



RESEARCH ARTICLE

Effects of environmental change on population nutrition and health: A comprehensive framework with a focus on fruits and vegetables [version 1; referees: 2 approved with reservations]

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Abstract

Environmental changes are likely to affect agricultural production over the next 20–30 years. The interactions between environmental change, agricultural yields and crop quality, and the critical pathways to future diets and health outcomes remain 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 between environmental change, diets and health, and forms the analytical baseline for future modelling and scenario testing. The framework identifies the inter-sectoral datasets and models that need to be defined and populated to assess the impacts of environmental change on agricultural production, food availability, nutrition and population health.

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1. Introduction

Environmental changes, such as climate change, increased ground-level ozone, and changes in water availability, carbon dioxide fertilisation, soil degradation, deforestation and land use change may directly influence agricultural production, as well as having potential indirect effects through changes in the abundance and spread of pests, pathogens and pollinators. Environmental change may consequently also have a substantial impact on food quality and quantity, and therefore the nutrition and health of populations, unless adaptation and mitigation mechanisms are widely adopted (IPCC, 2014).

The scale of the impacts of environmental change on health are not straightforward to estimate and are dependent on many factors. Firstly, the magnitude of environmental change will depend on the current level of stressors (including current environmental conditions and existing technologies), as well as the possibilities for *mitigation* actions taken by society. Secondly, the effects of environmental change will depend on the *adaptation* mechanisms developed and adopted. Thirdly, markets play a key role in distributing food between production and consumption locations. Fourthly, food prices have an influence on consumer behaviour – consumption of some foods are much more sensitive than others to price changes (Cornelsen *et al.*, 2015). Finally, the effect of changing food availability on nutrition and health is likely to differ between countries and population groups. Therefore, predicting the impacts of environmental changes on diets and health requires a detailed understanding of the various interactions and feedback loops between numerous variables, as well as information on environmental, social and economic contexts.

Past research has been largely two-dimensional, concentrating only on the impacts of environmental change on crops or the impacts of different diets on health, and only relatively few studies have integrated environmental change, agriculture, markets, nutrition and health (Myers *et al.*, 2017; Smith *et al.*, 2015; Springmann *et al.*, 2016). The 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), whereas the impacts on fruits and vegetables have been less studied. Furthermore, studies considering the impacts of *multiple* environmental stressors on agricultural production and crop quality are lacking, so important interactions may be missed. Addressing these evidence gaps is critical to allow researchers and policy makers to understand and respond to the influences of environmental change on nutrition and health globally.

The aim of this paper is to illustrate a set of pathways that connect environmental change, agriculture, nutrition and health in a comprehensive framework. Our framework has a specific focus on fruits and vegetables due to their importance for nutrition and health: low consumption of fruits and vegetables is associated with a significant increase in risk of non-communicable diseases (NCDs), including coronary heart disease and certain types of cancer (Forouzanfar *et al.*, 2016). In addition, recent research has shown reduced risk of cardiovascular disease, cancer and all-cause mortality with fruit and vegetable intakes even beyond the WHO recommendation of 400 grams a day (Aune *et al.*, 2017). In addition, the framework

is designed to be used to consider many other pathways between environmental changes and health via agriculture and provides a basis for identification and detailed modelling of the key pathways that link environmental change – through agriculture and nutrition – with population health.

The framework was constructed based on an extensive literature search, including both peer-reviewed and grey literature. The selection of main component groups in the framework was informed by existing frameworks linking environmental change with food security (e.g. Ingram (2011); McMichael (2003)), and the framework was developed further following consultations with experts working in the fields of environment, agriculture, trade, nutrition and health.

The framework is presented in three stages: i) a schematic overview of the main components (Section 2, Figure 1); ii) illustration of the interactions between different environmental stressors (Figure 2); and iii) the links between environmental stressors and agriculture (Figure 3). The most important interactions between environmental change and production of fruits and vegetables are reviewed in Section 3, and the potential consequences of environmental change on food security, nutrition and health outcomes are discussed in Section 4. The feedback loops from dietary choices to agricultural production and the impacts of agriculture on environmental change are discussed in Section 5.

2. 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 3). The interventions component includes research, 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 operate over different time scales, for example, the change 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.

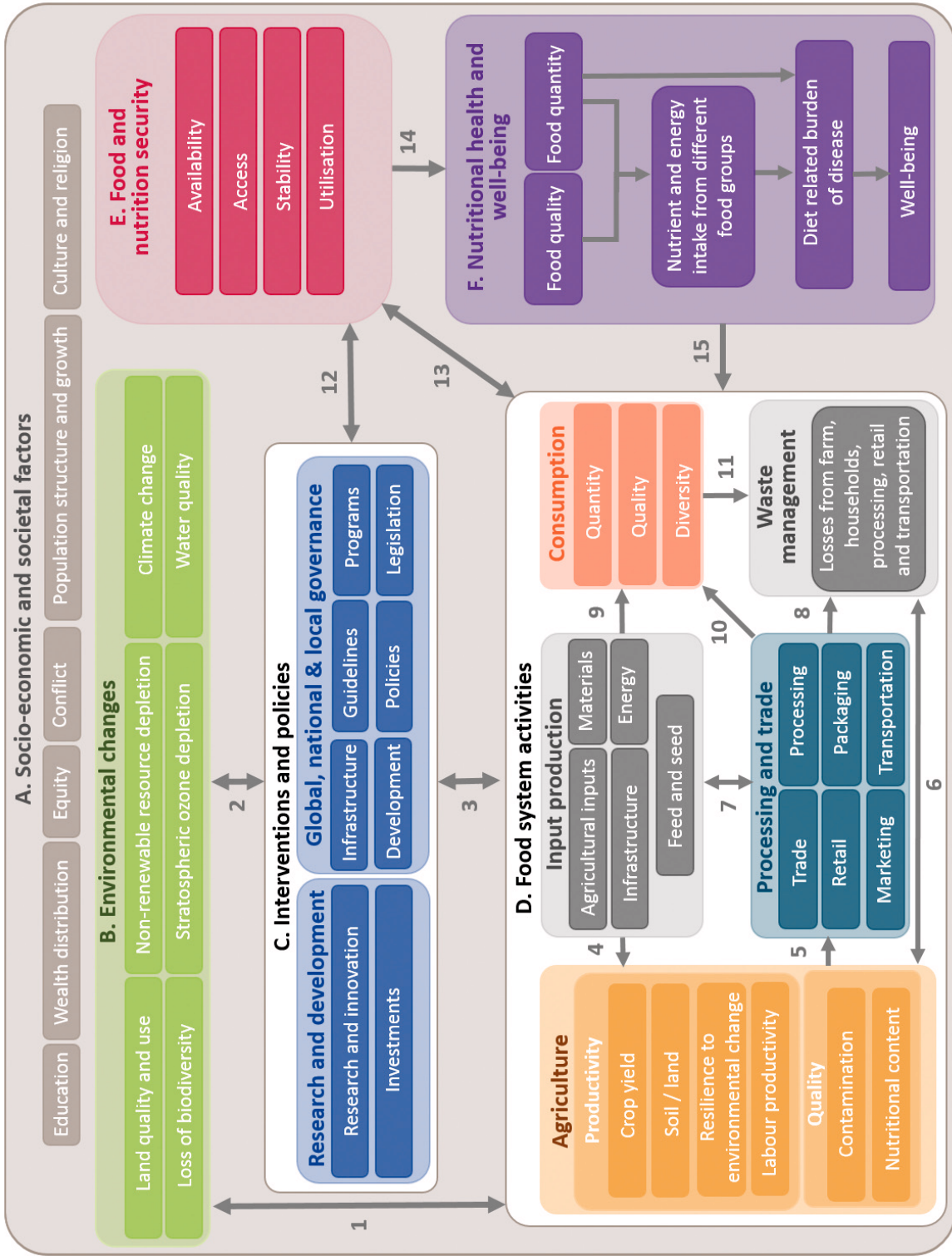


Figure 1. Overall framework connecting environmental change, agriculture, nutrition and health.

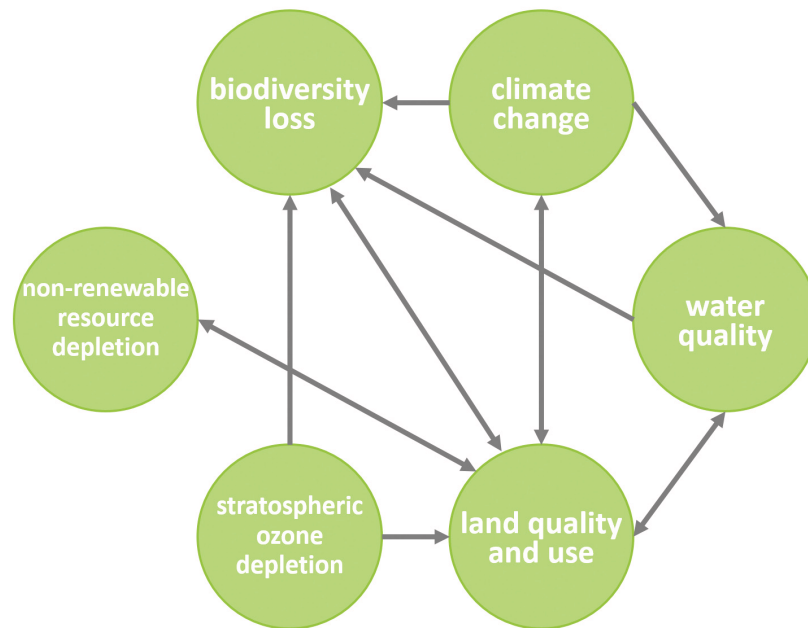


Figure 2. Links between environmental changes.

3. Impacts of environmental change on agricultural production

3.1. Climate change

Climate change has been predicted to impact agricultural production through multiple direct and indirect pathways. 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). Climate change is also likely to increase crop losses and damages due to pests, pathogens, fungi and weeds (Flood, 2010). However, there are also positive impacts reported: increased carbon dioxide concentrations in the atmosphere can boost photosynthesis and water use efficiency, and improve crop growth (Long *et al.*, 2006). However, this can lead to a yield dilution effect, whereby concentrations of micronutrients in the edible product decline (Myers *et al.*, 2014; Myers *et al.*, 2015).

Indirectly, increased temperatures may affect the 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.

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 decrease of plant pollinator populations, for example, it could have multiple impacts on agricultural production (see Section 3.6).

3.2. Stratospheric ozone depletion

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. The depletion of the stratospheric ozone layer by 1% increases the UV-B radiation that reaches the planet by 2% (Cutchis, 1974). 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). Many factors such as cloud cover, altitude, ground reflectance and atmospheric path length, impact on the level of UV-B reaching plants.

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). A meta-analysis found that 18–100% increases in UV-B radiation compared to the ambient level reduced the biomass accumulation in woody and herbaceous plants by 7–14.6% (Li *et al.*, 2010). Herbaceous plants including most vegetables (e.g. beans, tomatoes, spinach, radish, carrots, cucumber and gourd) and many fruits (such as strawberries and sea-buckthorn) were found to be more affected than woody plants.

3.3. 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).

Environmental changes

Agriculture

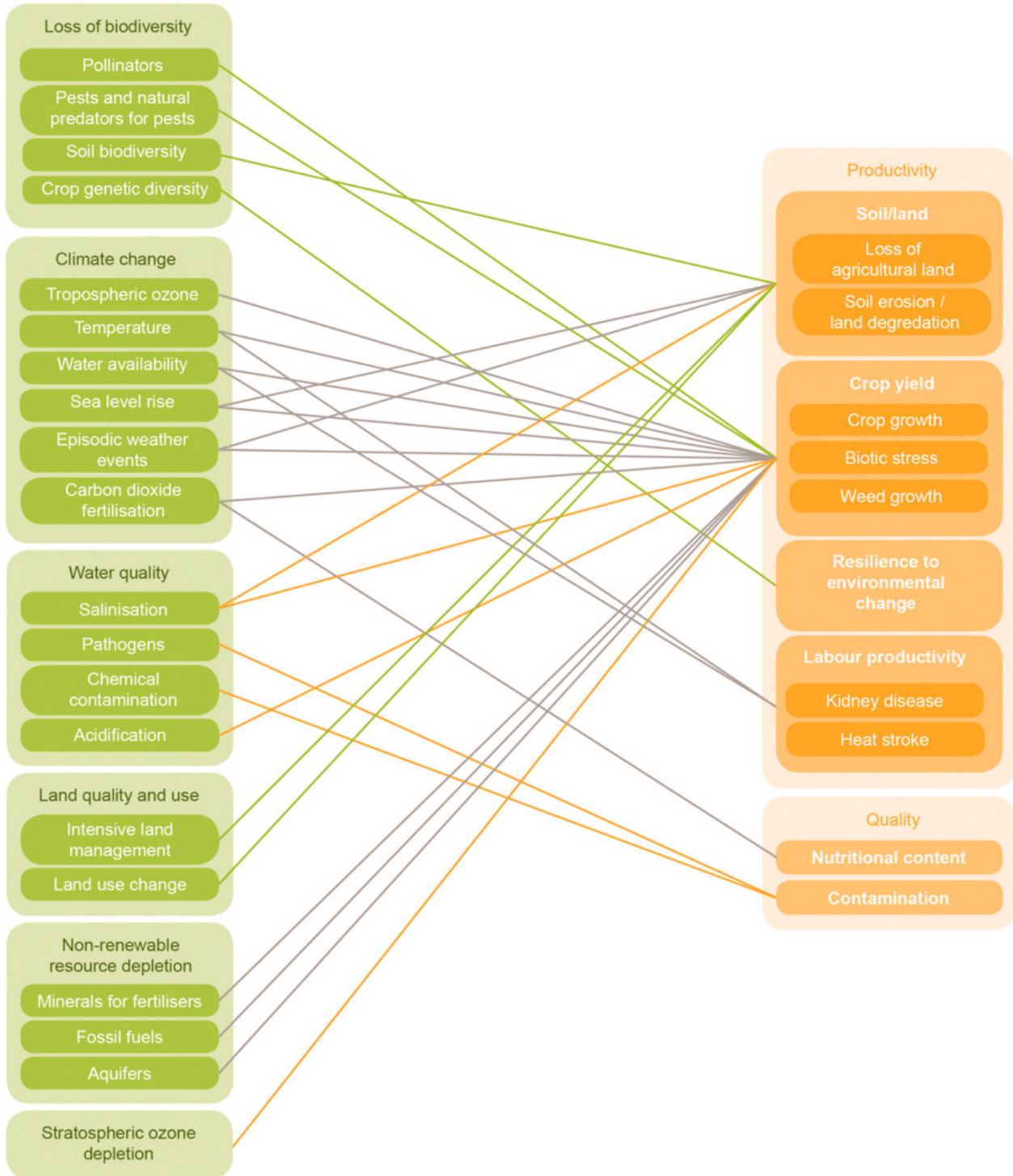


Figure 3. Pathways between environmental changes and agriculture.

A major threat to irrigation water quality is salinization. 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. 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).

Toxicity of irrigation water is another major water quality problem that could affect crop quantity and quality. Problems 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 water-sheds 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)fertilization of agricultural land, whereby excess fertilisers end up in water sources used for irrigation and may damage marine ecosystems. In sensitive 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.

3.4. 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 may pose a threat for agricultural production unless renewable energy sources can be significantly scaled up. Finally, the depletion of aquifers can have negative impacts on agricultural production in areas where aquifers provide an important source of irrigation water. This may reduce agricultural production or require switching to less water demanding crops (Harris *et al.*, 2017).

3.5. 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.

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 an important 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. Soil acidification could alter nutrient availability, and therefore, plant growth: the effects on plants are generally negative, however acidification could be beneficial in alkaline soils (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.

3.6. Biodiversity loss

Field-grown crops and livestock are 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). A complete loss of pollinators has been predicted to reduce global fruit supply by 23%, vegetables by 16% and nuts and seeds by 22% (Smith *et al.*, 2015). Due to the importance of fruits and vegetables in a healthy diet, their reduced availability resulting from pollinator loss would likely have serious implications for human health.

In some cases, losses of biodiversity can have direct impacts on food availability in areas where wild food, such as wild plants, game meat and insects, compose a substantial proportion of diets.

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).

4. Impact of drivers, influencers and activities on intermediate and final outcomes

4.1. 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.

Considering the predominantly negative influences of environmental stressors on both fruit and vegetable yield and quality (see previous sections), populations relying on subsistence farming appear likely to have food insecurity in the future (Morton, 2007; Shrestha & Nepal, 2016; Tibesigwa *et al.*, 2015). The extent of the influence on their nutrition and health depends on the farmers' ability to adapt to these environmental changes (Shisanya & Mafongoya, 2016; Tibesigwa *et al.*, 2015). This large group is often particularly vulnerable due to its 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 context 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 determines the impact of suboptimal yields on food security, including market mechanisms and food choices (■ D), possible technological or political interventions (■ C) and the influence of social factors (■ 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 no substitution for the “missing” vegetable, etc. Their substitution strategy will partly determine the impact on their and their family's nutritional health (UNSCS, 2010). However, 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). Especially 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 encourage less consumption, which could also have an impact on their food security (Anriquez *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 (▲ 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 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, small changes in vitamin and mineral concentration in crops – but no actual change in diet – could be crucial for food and nutrition security. Fruits and vegetables are therefore particularly important as they provide essential micronutrients that are present in much lower concentrations in other food groups.

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

There is a large 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 (▲ 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, toxins, etc.). 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 (■ F).

Fruits and vegetables play a key role in the link between nutrition and 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 mortality, coronary heart disease, strokes, and several types of cancer (Forouzanfar *et al.*, 2016).

To further explore the importance of the pathway between fruit and vegetable consumption and health, full dietary compositions (i.e. consumption besides fruits and vegetables) should be taken into account, as well as the drivers for food choices. Low fruit and vegetable intake can in some situations be the direct results of food insecurity, 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.

5. Feedback loops from dietary choices and agriculture to environmental change

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

A remarkable example of these feedback loops is based on the consumer-driven rapid global shift towards a more “Western” diet (Popkin, 2006). 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 through expansion of agricultural land (Gerber *et al.*, 2013).

Agricultural land, including arable and grassland, occupied 38.5% of the ice-free land area globally in 2011 (FAO, 2017). Global deforestation is mainly driven by an increased need for agricultural land, especially for feed production. Fruit and vegetable production occupies only a small percentage of the total agricultural land area.

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 ~2.5% of the UK's total emissions (Garnett, 2006). Generally, fruits and vegetables have a lower carbon footprint compared to livestock products and grains when measured per unit of product weight, but 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 m³/t for watermelon to 3350 m³/t for 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 (Tuomisto *et al.*, 2012). 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. Tschamntke *et al.* (2012) points out that there is a clear difference between the type of biodiversity that land

sparing and land sharing approaches support. The land sparing idea mostly ignores the value of functional agrobiodiversity that helps to increase the resilience of the farming systems to environmental changes. Furthermore, it is not guaranteed that land sparing leads to additional conservation of natural habitats.

6. Conclusions

The evidence-based framework provides an overview of the multidimensional and complex interactions between environmental change, the food system, nutrition and health, and forms an analytical baseline for detailed investigation of these interactions. The framework has a focus on fruits and vegetables and takes a global view, but can be used more generically for all food groups as well as for regional case studies. Some 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 important 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.

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: ? ?

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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 2016,¹ ; 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 study² 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 studies³, 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 article⁴ 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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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 2016,¹; 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 study² 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 studies³, 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 article⁴ 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.

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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](#)

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

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**John McDermott**

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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/). 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 production¹. 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:

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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/). 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 2016,¹; 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 study² 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 studies³, 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 article⁴ 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](#)
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