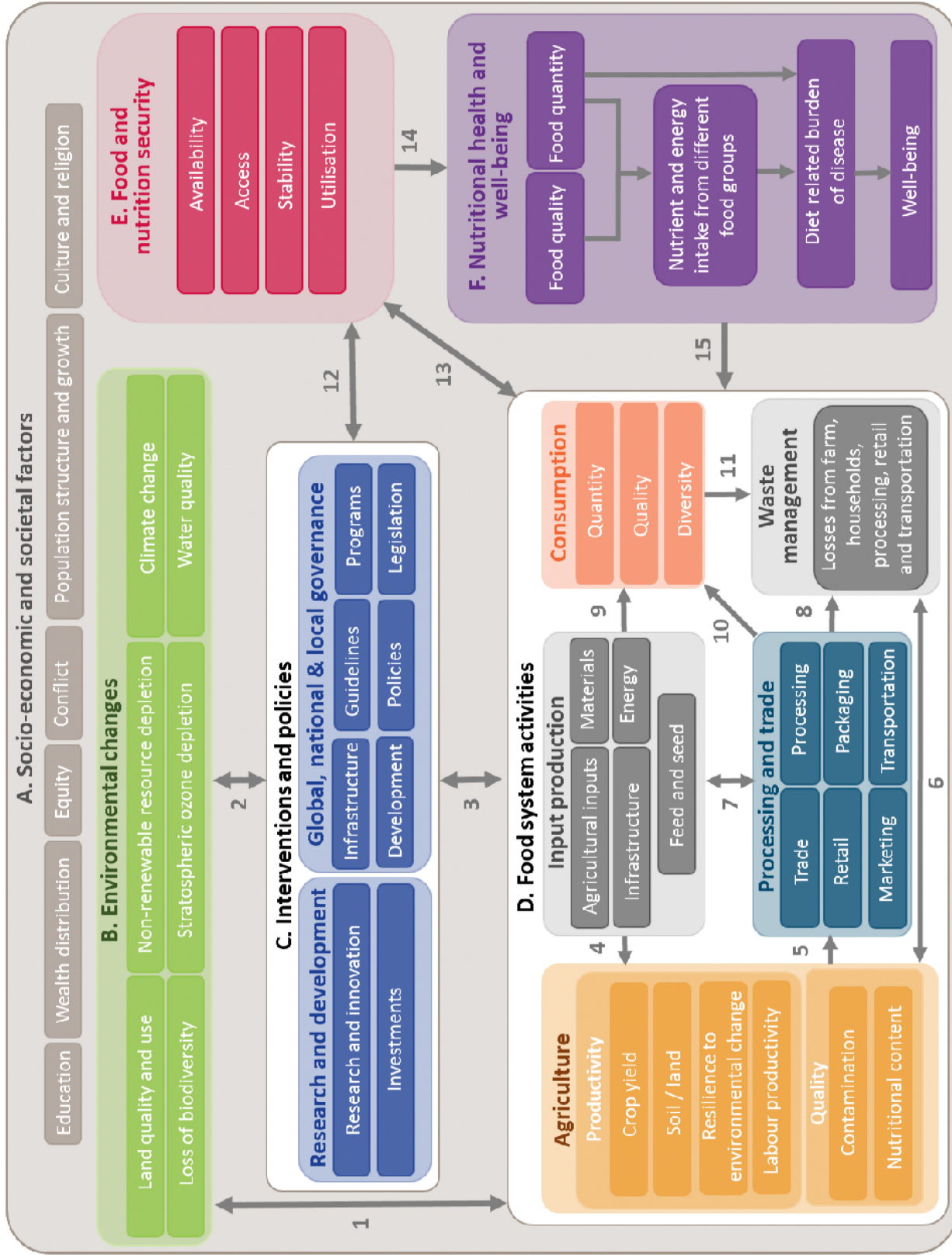
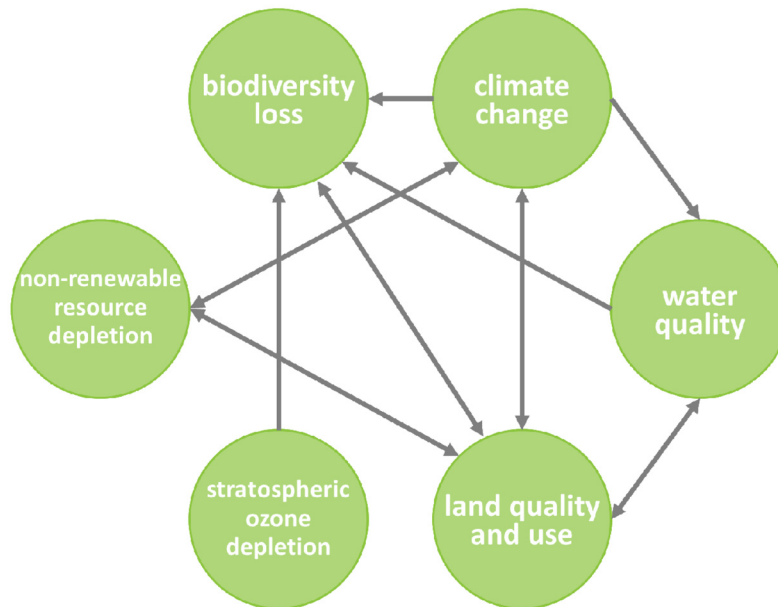


Figure 1. Overall framework connecting environmental change, agriculture, nutrition and health.





**Figure 2.** Links between environmental changes.

decrease of plant pollinator populations, for example, could have multiple impacts on agricultural production (Pacifi *et al.*, 2015) (see Section 4.6). Climate change is also likely to increase crop losses and damages due to pests, pathogens, fungi and weeds (Flood, 2010). It has been estimated that hundreds of pests and pathogens have moved towards poles on average by 2.7 km yr<sup>-1</sup> between 1960 and 2012 (Bebber *et al.*, 2013).

#### 4.2. Historical ozone depletion & current ozone layer recovery

The stratospheric ozone layer, protecting the earth from solar ultraviolet (UV) radiation, has been depleting over the past decades due to anthropogenic emissions of chlorofluorocarbon and nitrous oxides, although the recent evidence indicates healing of the ozone layer due to reduced chlorofluorocarbon emissions (Solomon *et al.*, 2016). However, in Antarctica, ozone depletion continues to occur each year, whereas the Arctic ozone shows high year-to-year variability (Andrady *et al.*, 2015).

Many factors such as cloud cover, altitude, ground reflectance and atmospheric path length, impact on the level of UV-B reaching plants. Due to the natural variations of those factors, the effect of stabilization of the ozone layer is not yet detected in the measurements of UV-B radiation.

UV-B radiation has been found to damage DNA, RNA, proteins and membranes of plants and to impair photosynthesis (Björn *et al.*, 1999; Caldwell *et al.*, 2007). A meta-analysis of the effect of increases in UV-B on yields found that herbaceous plants including most vegetables (e.g. beans, tomatoes, spinach, radish, carrots, cucumber and gourd) and many fruits (such as strawberries and sea-buckthorn) showed a more significant decrease in yield due to the UV-B exposure than woody plants (Li *et al.*, 2010).

#### 4.3. Water quality

The quality of irrigation water has a direct impact on crop quality and quantity. In the past decades, several trends in water quality – with a strong link to environmental change – have put increasing pressure on the agricultural sector, and it is expected that these trends will continue in the future (Turrall *et al.*, 2011).

Salinization is major threat to irrigation water quality. Salt tolerance levels vary greatly from crop to crop. Predominantly, salinization decreases yields, but the impact on crop quality is mixed (Hoffman *et al.*, 1989). Many vegetable crops are negatively affected and salinity can substantially reduce their market value. However, in some crops, such as carrots and asparagus, salinity can increase sugar content, whilst in tomato and melon it can increase soluble solids. Generally, however, salinity-induced decreases in yield outweigh any beneficial effects (Hoffman, 2010).

Climate change may exacerbate salinity problems which in turn impact health through drinking water and diet (Khan *et al.*, 2014; Scheelbeek *et al.*, 2017). In several low-lying coastal areas, the increased frequency of tropical cyclones and inundations can have a serious impact on the sodium (and other salts) content of soils as well as ground- and surface-water. In climate-vulnerable coastal areas, such as Bangladesh, an additional problem arises when farmers move away from saline irrigation sources and obtain water from deeper groundwater layers; high arsenic concentrations have been measured in these groundwater sources. Arsenic can remain on the crop's surface after harvesting and could form a serious health threat to its consumers (Das *et al.*, 2004; Su *et al.*, 2014). Further inland, changing precipitation patterns and drought can cause significant increase in sodium concentrations in freshwater bodies, affecting irrigation and drinking water quality (Jeppesen *et al.*, 2015).

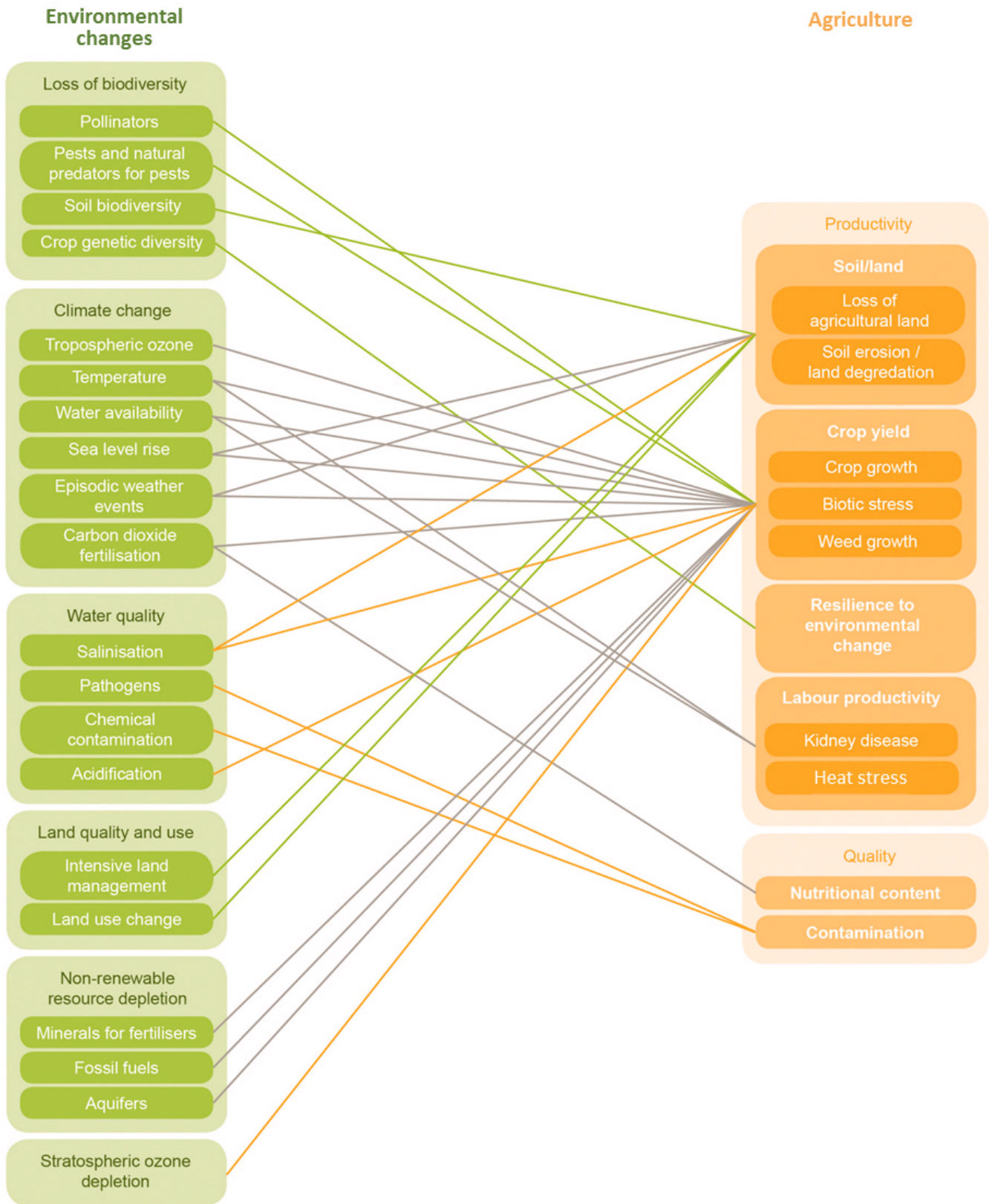


Figure 3. Pathways between environmental changes and agriculture.

Contaminated irrigation water affects crop quantity and quality significantly. More than 10% of the global population consumes foods that are irrigated with untreated wastewater or faecal contaminated surface water, and most of those people live in low-income countries with arid and semi-arid climates (WHO, 2006). Increasing water scarcity, expanding populations and recognition of the fertilisation value of wastewater are the main drivers for the increasing use contaminated water for irrigation. The use of pathogen (e.g. *Salmonella* spp., norovirus, *E. coli*, *Clostridium perfringens* and *Cambylobacter* spp.) contaminated urban wastewater for irrigation and post-harvest processes has been linked to food-borne disease outbreaks (Antwi-Agyei *et al.*, 2015; WHO, 2015). This is particularly a problem with fruits and vegetables that are often eaten without cooking.

Problems also occur if high concentrations of certain toxic ions in irrigation water - such as chloride, sodium and boron - are taken up by the plant and accumulate to concentrations that can cause damage in the crop and reduce yields (Bañón *et al.*, 2011). Both agricultural and industrial factors play an important role in toxin concentrations in water, including chemical wastewater being released in watersheds used for agriculture and/or pumping up irrigation water, as well as farm-disposal of agrochemicals. Most irrigation water sources contain concentrations of elements below toxicity thresholds; however, boron tolerance of most vegetable crops is relatively low and even quite low boron concentrations could damage crops (Hoffman, 2010). The magnitude of damage varies per crop; permanent perennial-type crops are believed to be most sensitive to irrigation water toxicity (WHO, 2006).

A third important water quality threat is the occurrence of excessive nutrients in irrigation water, notably nitrogen. This is often the result of (over)fertilisation of agricultural land, whereby excess fertilisers end up in water sources used for irrigation and may damage marine ecosystems. In susceptible crops - such as apricot, citrus and avocado - high nitrogen concentrations trigger excessive vegetative growth and delay of maturing. In leafy vegetables, this causes a decrease in harvestable product and could negatively affect fruit quality parameters, such as sugar content (Ayers & Westcot, 1985). It could also cause crops to grow taller and hence to be more vulnerable to lodging (bending over of stems) in extreme weather events, such as tropical storms.

#### 4.4. Non-renewable resource depletion

Non-renewable resource depletion includes reduced availability of minerals used for fossil fuels, fertilisers or infrastructure, and depletion of aquifers that can be used for irrigation water. The reduced availability of these resources can have an impact on crop production, unless alternative technologies are adopted (e.g. use of renewable energy sources or organic fertilisers).

For example, it has been estimated that the current economically exploitable phosphate reserves will be depleted in approximately 50–100 years (Cordell *et al.*, 2009). Therefore, options to recycle nutrients back to the fields from bio-waste and sewage sludge may become more financially attractive. Similarly, industrial agriculture relies heavily on the use of fossil fuels for producing

nitrogen fertilisers, running farm machinery and other uses. The depletion of fossil fuel reserves or the inability to exploit them because of climate change imperatives may pose a threat for agricultural production unless renewable energy sources can be significantly scaled up. However, this will be more of a problem in industrial farming systems than in subsistence farming that relies mainly on manual labour.

Finally, the depletion of water resources can have negative impacts on agricultural production, especially in areas where aquifers provide an important source of irrigation water. The depletion of aquifers is linked to changes in precipitation levels, exhaustion of rivers and increased use of water. Climate model simulations project precipitation increases in high latitudes and parts of the tropics, and decreases in some tropical and lower mid-latitude regions (Bates *et al.*, 2008). Poor rural farmers in the arid and semi-arid tropics and Asian and African mega-deltas are likely to be the most vulnerable to these changes in water availability. Furthermore, international food trade contributes to the decline of aquifers in the producing countries (Dalin *et al.*, 2017). Most of the irrigation water globally is used for staple crops (mainly for wheat) and less than 10% of all irrigation water is used for fruits and vegetables, which is in line with the percentage of land used for fruits and vegetables (FAOSTAT, 2017).

#### 4.5. Land use

Agricultural land is a limited natural resource. It is estimated that nearly a third of global arable land has been lost due to soil erosion and pollution during the past 40 years (Cameron *et al.*, 2015). Other reasons for loss of agricultural land include urbanisation, sea level rise, and renewable energy production (e.g. solar panels on agricultural land), as well as land requirements for bio-fuels and other non-food crops. At the same time, forests have been converted to agricultural land, mainly driven by increased consumption of meat and need of land for feed production. Therefore, the percentage of agricultural area of the total global land area has been relatively stable during the past decades. However, deforestation contribute to the acceleration of many environmental changes, such as climate change and loss of biodiversity, and therefore, can have negative indirect impacts on food security, e.g. through loss of wild foods (Section 6).

Soil degradation typically refers to multiple processes, such as erosion, desertification, salinization, compaction and encroachment of invasive species (Gibbs & Salmon, 2015). Soil organic matter plays a vital role in maintaining the long-term productivity of soils. The increased use of industrial farming practices, such as monocropping, minimal use of organic fertilisers and removal of crop residues from fields, is one of the main reasons for decline in soil organic matter contents.

Acidification of soils is caused by acid rains or use of synthetic nitrogen fertilisers in some conditions. Acid rains generally result from the reaction of water molecules and sulphur dioxide or nitrogen oxide in the atmosphere, which mainly originate from anthropogenic sources, such as energy generation and industrial processes (Klimont *et al.*, 2013). Soil acidification can alter nutrient availability, and has generally negative impact on plant growth,



except in alkaline soils some acidification can be beneficial (Lee *et al.*, 1981). Application of lime and balanced fertilisers help to mitigate crop losses caused by acidification (Mason *et al.*, 1994).

Phytotoxicity means the toxic effect on plants caused by compounds such as trace metals, allelochemicals, pesticides, phytotoxins or salinity. Contamination of soil with toxic metals, such as cadmium and high concentrations of aluminium, has negative impacts both on crop yields and human health (Khan *et al.*, 2015). Metals cause oxidative stress for plants, which reduces biomass accumulation.

#### 4.6. Biodiversity loss

In some cases, losses of biodiversity can have direct impacts on food availability in areas where wild food, including wild fruits and vegetables, comprise a substantial proportion of diets. Field-grown crops and livestock are also heavily dependent on multiple ecosystem services, such as pollination, natural predation of pests and services provided by soil macro- and micro-organisms.

During the past decade, the numbers of pollinators have declined, due to combined stress from parasites, pesticides and habitat loss (Goulson *et al.*, 2015). As many fruit and vegetable species rely on pollinators, a complete loss of pollinators has been predicted to reduce global fruit supply by 23%, vegetables by 16% and nuts and seeds by 22% with major adverse effects on health (Smith *et al.*, 2015).

Ecosystem functions are complex and it is currently not possible to model the required level of biodiversity needed for sustaining agricultural production. Therefore, maintaining a high level of biodiversity is regarded as a precautionary mechanism that increases the resilience of agro-ecosystems to environmental changes (Koohafkan *et al.*, 2012; Lin, 2011). Farming practices that reduce vulnerability to environmental change include diversification of agro-ecosystems, high genetic diversity of crops, integration of livestock and crop production, management of soil organic matter and water conservation. Crop diversification reduces pest, disease and weed outbreaks, and increases resilience towards greater climate variability and extreme events. In low income settings, farms with a high level of biodiversity have been found to be more resilient to climate disasters, such as hurricanes and droughts (Altieri *et al.*, 2015). Smallholder farmers in tropical regions are particularly vulnerable to climate variability, including erratic rainfall, and as a coping mechanism they rely on agricultural biodiversity, such as planting a high diversity of crops each year, including many varieties of the same crop, using drought tolerant crop varieties, changing the locations of crops and planting trees to provide shade and to maintain humidity (Meldrum *et al.*, 2013).

### 5. Impact of drivers, influencers and activities on food security and health outcomes

#### 5.1. Links between agriculture and food security: From subsistence farming to international trade

The most direct link between agriculture and food security occurs in subsistence farming communities and involves the production and quality of crops and their impact on the availability of

nutritious food to producing households. Most people living in the rural areas in low income countries, especially in sub-Saharan Africa, are dependent from subsistence farming, and 72% of all farms in the world are under 1 hectare (FAO, 2014; Herrero *et al.*, 2017).

Considering the predominantly negative influences of environmental stressors on both fruit and vegetable yield and quality (see previous sections), populations heavily reliant on subsistence farming appear likely to have food insecurity in the future (Morton, 2007; Shrestha & Nepal, 2016; Tibesigwa *et al.*, 2015). The extent of these influences on their nutrition and health depends on the farmers' ability to adapt to these environmental changes (Shisanya & Mafongoya, 2016). Many subsistence farmers are particularly vulnerable due to a high dependence on rain-fed agriculture and limited adaptation strategies: rain-fed agriculture accounts for approximately 95% of farmed land in sub-Saharan Africa and 90% in Latin America (Wani *et al.*, 2009). Moreover, in contexts where agricultural surpluses are sold at the local market as critical sources of cash, reduced yields will likely decrease household incomes.

In larger and more complex trade systems – ranging from farmers producing for the local markets to agribusinesses and international trade – a more complex interplay of mechanisms determine the impact of suboptimal yields on food security, including market mechanisms and food choices (Figure 1, ■ D), possible technological or political interventions (Figure 1, ■ C) and the influence of social factors (Figure 1, ■ A).

Compromised production – and therewith reduced availability – of a locally important vegetable could, for example, push up local or regional prices, and make the specific vegetable unaffordable for the less affluent (Brown *et al.*, 2012). Households' purchasing power and preference will determine their substitution strategy, e.g. buying another cheaper vegetable if available, buying more staples, or not substituting the “missing” vegetable. The price elasticities of fruits and vegetables tend to be higher than those for cereals, which means that consumers reduce their demand more in response to an increase in price (Cornelsen *et al.*, 2015). The household substitution strategy used will partly determine the scale of health impacts (UNSCS, 2010).

Forced switches to alternative crops could also have far reaching consequences for farmers, in case the switches become permanent (i.e. consumers start preferring the “new” vegetable above the “conventional” one), as sometimes experienced after temporary food aid programmes (Barrett, 2006). This applies especially to small farmers that might lack the financial resources to shift to another (more commercial) crop as a response to the changed commodity prices, even if this would be much more profitable (García-Germán *et al.*, 2013). Higher prices may push subsistence farmers to sell more and consume less of their own yields, which could also have an impact on their food security (Anríquez *et al.*, 2013; Zezza *et al.*, 2008). Nonetheless, it has been argued that higher food prices will generally affect food security of net consumer countries more than net producer countries (ODI, 2008),

and nutritional health, especially among children under 5 years of age (Figure 1, ▲13, 14). In larger markets with more producers integrated across diverse environments, the abundance of competitors offering the same vegetable crop may stabilise the commodity prices, and may therefore directly affect the financial security of farmers that experienced compromised yields of that specific vegetable.

Crop quality, including nutritional content, may affect dietary micronutrient supplies of consumers and subsistence farmers. Especially in areas where nutritional needs are only marginally met or where there is a widespread marginal nutrient deficiency, slight changes in vitamin and mineral concentration in crops – even without any actual change in diet – could be crucial for food and nutrition security. Fruits and vegetables are therefore particularly important as they provide a rich source of essential micronutrients that are present in much lower concentrations in other food groups.

## 5.2. Links between food security, consumption, health and well-being

There is a substantial evidence base on the impact of food security on population diets. Furthermore, the links between diets, health and well-being are the most well-researched parts of the framework (Figure 1, ▲14). Non-optimal diets are estimated to account for ~10% of the global burden of disease (Forouzanfar *et al.*, 2016).

There are two main pathways leading from nutrition to population health: non-optimal *quantity* of food intake (under- and over-nutrition) and non-optimal *quality* of food intake (nutrient deficiencies due to poor dietary composition, toxins, pathogens, etc.). In terms of the former pathway, overweight and obesity increases the risk of various NCDs, including diabetes, certain cancers and cardiovascular disease, whilst undernutrition can lead to several deficiencies, affecting, for example, child growth and development and immune system function (Figure 1, ■ F).

As well as contributing to daily dietary energy requirements, fruits and vegetables play a key role in the second pathway, linking sub-optimal quality of food intake and poor health. For many populations around the world, fruits and vegetables provide several essential vitamins, minerals and amino acids usually found in limited amounts in other components of the diet, particularly where consumption of animal-source foods is low. Low fruit and vegetable intake is associated with increased risk of vitamin deficiencies, all-cause mortality, coronary heart disease, strokes, and several types of cancer (Forouzanfar *et al.*, 2016; Miller *et al.*, 2017; Wang *et al.*, 2014).

To further explore the importance of the pathway between fruit and vegetable consumption and health, full dietary composition (i.e. consumption besides fruits and vegetables) should be considered, as well as the drivers for food choices. Low fruit and vegetable intake can in some situations be the direct results of food insecurity (i.e. limited access, affordability of stability of fruits and vegetables), whilst in other situations it reflects the population's preferences to consume foods high in sugar, salt and saturated fats instead of fruits and vegetables.

Where clinical health outcomes are difficult to measure, anthropometric indicators, such as height-for-age, weight-for-height and biomarkers, including cholesterol level, blood pressure and blood glucose, can be used for modelling the health implications of a diet.

## 6. Feedback loops from dietary choices and agriculture to environmental change

The framework highlights that – in addition to the described “environment – food system – health” pathway – there are several feedback loops linking dietary choices and nutrition back to agricultural strategies (Figure 1, ▲15) and environmental change (Figure 1, ▲1).

A remarkable example of these feedback loops is based on the rapid global shift towards a more “Western” diet, which is driven by urbanisation, economic growth and changes in technology and culture (Popkin, 2006; Tilman & Clark, 2014). Western diets are characterised by greater consumption of animal source and highly processed foods often in parallel with a reduction of the consumption of vegetables and pulses. To meet the growing demand in animal source products, livestock and dairy farming has increased enormously (FAO, 2015), contributing directly to increased greenhouse gas emissions, eutrophication (the enrichment of an ecosystem with nutrients), and loss of biodiversity due to intensification of agriculture and conversion of forests and natural habitats to agricultural land (Gerber *et al.*, 2013). Currently, livestock production occupies approximately 80% of global agricultural land (including arable and grassland), whereas only a few percent of the land is used for fruits and vegetables (FAO, 2017).

Agriculture is also one of the main contributors to climate change, accounting for ~25% of global anthropogenic emissions (Vermeulen *et al.*, 2012), while livestock production alone has been estimated to account for 14.5% of global greenhouse gas emissions (Gerber *et al.*, 2013). It has been estimated that the consumption of fruits and vegetables accounts for only 7% of all food related GHG emissions globally (Springmann *et al.*, 2016b). Generally, fruits and vegetables have a lower carbon footprint compared to livestock products and grains when measured per unit of product weight, although this is not necessarily the case when measured per unit of energy content, especially if the fruits and vegetables are processed (Drewnowski *et al.*, 2015).

Agriculture is estimated to account for ~70% of global water withdrawals (Mekonnen & Hoekstra, 2010). The water footprint of fruits and vegetables is relatively low compared to cereals and oil crops when measured per unit of product, but higher when measured per unit of energy. However, the variation between different fruits is high - ranging from 235 m<sup>3</sup> water per tonne of watermelon to 3350 m<sup>3</sup> water per tonne of figs (Mekonnen & Hoekstra, 2010).

Particularly in developed countries, agriculture is the main contributor to eutrophication of waterways, due to nitrogen and phosphorus leached from fields (Withers *et al.*, 2014). Eutrophication disturbs the natural balance of the ecosystem by favouring certain species and causing harm to others, e.g. in aquatic ecosystems the nutrient inputs increase the growth of algae and plants, and

the decay of the biomass leads to oxygen depletion, causing death of fish and other aquatic animals. The eutrophication potential of fruit and vegetable production is generally higher than that of cereals (Xue & Landis, 2010), due to the relatively high nutrient inputs required for production of fruits and vegetables.

Agricultural emissions, such as ammonia, toxic organic compounds, pesticides and particulates, have an impact on air quality, which has direct implications for human health. Agriculture accounts for ~30% of all acidifying emissions and 90% of ammonia emissions in Western Europe (Erisman *et al.*, 2008). Ammonia emissions are mainly produced from manure management and use of nitrogen fertilisers. The contribution of agriculture to particulate matter emissions in Europe has been estimated to be ~20% (Erisman *et al.*, 2008). Particulate matter emissions from agriculture originate from field operations such as ploughing, tillage and harvesting, and from livestock bedding materials and manure.

Industrialisation of agriculture has also contributed to the losses in biodiversity due to simplification of agroecosystems, reduced number of crops and crop varieties grown, use of chemical fertilisers and pesticides, intensification of agriculture, increase in field size and clearance of natural forests for agricultural land. The increased demand for agricultural products is causing a pressure for converting forests to agricultural land, especially in tropical regions (Laurance *et al.*, 2014). Extensive farming systems, such as organic farming systems, generally have higher on-farm biodiversity compared to intensive farming (Bengtsson *et al.*, 2005; Tuomisto *et al.*, 2012a). However, many studies have questioned whether land sparing, i.e. using intensive farming systems and leaving land out from agriculture for biodiversity conservation would lead to higher total biodiversity benefits compared to land sharing (Phalan *et al.*, 2011; Tschamtko *et al.* (2012); Tuomisto *et al.*, 2012b; points out that there is a clear difference between the type of biodiversity that land sparing and land sharing approaches support. The land sparing concept can under value functional agrobiodiversity that helps to increase the resilience of the farming systems to environmental changes.

## 7. Adaptation and mitigation options

There are many possibilities for farmers and societies to adapt to and mitigate environmental changes (FAO, 2010; FAO, 2012). These practices can happen at various levels and range from minor changes to major system level changes. The agriculture and food production industries can implement adaptation practices that ensure increased high-quality food production with lower environmental burdens. However, as increasing food production does not guarantee that food would be distributed equally, additional policies will be required to improve the availability and access to healthy and nutritious foods to everybody.

Farmers have possibilities to adapt to environmental changes by altering farm management practices, such as changing crop varieties, planting times, irrigation practices and residue management, or by implementing major systemic changes, such as switches to different crop species and changes in farming systems or even relocation of agriculture to new areas (Challinor *et al.*, 2014). Many farming practices that increase the climate resilience of

agriculture also help to mitigate GHG emissions (Altieri & Nicholls, 2017).

Agriculture can also benefit from technological innovations, such as biotechnology and precision farming. Novel plant breeding technologies can provide crop varieties that are more suitable to new environmental conditions, e.g. drought resistant crops (Hu & Xiong, 2014), or have higher concentrations and bioavailability of micronutrients (Bhullar & Gruijssem, 2013). Precision farming technologies apply geographical information systems, remote sensing and GPS for identifying variations in fields, and therefore help farmers to target the use of fertilisers and pesticides where they are needed the most. Small unmanned aerial systems are increasingly used for field imaging to find the problem areas at an early stage (Zhang & Kovacs, 2012). The use of robots in agriculture is increasing, especially for activities that are currently often carried out manually, e.g. weed control, fertilisation and harvesting of fruits and vegetables (Bogue & Bogue, 2016). The replacement of human labour by robots can be extremely beneficial as an adaptation to climate change, especially in areas where high daytime temperatures will make working on the fields impossible.

Novel technologies can also provide solutions to more systemic changes. Indoor farming and cellular agriculture enable food production without direct exposure to environmental stressors. Indoor farming in vertical systems (e.g. tall buildings) reduces land requirements and transportation needs, as production can take place closer to cities. The need for artificial lighting in many indoor farming systems is energy consuming (Cheng, 2014), but developments in LED light technology may improve the energy efficiency of those systems in the future (Darko *et al.*, 2014).

Cellular agriculture or the production of agricultural products by using cell culturing technologies, has the potential to revolutionise food production. The products from cellular agriculture include both acellular and cellular products. Acellular products are produced by culturing yeast or bacteria that synthesize a protein (e.g. milk protein or egg albumin) that is used for the final product. Cellular products, such as cultured meat or leather, consist of living or once living cells (Post, 2012). Cellular agriculture is not limited only to replacing animal source foods, but plant cells and algae can also be cultivated in bioreactors for food (Räty, 2017). Most of these technologies are currently at the development stage, but commercial products are expected to appear in the supermarkets during the next few years. Some preliminary studies have estimated that products from cellular agriculture could have potential to reduce environmental impacts substantially compared to conventionally produced livestock products (Mattick *et al.*, 2015; Tuomisto & de Mattos, 2011; Tuomisto *et al.*, 2016). Studies on the environmental impact of plant products produced through cellular agriculture are currently lacking.

Adaptation and mitigation mechanisms are required also in the post-farm/post-primary production stage. Extreme climatic and hydrological events can make transportation of food less reliable due to floods, heavy rains, landslides etc. Therefore, diversification of supply chains and increased local production may increase the resilience and stability of food supply chains (Miller *et al.*, 2016b).

This may require food industries and consumers to adopt purchasing strategies that take into account seasonality based on the local climate. However, relying solely on local production is not a secure strategy due to the risk of extreme climatic and hydrological events affecting the local area.

Consumers have also a key role to play as they have the power to influence in the sustainability of food system by their consumption behaviour and dietary choices. As discussed in section 5&6 the consumption choices regarding quantities of animal source foods have a major impact on the environmental burden of diets. Environmental changes may also require consumers to alter the consumption of fruits and vegetables, as the availability and prices of most popular products may change. Therefore, consumers might need to choose different fruits and vegetables at different seasons and get used to a wider variety of species. Purchasing locally produced commodities could also promote the expansion of local production.

## 8. Conclusions

The evidence-based framework presented in this paper provides an overview of the multidimensional and complex interactions with feedback between environmental change, the food system, nutrition and health, and forms an analytical basis for detailed investigation of these interactions. The novelty of the framework is in its focus on fruits and vegetables, and in the detailed presentation of the pathways between environmental stressors and plant production (Figure 3). This paper emphasises the importance of considering multiple environmental stressors and their interactions instead of focusing only on a single stressor (e.g. climate change). The focus on fruits and vegetables highlights the need for more research on this nutritionally-important food group as the majority of research efforts to-date have been targeted on staple crops and animal source foods.

The framework can be adapted for other food groups as well as for regional case studies. The inclusion of the livestock sector would require adding livestock specific pathways into the framework, such as changes in livestock diseases and changes in grassland quality and feed production. The current framework can be directly used for staple crops.

This paper has highlighted many environmental issues that can potentially have major nutrition and health consequences unless mitigation and adaptation practices are implemented. However, many of the major risks may be faced by farmers and poor consumers in developing countries whose adaptation possibilities are limited especially in the short term. Therefore, this framework helps to develop further research to estimate the potential nutrition and health consequences of environmental changes on different population groups, and the effectiveness of alternative mitigation and adaptation options with various timeframes.

Some other more specific potential applications of the framework include:

- Guiding our understanding of the complex interactions of environmental, social, political, agricultural, market-related

food security, diet and health mechanisms within food systems. It could be used for teaching and training sessions, research priority settings, as well as advocacy purposes.

- Identifying research gaps, determining research directions and guiding proposal writing. Likewise, the information can be used by funders to specify calls for proposals.
- Use as a heuristic tool for future food system and multi-sectoral modelling. This will enable further quantification of the impacts of environmental change – through agriculture and food security – on population health, as well as the assessment of the effectiveness of adaptation mechanisms at different parts of the system. By using an open-source platform, further detail could be added to the framework – and shared with the research community – when more evidence will become available.
- For food system programmes and policy makers, the framework gives an overview of where in the food system there are barriers and opportunities for change. With the available evidence, it would be possible to identify crucial links and mechanisms, which can guide health and sustainability programmes, as well as food system policy formulation.
- Although the framework was written for environment, food system and health interactions, similar frameworks could potentially be constructed in other sectors. The key role and interactions that societal factors, policies and research play within the “core” system mechanisms, is something commonly observed in other sectors (e.g. urban planning). The framework provides an example of how these complex interactions can be captured.

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### Author contributions

All authors contributed to the development of the framework. HT and PS wrote the first draft of the manuscript. All authors were involved in the revision of the draft manuscript and have agreed to the final content.

### Competing interests

No competing interests were disclosed.

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# Open Peer Review

Current Referee Status:  

Version 2

Referee Report 15 February 2018

doi:[10.21956/wellcomeopenres.13915.r30892](https://doi.org/10.21956/wellcomeopenres.13915.r30892)



**John McDermott**

CGIAR Research Program on Agriculture for Nutrition and Health (A4NH), International Food Policy Research Institute (IFPRI), Washington, DC, USA

In this second review, I will restrict my comments to how the authors have responded to my initial review. As in most work on food systems, the challenge is to investigate complex and dynamic systems and then consider the implications of different actors and actions in the system. Actors and actions may operate at different scales (global, continental, national and sub-national), in different food commodities (plant or animal, cultivated or gathered) and at different stages in the food supply chain (production, logistics, processing, retail and meal preparation). I appreciate the authors efforts in revising this paper to more realistically focus the paper on fruits and vegetables while considering broader system variables. The title and content more accurately reflect that focus.

I am also pleased that the authors have acknowledged and partially addressed the differences between food systems in low- and middle-income countries and rich countries. This is a fundamental issue. In low-income countries 40-80% of people are engaged in agriculture and the agricultural sector accounts for approximately 20-40% of national GDP. With national economic “development” and increasing incomes in countries, the percentage of people engaged in agriculture declines dramatically (<2% in most high-income countries) and most of the value addition in the food systems occurs beyond the farm in logistics, processing, retail and food preparation. Because agriculture is such a major sector in LMICs and has profound environmental implications, I do appreciate the acknowledgement by the authors of the current article’s limitations and the need for further research in the agricultural-environmental implications of food system transformation in LMICS.

With the narrowing of the focus of the article, some of the other environmental concerns I raised are less critical. Relative to habitat change and biodiversity conservation, the expansion of fruit and vegetable production into forests is less important than for more extensive agriculture. The bigger habitat issue for fruits and vegetables will be around the environmental impact on natural wetlands, which are often major sites for fruit and vegetables production. Also, given the perishability of fruits and vegetables, they are often produced close to or in urban areas. In urban and peri-urban settings, more attention to spatial analysis is warranted, particularly relative to important consumer concerns such as microbial and chemical contamination.

**Competing Interests:** No competing interests were disclosed.

**I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.**



Referee Report 18 December 2017

doi:[10.21956/wellcomeopenres.13915.r27449](https://doi.org/10.21956/wellcomeopenres.13915.r27449)



**Marco Springmann**

Oxford Martin Programme on the Future of Food, Centre on Population Approaches for Non-Communicable Disease Prevention, Nuffield Department of Population Health, University of Oxford, Oxford, UK

In their revision, Hanna Tuomisto and colleagues have addressed my comments. The manuscript provides a good overview of the various linkages of the food system with environmental change, and I think it will make a useful addition to the literature. I approve the manuscript and recommend it for publication/indexing. There are just three small comments, the authors might want to consider before that.

First, in their abstract, it is stated that "[t]here are currently no quantitative models to test the impact of multiple environmental changes on nutrition and health outcomes." I find that a rather strong statement, in particular as several research groups are working on such models, and some existing ones could be interpreted as being in that realm. Thus, the statement is or might be out of date soon. In addition, the manuscript does not address this gap, because it focuses on developing a qualitative framework. I would therefore suggest to omit it.

Second, in section 5.2, it is stated that "[n]on-optimal diets are estimated to account for ~10% of the global burden of disease (Forouzanfar et al., 2016)." I find that statement a bit unclear. For example, if one looked at the percentage of attributable deaths that was due to dietary risks, then it was actually 11 million out of 31 million (~35%), and if one looked at attributable DALYs, the reported estimate was 241 million out of 997 million (~24%), both a bit higher than the 10% that was reported in the manuscript. The attributable disease burden that was due specifically to diets low in fruits and vegetables in 2013 were 17% and 11% for deaths and DALYs, respectively. I would suggest to clarify the statement in the manuscript.

Third, would it be possible to supply Figure 1 in a higher resolution? In the current version, it appears to be rather blurry.

**Competing Interests:** No competing interests were disclosed.

**Referee Expertise:** Environmental and health implications of dietary change, public health and sustainability research, policy analysis

**I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.**

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Version 1

Referee Report 30 May 2017

doi:[10.21956/wellcomeopenres.12073.r22178](https://doi.org/10.21956/wellcomeopenres.12073.r22178)



**Marco Springmann**

Oxford Martin Programme on the Future of Food, Centre on Population Approaches for Non-Communicable Disease Prevention, Nuffield Department of Population Health, University of Oxford, Oxford, UK

In their article 'Effects of environmental change on population nutrition and health: A comprehensive framework with a focus on fruits and vegetables,' Hanna Tuomisto and colleagues aim to develop a framework that details the interactions between environmental change, diets, and health, with a particular focus on fruits and vegetables. Their article is a welcome review of the impacts of environmental change on agriculture and health, and I recommend it for indexing subject to addressing a few comments that I am detailing below.

First, I think the motivation of the review could be strengthened. What sets it apart from other reviews, such as the IPCC's, or maps of the food system? Related to that, the article does not contain any methods and discussion sections. This might be fine for a review/overview article, but if the stated aim is to develop a framework of interactions, then one would expect at least some detail on what the added value of that framework is, how it was constructed, and how it compares to other frameworks. From my reading of the article, it is a review of interactions between environmental change and mostly agriculture, with special emphasis on the implications for fruits and vegetables, and some discussion on health implications. It might therefore be advisable to describe it as such.

That would also address some problems I have with the conclusions, which seem to be a little bit of an overstretch to me. For most of the points raised, what would actually be required is some information on the relative importance of each factor. For advocacy or funding purposes, for example, one would want to know how significant a particular aspect is to gauge whether focussing on it would be worth the investment. The review, I think, nicely catalogues the various interactions between environmental change and agriculture, but it does not contain any interpretation of the information that is presented, or a discussion on what to do with it.

For some of the aspects that are discussed I found myself going back to related IPCC chapters, in particular those on Agriculture, Forestry and Other Land Use (AR5, WG3, Chapter 11), Food Security and Food Production Systems (AR5, WG3, Chapter 7), and Human Health: Impacts, Adaptation, and Co-Benefits (AR5, WG2, Chapter 11). Many of the aspects discussed in the article are reviewed at great length there, and in part using more recent studies. I would at least expect that a review like the present one would mention those reports, so that interested individuals know where they can find more detailed information.

The section on stratospheric ozone depletion is a good case in point. The impacts of changes in ultraviolet radiation on biomass are reviewed, but it is not clear whether it is an important effect or not. For example, what is missing from the discussion is the fact that the ozone hole has started to "heal" (see, e.g., Solomon et al, Science 2016,<sup>1</sup> ; or an earlier IPCC special report on the ozone layer), and where to read on. In addition to the agricultural impacts, changes in ultraviolet radiation also impact human health directly. It might be worth re-emphasizing that the direct health impacts of many of the environmental changes reviewed are not discussed in the article. (That is also the case for tropospheric ozone, which is briefly mentioned in relation to oxidative stress for plants, but which arguably has a bigger direct health impact in its relationship to urban air pollution).

At a couple of instances, it might be worth to add some detail related to attribution. For example, in the discussion on acid rain (3.5), one could get away with the impression that it is a natural phenomenon

("Acid rains generally result from the reaction of water molecules and sulphur dioxide or nitrogen oxide in the atmosphere," p. 6). Whilst natural phenomena, such as volcanic eruptions, surely contribute to acid-rain precursors, the principal causes are anthropogenic emissions of sulphur and nitrogen compounds, especially from coal-fired power plants. Another clarification regarding attribution might be when discussing fruit and vegetable consumption. On page 8, it is mentioned that in some situation, low consumption reflects population preferences. Although one can surely see it that way, another way of explaining consumption behaviour is by pointing to the food environment and its role in shaping preferences. The benefit of this angle is that it allows one to study the influences of actors, such as governments and the food industry, on the food environment and on the preferences shaped by it.

Despite being in the title, health is actually not discussed to a great extent in the review. That's totally fine, but it might be worth being a bit clearer about what is, and what is not discussed in the article. A specific aspect I was missing from the discussion of pathways leading from nutrition to population health (pp. 7-8) is dietary composition. What is mentioned are the quantity and quality of food intake. Although dietary composition is sometimes subsumed under the banner of quality of food intake, that is not obvious from the related paragraph and could be clarified. Of note here is that changes in dietary composition are broader, and more impactful for health than changes in specific nutrient levels – a point illustrated by the ranking of risk factors in the Global Burden of Disease study<sup>2</sup> that is referred to a couple of times in the article.

A final comment is that the literature used could be a bit more general at times. For example, I don't understand why when discussing the greenhouse gas emissions related to agriculture, the only study referred to for quantifying the emissions attributable to fruit and vegetable consumption is a working paper focussed on the UK. There are several more general sources that have quantified the emissions attributable to both global and regional consumption of fruits and vegetables. For example, in one of my own studies<sup>3</sup>, I calculated that about 7% of all food-related greenhouse gas emissions in 2005/07 were related to fruit and vegetable consumption. Tilman and Clark's article<sup>4</sup> also includes some global estimates and could be consulted in that regard. Another example is the discussion on changes in water demand (p. 6) where a national case-study on India is cited, without noting more comprehensive, global analyses. Good resources here are again the IPCC, and the Agricultural Model Intercomparison and Improvement Project (AgMIP). In general, I think it is good practice in reviews to indicate whether a reference provides a specific example, or whether it supports a general argument.

Good luck with the revisions. I enjoyed reading the article.

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2. GBD 2015 Risk Factors Collaborators: Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990-2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet*. 2016; **388** (10053): 1659-1724 [Publisher Full Text](#)
3. Springmann M, Godfray HC, Rayner M, Scarborough P: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proc Natl Acad Sci U S A*. 2016; **113** (15): 4146-51 [PubMed Abstract](#) | [Publisher Full Text](#)
4. Tilman D, Clark M: Global diets link environmental sustainability and human health. *Nature*. 2014; **515** (7528): 518-22 [PubMed Abstract](#) | [Publisher Full Text](#)

**Is the work clearly and accurately presented and does it cite the current literature?**

Partly

**Is the study design appropriate and is the work technically sound?**

Partly

**Are sufficient details of methods and analysis provided to allow replication by others?**

No

**If applicable, is the statistical analysis and its interpretation appropriate?**

Not applicable

**Are all the source data underlying the results available to ensure full reproducibility?**

No source data required

**Are the conclusions drawn adequately supported by the results?**

No

**Competing Interests:** No competing interests were disclosed.

**Referee Expertise:** Environmental and health implications of dietary change, public health and sustainability research, policy analysis

**I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.**

Author Response 17 Oct 2017

**Hanna Tuomisto**, London School of Hygiene & Tropical Medicine, UK

### Responses to Reviewer 2

*Dear Dr Springmann,*

*Thank you very much for your excellent comments that have helped us to improve our paper. We have revised the paper based on your suggestions as detailed below. In addition, we made revisions based on comments from Dr McDermott and we added a new section discussing adaptation and mitigation options (section 7).*

“In their article ‘Effects of environmental change on population nutrition and health: A comprehensive framework with a focus on fruits and vegetables,’ Hanna Tuomisto and colleagues aim to develop a framework that details the interactions between environmental change, diets, and health, with a particular focus on fruits and vegetables. Their article is a welcome review of the impacts of environmental change on agriculture and health, and I recommend it for indexing subject to addressing a few comments that I am detailing below.

First, I think the motivation of the review could be strengthened. What sets it apart from other reviews, such as the IPCC’s, or maps of the food system?”

*Authors: We appreciate the motivation/difference was not stipulated clearly: the focus on fruits and vegetables rather than on staple crops. We have strengthened the justification for this in the*



*introduction section.*

“Related to that, the article does not contain any methods and discussion sections. This might be fine for a review/overview article, but if the stated aim is to develop a framework of interactions, then one would expect at least some detail on what the added value of that framework is, how it was constructed, and how it compares to other frameworks.”

*Authors: We have expanded the description of the methods, and added a methods heading. We have also strengthened the explanation of the added value and differences compared to the other frameworks. A brief discussion of the potential uses of the framework as well as some limitations can be found in section 8.*

“From my reading of the article, it is a review of interactions between environmental change and mostly agriculture, with special emphasis on the implications for fruits and vegetables, and some discussion on health implications. It might therefore be advisable to describe it as such.”

*Authors: The title and introduction of the paper have been amended to clarify that it presents a framework with a particular emphasis on fruit and vegetable production. As the paper is designed to be read by a primarily health-focused audience, we have added particular detail on the interactions between environmental change and fruit and vegetable production, as this is the area of the framework the journal’s readership is likely to be least familiar with.*

“That would also address some problems I have with the conclusions, which seem to be a little bit of an overstretch to me. For most of the points raised, what would actually be required is some information on the relative importance of each factor. For advocacy or funding purposes, for example, one would want to know how significant a particular aspect is to gauge whether focussing on it would be worth the investment. The review, I think, nicely catalogues the various interactions between environmental change and agriculture, but it does not contain any interpretation of the information that is presented, or a discussion on what to do with it.”

*Authors: The aim of the framework is to provide a basis for modelling and quantification of the relative importance of the different factors, and as such the quantification itself is beyond the scope of this piece of work. However, we also identified some uses for the framework itself, which are listed in the conclusions section. We will look into possibilities for other research groups to add to the framework in the future (perhaps using open source software) to further quantify each of the indicated links.*

“For some of the aspects that are discussed I found myself going back to related IPCC chapters, in particular those on Agriculture, Forestry and Other Land Use (AR5, WG3, Chapter 11), Food Security and Food Production Systems (AR5, WG3, Chapter 7), and Human Health: Impacts, Adaptation, and Co-Benefits (AR5, WG2, Chapter 11). Many of the aspects discussed in the article are reviewed at great length there, and in part using more recent studies. I would at least expect that a review like the present one would mention those reports, so that interested individuals know where they can find more detailed information.”

*Authors: Thank you for the suggestion. We have added citations to the suggested reports in the paper.*

“The section on stratospheric ozone depletion is a good case in point. The impacts of changes in ultraviolet radiation on biomass are reviewed, but it is not clear whether it is an important effect or not. For example, what is missing from the discussion is the fact that the ozone hole has started to “heal” (see, e.g., Solomon et al, Science 2016,<sup>1</sup>; or an earlier IPCC special report on the ozone layer), and where to read on.”

*Authors: Thank you for the comment. We have added the point that the ozone layer is healing and added a reference to the Solomon et al 2016 paper. We also removed the following sentence as*

*the reference is relatively old and is contradicting the fact that the ozone layer is healing: "It has been estimated that the springtime UV doses will increase 14% in the Northern hemisphere and 40% in the Southern hemisphere in 2010–2020 compared to levels in 1979–1992 (Taalas et al., 2000)."*

"In addition to the agricultural impacts, changes in ultraviolet radiation also impact human health directly. It might be worth re-emphasizing that the direct health impacts of many of the environmental changes reviewed are not discussed in the article. (That is also the case for tropospheric ozone, which is briefly mentioned in relation to oxidative stress for plants, but which arguably has a bigger direct health impact in its relationship to urban air pollution)."

*Authors: We have added a note in the introduction section (end of the fourth paragraph) stating the fact that the paper doesn't cover direct health impacts.*

"At a couple of instances, it might be worth to add some detail related to attribution. For example, in the discussion on acid rain (3.5), one could get away with the impression that it is a natural phenomenon ("Acid rains generally result from the reaction of water molecules and sulphur dioxide or nitrogen oxide in the atmosphere," p. 6). Whilst natural phenomena, such as volcanic eruptions, surely contribute to acid-rain precursors, the principal causes are anthropogenic emissions of sulphur and nitrogen compounds, especially from coal-fired power plants."

*Authors: We have clarified the point on acid rains and screened the paper for additional paragraphs that would benefit from more detail related to attribution: more detail was added to these sections.*

"Another clarification regarding attribution might be when discussing fruit and vegetable consumption. On page 8, it is mentioned that in some situation, low consumption reflects population preferences. Although one can surely see it that way, another way of explaining consumption behaviour is by pointing to the food environment and its role in shaping preferences. The benefit of this angle is that it allows one to study the influences of actors, such as governments and the food industry, on the food environment and on the preferences shaped by it."

*Authors: Thank you for this excellent comment. We edited the sentence to: "A remarkable example of these feedback loops is based on the consumer-driven rapid global shift towards a more "Western" diet, which is driven by urbanisation, economic growth and changes in technology and culture ( Popkin, 2006)."*

"Despite being in the title, health is actually not discussed to a great extent in the review. That's totally fine, but it might be worth being a bit clearer about what is, and what is not discussed in the article."

*Authors: we have now clarified the desired focus of the paper, expanded the health section (5.2) and briefly discussed possible implications for health.*

"A specific aspect I was missing from the discussion of pathways leading from nutrition to population health (pp. 7-8) is dietary composition. What is mentioned are the quantity and quality of food intake. Although dietary composition is sometimes subsumed under the banner of quality of food intake, that is not obvious from the related paragraph and could be clarified. Of note here is that changes in dietary composition are broader, and more impactful for health than changes in specific nutrient levels – a point illustrated by the ranking of risk factors in the Global Burden of Disease study<sup>2</sup> that is referred to a couple of times in the article."

*Authors: we clarified that the term 'food quality' covers also dietary composition, and have altered this section to focus more explicitly on fruits and vegetables and their contribution to quality of dietary intake.*

"A final comment is that the literature used could be a bit more general at times. For example, I

don't understand why when discussing the greenhouse gas emissions related to agriculture, the only study referred to for quantifying the emissions attributable to fruit and vegetable consumption is a working paper focussed on the UK. There are several more general sources that have quantified the emissions attributable to both global and regional consumption of fruits and vegetables. For example, in one of my own studies<sup>3</sup>, I calculated that about 7% of all food-related greenhouse gas emissions in 2005/07 were related to fruit and vegetable consumption.”

*Authors: thanks for this information. We have added a reference to your paper.*

“Tilman and Clark's article<sup>4</sup> also includes some global estimates and could be consulted in that regard. Another example is the discussion on changes in water demand (p. 6) where a national case-study on India is cited, without noting more comprehensive, global analyses. Good resources here are again the IPCC, and the Agricultural Model Intercomparison and Improvement Project (AgMIP). In general, I think it is good practice in reviews to indicate whether a reference provides a specific example, or whether it supports a general argument.”

*Authors: We have improved this section and added a reference to the IPCC report.*

### References

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4. Tilman D, Clark M: Global diets link environmental sustainability and human health. *Nature*. 2014; **515** (7528): 518-22 [PubMed Abstract](#) | [Publisher Full Text](#)

**Competing Interests:** We declare that we have no conflict of interest

Referee Report 27 April 2017

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### John McDermott

CGIAR Research Program on Agriculture for Nutrition and Health (A4NH), International Food Policy Research Institute (IFPRI), Washington, DC, USA

The objective of this paper is to provide a comprehensive framework for the effects of environmental change on population nutrition and health. The authors correctly, in my opinion, advocate for a more comprehensive approach that considers multiple disciplines and key interactions between the environment, food production and population nutrition and health. The framework is less comprehensive than the title, restricting itself to environmental change and a subset of food production from major crops, and extending that to fruits and vegetables. These could be brought into alignment with revisions by rephrasing the title and narrowing the scope to focus on the subset of issues addressed. If a more comprehensive approach, addressing issues raised below, is desired, the paper would need to be changed much more dramatically.

My comments focus on the utility of the framework for policies and actions for linking the environment, food production, and population nutrition and health in low- and middle-income countries (LMICs). In general, the framework proposed has important elements but seems better suited to the context of high-income countries. Agriculture is the sector with the greatest influence on natural systems globally, and it is changing rapidly in LMICs. Some of the biggest environmental influences of agriculture on the environment in LMICs are:

1. expansion of agricultural lands into natural forests,
2. intensification of livestock and fish systems (that can have beneficial or negative effects, depending on management),
3. depletion of ground water, and
4. land / soil degradation.

All these agricultural changes have important implications for greenhouse gas production and climate change adaptation and mitigation. For all these topics, there are important interactions between agriculture and the environment which have implications for population nutrition and health. As issues 1-3 are not considered in the paper, the comprehensive framework proposed does not adequately address some of the biggest food system issues in LMICs.

In particular, for a paper linking environmental change to population nutrition and health through food, the failure to consider animal production (livestock and fish) is a profound omission. In smallholder systems across Africa and Asia, mixed farming with both animals and plants is very common. The combination of plants and animal production are synergistic – socio-economically and biologically.

The methodology followed has led to a useful initial framework. However, if this framework is to be more generally applicable in LMICs (as is implied) I would suggest that the current framework be revised considering the general points above and some additional, more specific, points below. These points highlight some of the many tradeoffs and challenges that decision makers struggle with in the environment, food, and health nexus that a comprehensive framework needs to consider.

1. Water: water quality is an important issue and is intimately linked with food safety, particularly for vegetables. The landmark WHO Foodborne Disease Burden Epidemiology Reference Group (FERG) report from December 2015 estimates that the main burdens associated with fresh foods are overwhelmingly due to biological pathogens rather than chemicals ([http://www.who.int/foodsafety/areas\\_work/foodborne-diseases/ferg/en/](http://www.who.int/foodsafety/areas_work/foodborne-diseases/ferg/en/)). In general, consumers are more concerned with chemical contamination. Many of the vegetables consumed in urban and peri-urban areas are grown with contaminated wastewater. How this wastewater is managed is a critical issue for vegetable production<sup>1</sup>. The issue of water availability is ignored in the framework, but it is of critical importance. Subsidized water for cereal production is leading to a depletion of groundwater in the western Indo-Gangetic plains. Over-exploitation of ground water is also critical in dryland farming areas in Australia, Central Asia and North America. These systems will be forced to de-intensify or become unproductive. In Africa, there has been relatively little investment in irrigation to date, but it is a very dry continent and sustainable irrigation will be critical to adapting food production systems to increasing climate variability.
2. Biodiversity loss: this is one example of the need to go beyond listing issues to assessing tradeoffs. As noted by the authors, this is complex to model and decide, but people are constantly making decisions between adhering to a precautionary principle of maintaining natural areas, and adopting more intensive and less diverse systems. The framework would need to consider how such tradeoffs can be considered and monitored, and evolve over time.

3. Diet quality in sustainable and healthy food systems: implied in the discussion of fruits and vegetables is the diversification of diets and improving diet quality by promoting consumption of healthy foods (and reducing consumption of unhealthy foods). In LMICs, most agricultural policies provide subsidies and greater investment for cereals with the result that supply chains for cereals are more efficient and the prices lower relative to more nutritious foods such as pulses, fish and vegetables. Thus, rebalancing agricultural policies to make them more commodity-neutral is needed to improve diet quality.
4. Tradeoffs between sustainability and health. Animal-source foods represent the greatest challenge in this regard since they are very nutritious but much more environmentally costly. A strong case can be made that the poor (especially mothers and children) should eat more animal-source foods, but it is desirable, for both sustainability and health reasons, to limit the dramatic increases in consumption of animal-source foods observed as incomes rise in LMICs.

In revising the framework, these are some key issues to consider. It might be useful to get other inputs to adapt or add that a functional comprehensive framework should address.

### References

1. Antwi-Agyei P, Cairncross S, Peasey A, Price V, Bruce J, Baker K, Moe C, Ampofo J, Armah G, Ensink J: A Farm to Fork Risk Assessment for the Use of Wastewater in Agriculture in Accra, Ghana. *PLoS One*. 2015; **10** (11): e0142346 [PubMed Abstract](#) | [Publisher Full Text](#)

### Is the work clearly and accurately presented and does it cite the current literature?

Partly

### Is the study design appropriate and is the work technically sound?

Partly

### Are sufficient details of methods and analysis provided to allow replication by others?

Partly

### If applicable, is the statistical analysis and its interpretation appropriate?

Not applicable

### Are all the source data underlying the results available to ensure full reproducibility?

No source data required

### Are the conclusions drawn adequately supported by the results?

Partly

**Competing Interests:** No competing interests were disclosed.

**Referee Expertise:** Epidemiology, agriculture and livestock production, food systems in low and middle income countries, veterinary medicine, agriculture intensification and infectious disease risk (food safety, emerging diseases)

**I have read this submission. I believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.**



Author Response 03 Oct 2017

**Hanna Tuomisto**, London School of Hygiene & Tropical Medicine, UK

### Responses to Reviewer 1

*Dear Dr McDermott,*

*Thank you very much for your excellent comments that have helped us to improve our paper. We have revised the paper based on your suggestions as detailed below. In addition, we made revisions based on comments from Dr Springmann and we added a new section discussing adaptation and mitigation options (section 7).*

“The objective of this paper is to provide a comprehensive framework for the effects of environmental change on population nutrition and health. The authors correctly, in my opinion, advocate for a more comprehensive approach that considers multiple disciplines and key interactions between the environment, food production and population nutrition and health. The framework is less comprehensive than the title, restricting itself to environmental change and a subset of food production from major crops, and extending that to fruits and vegetables.”

*Authors: we have changed the title, so that it reflects the focus of the paper better (fruits and vegetables). The new title is: Effects of environmental change on agriculture, population nutrition and health: A framework with a focus on fruits and vegetables*

“These could be brought into alignment with revisions by rephrasing the title and narrowing the scope to focus on the subset of issues addressed. If a more comprehensive approach, addressing issues raised below, is desired, the paper would need to be changed much more dramatically.”

*Authors: we have revised the paper throughout to be clearly focused on fruits and vegetables.*

“My comments focus on the utility of the framework for policies and actions for linking the environment, food production, and population nutrition and health in low- and middle-income countries (LMICs). In general, the framework proposed has important elements but seems better suited to the context of high-income countries. Agriculture is the sector with the greatest influence on natural systems globally, and it is changing rapidly in LMICs. Some of the biggest environmental influences of agriculture on the environment in LMICs are:

1. expansion of agricultural lands into natural forests,
2. intensification of livestock and fish systems (that can have beneficial or negative effects, depending on management),
3. depletion of ground water, and
4. land / soil degradation.

All these agricultural changes have important implications for greenhouse gas production and climate change adaptation and mitigation. For all these topics, there are important interactions between agriculture and the environment which have implications for population nutrition and health. As issues 1-3 are not considered in the paper, the comprehensive framework proposed does not adequately address some of the biggest food system issues in LMICs.”

*Authors: we agree with the reviewer about the many interactions between agriculture and the environment. It would be very useful to further explore all of these in detail, and this is certainly*

*something we would like to commit to in our future research. For this first paper, we decided to describe the impacts of environmental changes on agriculture and have now further clarified in the text that this was our focus. In a future paper, we could subsequently look at the impacts of agriculture on the environment: for now these are only briefly discussed in section 6. Depletion of groundwater is briefly covered in section 4.4, which we have slightly expanded. We appreciate the reviewer's comments concerning the relevance of the framework to LMICs as well as high income countries: we have now made sure more LMIC examples have been added throughout the revised manuscript.*

*"In particular, for a paper linking environmental change to population nutrition and health through food, the failure to consider animal production (livestock and fish) is a profound omission. In smallholder systems across Africa and Asia, mixed farming with both animals and plants is very common. The combination of plants and animal production are synergistic – socio-economically and biologically."*

*Authors: we agree with this comment and have improved the reasoning why the paper focuses on fruits and vegetables in the introduction section.*

*"The methodology followed has led to a useful initial framework. However, if this framework is to be more generally applicable in LMICs (as is implied) I would suggest that the current framework be revised considering the general points above and some additional, more specific, points below. These points highlight some of the many tradeoffs and challenges that decision makers struggle with in the environment, food, and health nexus that a comprehensive framework needs to consider.*

- 1. Water: water quality is an important issue and is intimately linked with food safety, particularly for vegetables. The landmark WHO Foodborne Disease Burden Epidemiology Reference Group (FERG) report from December 2015 estimates that the main burdens associated with fresh foods are overwhelmingly due to biological pathogens rather than chemicals ([http://www.who.int/foodsafety/areas\\_work/foodborne-diseases/ferg/en/](http://www.who.int/foodsafety/areas_work/foodborne-diseases/ferg/en/)). In general, consumers are more concerned with chemical contamination. Many of the vegetables consumed in urban and peri-urban areas are grown with contaminated wastewater. How this wastewater is managed is a critical issue for vegetable production (for example, see <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4640866/>)."*

*Authors: thank you for this comment. We have added the issue of pathogen contaminated irrigation water with the above references in section 4.3.*

*"The issue of water availability is ignored in the framework, but it is of critical importance. Subsidized water for cereal production is leading to a depletion of groundwater in the western Indo-Gangetic plains. Over-exploitation of ground water is also critical in dryland farming areas in Australia, Central Asia and North America. These systems will be forced to de-intensify or become unproductive. In Africa, there has been relatively little investment in irrigation to date, but it is a very dry continent and sustainable irrigation will be critical to adapting food production systems to increasing climate variability."*

*Authors: We appreciate that the issue of water availability was not appropriately covered and was only partly included in the "non-renewable resource depletion" section of the framework (section 4.4). We have now expanded the text explaining the issue of water availability and referencing the points made by the reviewer above.*

1. “Biodiversity loss: this is one example of the need to go beyond listing issues to assessing tradeoffs. As noted by the authors, this is complex to model and decide, but people are constantly making decisions between adhering to a precautionary principle of maintaining natural areas, and adopting more intensive and less diverse systems. The framework would need to consider how such tradeoffs can be considered and monitored, and evolve over time.”

*Authors: we agree that trade-offs are very important to consider, but feel that exploring them is beyond the scope of a structural framework. Trade-offs between the links and interactions identified here will be addressed in the future modelling work that will be carried out by using the framework.*

“Diet quality in sustainable and healthy food systems: implied in the discussion of fruits and vegetables is the diversification of diets and improving diet quality by promoting consumption of healthy foods (and reducing consumption of unhealthy foods). In LMICs, most agricultural policies provide subsidies and greater investment for cereals with the result that supply chains for cereals are more efficient and the prices lower relative to more nutritious foods such as pulses, fish and vegetables. Thus, rebalancing agricultural policies to make them more commodity-neutral is needed to improve diet quality.”

*Authors: thank you for the helpful comment. This is again an issue that we can explore in our future modelling work, and is mentioned in section 8.*

1. “Tradeoffs between sustainability and health. Animal-source foods represent the greatest challenge in this regard since they are very nutritious but much more environmentally costly. A strong case can be made that the poor (especially mothers and children) should eat more animal-source foods, but it is desirable, for both sustainability and health reasons, to limit the dramatic increases in consumption of animal-source foods observed as incomes rise in LMICs.”

*Authors: as we have now narrowed the focus of the framework following reviewer suggestions to focus more explicitly on fruits and vegetables, animal-source foods are beyond the scope of the paper. We agree that it will be extremely important to explore trade-offs between sustainability and health in our future modelling work, however.*

## Responses to Reviewer 2

*Dear Dr Springmann,*

*Thank you very much for your excellent comments that have helped us to improve our paper. We have revised the paper based on your suggestions as detailed below. In addition, we made revisions based on comments from Dr McDermott and we added a new section discussing adaptation and mitigation options (section 7).*

“In their article ‘Effects of environmental change on population nutrition and health: A comprehensive framework with a focus on fruits and vegetables,’ Hanna Tuomisto and colleagues aim to develop a framework that details the interactions between environmental change, diets, and health, with a particular focus on fruits and vegetables. Their article is a welcome review of the impacts of environmental change on agriculture and health, and I recommend it for indexing subject to addressing a few comments that I am detailing below.

First, I think the motivation of the review could be strengthened. What sets it apart from other

reviews, such as the IPCC's, or maps of the food system?"

*Authors: We appreciate the motivation/difference was not stipulated clearly: the focus on fruits and vegetables rather than on staple crops. We have strengthened the justification for this in the introduction section.*

"Related to that, the article does not contain any methods and discussion sections. This might be fine for a review/overview article, but if the stated aim is to develop a framework of interactions, then one would expect at least some detail on what the added value of that framework is, how it was constructed, and how it compares to other frameworks."

*Authors: We have expanded the description of the methods, and added a methods heading. We have also strengthened the explanation of the added value and differences compared to the other frameworks. A brief discussion of the potential uses of the framework as well as some limitations can be found in section 8.*

"From my reading of the article, it is a review of interactions between environmental change and mostly agriculture, with special emphasis on the implications for fruits and vegetables, and some discussion on health implications. It might therefore be advisable to describe it as such."

*Authors: The title and introduction of the paper have been amended to clarify that it presents a framework with a particular emphasis on fruit and vegetable production. As the paper is designed to be read by a primarily health-focused audience, we have added particular detail on the interactions between environmental change and fruit and vegetable production, as this is the area of the framework the journal's readership is likely to be least familiar with.*

"That would also address some problems I have with the conclusions, which seem to be a little bit of an overstretch to me. For most of the points raised, what would actually be required is some information on the relative importance of each factor. For advocacy or funding purposes, for example, one would want to know how significant a particular aspect is to gauge whether focussing on it would be worth the investment. The review, I think, nicely catalogues the various interactions between environmental change and agriculture, but it does not contain any interpretation of the information that is presented, or a discussion on what to do with it."

*Authors: The aim of the framework is to provide a basis for modelling and quantification of the relative importance of the different factors, and as such the quantification itself is beyond the scope of this piece of work. However, we also identified some uses for the framework itself, which are listed in the conclusions section. We will look into possibilities for other research groups to add to the framework in the future (perhaps using open source software) to further quantify each of the indicated links.*

"For some of the aspects that are discussed I found myself going back to related IPCC chapters, in particular those on Agriculture, Forestry and Other Land Use (AR5, WG3, Chapter 11), Food Security and Food Production Systems (AR5, WG3, Chapter 7), and Human Health: Impacts, Adaptation, and Co-Benefits (AR5, WG2, Chapter 11). Many of the aspects discussed in the article are reviewed at great length there, and in part using more recent studies. I would at least expect that a review like the present one would mention those reports, so that interested individuals know where they can find more detailed information."

*Authors: Thank you for the suggestion. We have added citations to the suggested reports in the paper.*

"The section on stratospheric ozone depletion is a good case in point. The impacts of changes in ultraviolet radiation on biomass are reviewed, but it is not clear whether it is an important effect or not. For example, what is missing from the discussion is the fact that the ozone hole has started to "heal" (see, e.g., Solomon et al, Science 2016, <sup>1</sup>; or an earlier IPCC special report on the ozone

layer), and where to read on.”

*Authors: Thank you for the comment. We have added the point that the ozone layer is healing and added a reference to the Solomon et al 2016 paper. We also removed the following sentence as the reference is relatively old and is contradicting the fact that the ozone layer is healing: “It has been estimated that the springtime UV doses will increase 14% in the Northern hemisphere and 40% in the Southern hemisphere in 2010–2020 compared to levels in 1979–1992 (Taalas et al., 2000).”*

“In addition to the agricultural impacts, changes in ultraviolet radiation also impact human health directly. It might be worth re-emphasizing that the direct health impacts of many of the environmental changes reviewed are not discussed in the article. (That is also the case for tropospheric ozone, which is briefly mentioned in relation to oxidative stress for plants, but which arguably has a bigger direct health impact in its relationship to urban air pollution).”

*Authors: We have added a note in the introduction section (end of the fourth paragraph) stating the fact that the paper doesn’t cover direct health impacts.*

“At a couple of instances, it might be worth to add some detail related to attribution. For example, in the discussion on acid rain (3.5), one could get away with the impression that it is a natural phenomenon (“Acid rains generally result from the reaction of water molecules and sulphur dioxide or nitrogen oxide in the atmosphere,” p. 6). Whilst natural phenomena, such as volcanic eruptions, surely contribute to acid-rain precursors, the principal causes are anthropogenic emissions of sulphur and nitrogen compounds, especially from coal-fired power plants.”

*Authors: We have clarified the point on acid rains and screened the paper for additional paragraphs that would benefit from more detail related to attribution: more detail was added to these sections.*

“Another clarification regarding attribution might be when discussing fruit and vegetable consumption. On page 8, it is mentioned that in some situation, low consumption reflects population preferences. Although one can surely see it that way, another way of explaining consumption behaviour is by pointing to the food environment and its role in shaping preferences. The benefit of this angle is that it allows one to study the influences of actors, such as governments and the food industry, on the food environment and on the preferences shaped by it.”

*Authors: Thank you for this excellent comment. We edited the sentence to: “A remarkable example of these feedback loops is based on the consumer-driven rapid global shift towards a more “Western” diet, which is driven by urbanisation, economic growth and changes in technology and culture ( Popkin, 2006).”*

“Despite being in the title, health is actually not discussed to a great extent in the review. That’s totally fine, but it might be worth being a bit clearer about what is, and what is not discussed in the article.”

*Authors: we have now clarified the desired focus of the paper, expanded the health section (5.2) and briefly discussed possible implications for health.*

“A specific aspect I was missing from the discussion of pathways leading from nutrition to population health (pp. 7-8) is dietary composition. What is mentioned are the quantity and quality of food intake. Although dietary composition is sometimes subsumed under the banner of quality of food intake, that is not obvious from the related paragraph and could be clarified. Of note here is that changes in dietary composition are broader, and more impactful for health than changes in specific nutrient levels – a point illustrated by the ranking of risk factors in the Global Burden of Disease study<sup>2</sup> that is referred to a couple of times in the article.”

*Authors: we clarified that the term ‘food quality’ covers also dietary composition, and have altered this section to focus more explicitly on fruits and vegetables and their contribution to quality of*



*dietary intake.*

“A final comment is that the literature used could be a bit more general at times. For example, I don’t understand why when discussing the greenhouse gas emissions related to agriculture, the only study referred to for quantifying the emissions attributable to fruit and vegetable consumption is a working paper focussed on the UK. There are several more general sources that have quantified the emissions attributable to both global and regional consumption of fruits and vegetables. For example, in one of my own studies<sup>3</sup>, I calculated that about 7% of all food-related greenhouse gas emissions in 2005/07 were related to fruit and vegetable consumption.”

*Authors: thanks for this information. We have added a reference to your paper.*

“Tilman and Clark’s article<sup>4</sup> also includes some global estimates and could be consulted in that regard. Another example is the discussion on changes in water demand (p. 6) where a national case-study on India is cited, without noting more comprehensive, global analyses. Good resources here are again the IPCC, and the Agricultural Model Intercomparison and Improvement Project (AgMIP). In general, I think it is good practice in reviews to indicate whether a reference provides a specific example, or whether it supports a general argument.”

*Authors: We have improved this section and added a reference to the IPCC report.*

### References

1. Solomon S, Ivy DJ, Kinnison D, Mills MJ, Neely RR, Schmidt A: Emergence of healing in the Antarctic ozone layer. *Science*. 2016; **353** (6296): 269-74 [PubMed Abstract](#) | [Publisher Full Text](#)
2. GBD 2015 Risk Factors Collaborators: Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990-2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet*. 2016; **388** (10053): 1659-1724 [Publisher Full Text](#)
3. Springmann M, Godfray HC, Rayner M, Scarborough P: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proc Natl Acad Sci U S A*. 2016; **113** (15): 4146-51 [PubMed Abstract](#) | [Publisher Full Text](#)
4. Tilman D, Clark M: Global diets link environmental sustainability and human health. *Nature*. 2014; **515** (7528): 518-22 [PubMed Abstract](#) | [Publisher Full Text](#)

**Competing Interests:** we declare that we have no conflict of interest