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The effect of climatic factors on nutrients in foods: evidence from a systematic map

Scarpa Giulia¹, Berrang-Ford Lea², Zavaleta-Cortijo Carol³, Marshall Lisa⁴, Sherilee L Harper⁵ 
and Cade Janet Elizabeth⁶

¹ School of Environment and School of Nutrition, University of Leeds, Leeds LS2 9JT, UK

² School of Environment, University of Leeds, School of Environment, Leeds LS2 9JT, UK

³ Facultad de Salud Publica, Universidad Peruana Cayetano Heredia, Facultad de Salud Publica, San Martín de Porres 15102, Peru

⁴ School of Food Science, University of Leeds, School of Food Science, Leeds LS2 9JT, UK

⁵ School of Public Health, University of Alberta, School of Public Health, Edmonton AB T6G 2R3, Canada

⁶ School of Nutrition, University of Leeds, School of Nutrition, Leeds LS2 9JT, UK

E-mail: eegs@leeds.ac.uk

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Supplementary material for this article is available [online](#)

Abstract

Climate change is projected to negatively affect human health and nutrition. There is a growing literature on the effects of climatic changes on food availability, quantity, and agricultural production, but impacts on the nutritional content of foods has not been widely studied. The aim of this paper is to systematically characterise empirical literature exploring the effects of climatic drivers on macronutrients and micronutrients in foods causing malnutrition globally. 69 peer-reviewed empirical articles (excluding experimental and modelling studies) analysing the effect of climatic drivers on nutrients in foods were retrieved from Web of ScienceTM, Scopus[®] and PubMed[®] databases (2013–2019). Publication frequency and trends, and existing evidence of the extent of nutrient change associated with variation in climate-related conditions were assessed. There is relatively limited literature on associations between climate and nutrients in foods. Where it exists, only crude proxies of climate (e.g. wet/dry season) are used, with limited interrogation of the potential causal mechanisms linking climate to nutrient content. 98% of the articles showed a change in nutrient content in relation to a seasonal or meteorological variable. Most analysed the association of nutrient changes between seasons over 1–2 years, rarely over longer periods of time. Preliminary descriptive estimates point to variation in nutrient content by meteorological variability, particularly in ocean and freshwater food sources. Robust assessment of potential climate impacts on nutrient content of foods would benefit from more precise estimation of specific causal pathways and variables that mediate climate impacts on food, going beyond seasonal or crude proxies. There is need for clear articulation of how climate change might impact nutrient content given mechanisms linking meteorological and seasonal variation with nutrients. This research highlights emerging evidence that climate change may have impacts beyond agricultural productivity by affecting food nutrient content, an understudied but potentially important pathway for climate impact on global food and nutrition security.

1. Background

Malnutrition—associated with deficiencies or imbalances in caloric or nutrient intake—is a major cause of ill health and burden of illness worldwide (WHO 2013, 2018). Nearly half of deaths among children under 5 are attributable to undernutrition caused

by inadequate dietary intake and disease, typically stemming from a combination of food insecurity, inappropriate maternal and child feeding practices, and/or poor health services (WHO 2018). Climate change will affect the variability of the weather and environmental conditions that underpin global agriculture (Swinburn *et al* 2019). Agriculture and

crop production are, thus, expected to be among the major pathways of impact for climate on health, with growing projections of decreases in the productivity of major global crops (Hertwich *et al* 2010, Smith *et al* 2014, FAO and USAI 2017, IPCC 2019).

The effects of climate change on agriculture are projected to negatively impact global nutrition, and this is likely to increase in the future (Challinor *et al* 2007, Lobell *et al* 2008, UNSCN 2010, Godfray *et al* 2010, Wheeler and von Braun 2013, Springmann *et al* 2016). Effects will be particularly severe in sub-Saharan Africa and South Asian countries where the burden of malnutrition is already high and health systems are in many cases strained or weak (IPCC 2014, Springmann *et al* 2016, Willett *et al* 2019). Malnutrition is a risk factor for neonatal and child mortality, as well as for maternal reproductive and other health outcomes (Pelletier and Frongillo 2003, Black *et al* 2008, Xu *et al* 2012, Rylander *et al* 2013, Gakidou *et al* 2017, Rodriguez-Llanes *et al* 2011, Ly *et al* 2018). Further, poverty exacerbates food insecurity and undernutrition, and without adaptation strategies malnutrition is expected to increase (Grace *et al* 2012, FAO and USAI 2017).

There is a growing literature reviewing the evidence of climate change, or proxies of climate change such as seasonality or meteorological/weather variability, on food production and nutritional status. The predominant focus of this literature has been on assessing current/past associations of climate or weather variability with food quantity or crop productivity, or projecting future trends in nutritional status based on estimates of crop productivity. There has been relatively limited consideration, however, of potential climate impacts on malnutrition through mechanisms of *changing nutrient content of foods*. Macronutrients and micronutrients are part of a healthy diet, and they ensure appropriate development and wellbeing and prevent diseases. Children aged between 6 months and 5 years in particular suffer from micronutrient deficiencies (WHO 2013). Vitamin A, iodine, and iron are the most common deficiencies and a concern for public health (WHO 2014). Iron deficiencies in pregnant women increase the risk of maternal and child mortality, and low birth weight. Iodine deficiency affects the neurological development of children, while vitamin A deficiency raises the probability of blindness and mortality due to infectious diseases during childhood (WHO 2013). One systematic review (Phalkey *et al* 2015) analysed the impacts of climate change on undernutrition, but did not focus on mechanisms of impact via food micronutrients or macronutrients. A 2018 study by Scheelbeek *et al* (2018) systematically investigated the effect of environmental change on vegetable and legume yields, in particular exploring projections in the potential future nutritional quality of vegetable and legume yields under environmental change.

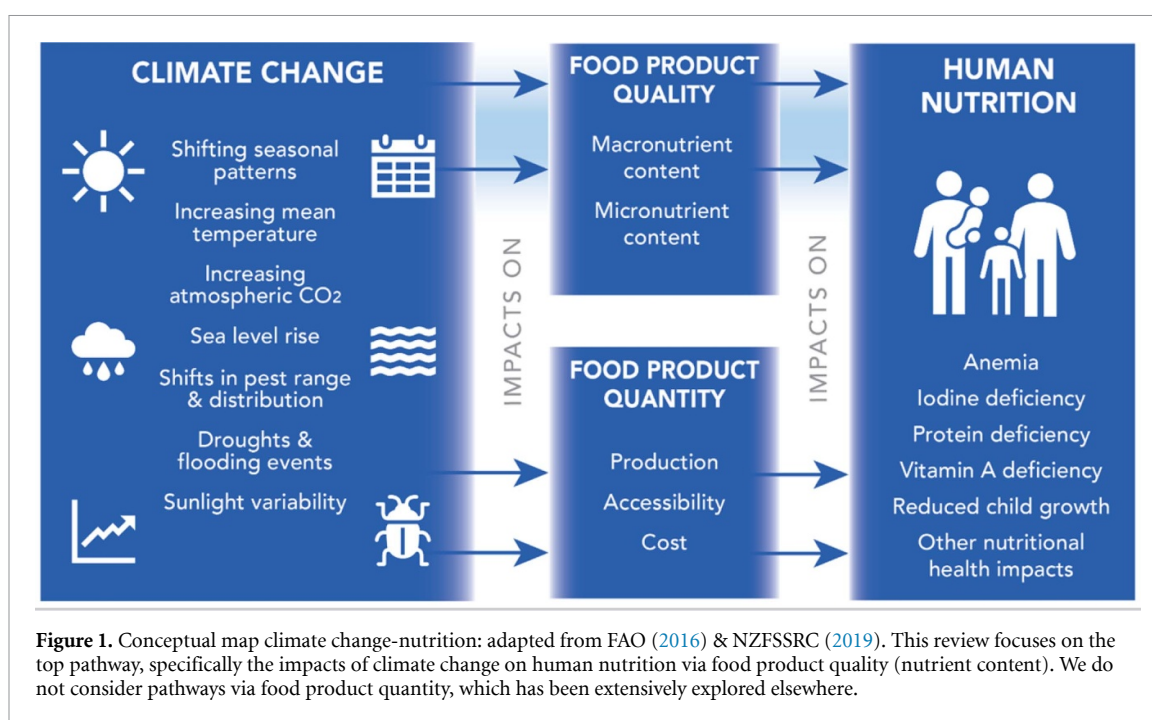
Generally, climate change affects the molecular function, the developmental process, the morphology and the physiological responses of plants (Myers *et al* 2014). Elevated CO₂ promotes higher yields, but alters the equilibrium of the plant carbon metabolism and mineral composition as well as nutrient-use efficiency (Nakandange and Seneweera 2018). Furthermore, the effect on plants mostly depends on genotype and interactions of each nutrient with climatic factors (Soares *et al* 2019). For example, drought and high temperatures induce oxidative damage in legume plants according to the review of Soares *et al* (2019), and this is more likely to have an effect on the macronutrients.

Despite this emerging interest, we identified no systematic reviews of studies focusing on the impact of climate and climate change on nutrients in foods. This review responds to a research gap on the impact of climate, climate change, and its proxies on nutrient content of foods. The particular and unique focus of this review is on systematically synthesising empirical evidence on the impact of weather, climate, and climate change on *nutritional content* of foods. This focus adds new value to existing evidence, and complements a predominant focus in existing literature on climate impacts via crop productivity.

2. Methods

2.1. Conceptualising climate impacts on food nutrient content

Though interested primarily in climate and climate change, we consider proxies of climate change as eligible exposures in this review. Climate is not synonymous with weather/meteorological variability. 'Climate' refers to long-term changes in the atmosphere, with climate variability observed over long temporal scales (years, decades, centuries). 'Weather' or meteorological variability, in contrast, represents daily observable conditions such as temperature, precipitations and wind, which vary and can be observed throughout the day and at finer timescales (IPCC 2013, 2018). Climate change will impact malnutrition by affecting patterns in weather, including trends in precipitation and temperature, as well as the frequency and magnitude of extreme weather events. It is difficult to study climate associations with human health given that data for both climate and health would be required for long time periods (ideally > 10 years) (Descoux *et al* 2012). It is thus common for research to explore the associations between weather and health outcomes at more feasible temporal scales (daily, weekly, monthly, or yearly over < 5 years) as a proxy for potential climate change impacts. This includes variables such as season, short-term trends and variation in precipitation or temperature, and meteorological events such as heatwaves, droughts, and floods (Haines *et al* 2006, Hunter 2012) as proxies for climatic change. Notably, associations



between weather and meteorological variability and health outcomes are not necessarily representative of how outcomes will change under a changing climate. Recognising the predominant use of proxies of climate change, however, eligible articles included variables related to weather and meteorological variability.

Indeed, climate change influences seasonal variability, in terms of averages and variation in precipitation and temperature, as well as the frequency of extreme events (figure 1), and those may impact on human health. For example, there is an association between higher temperatures and increased heat stress during pregnancy (Grace *et al* 2015), while droughts and floods have the potential to enhance food insecurity, reduce child growth, and increase the burden of diseases (Danysh *et al* 2014, Pradhan *et al* 2015).

While the impact of climatic stressors on food security has been explored (Challinor *et al* 2007, Lobell *et al* 2008, UNSCN 2010, Godfray *et al* 2010, Wheeler and von Braun 2013), less attention in the literature has focused on how climate change could affect nutritional content of foods as existing nutritional analyses rarely consider changes over time. Some modelling and experimental studies conducted in laboratory have identified correlations between climate change or meteorological variation and a decrease in food quality in terms of diversity, nutrient density, and safety (Patz *et al* 2005, McMichael *et al* 2006, Kuhnlein *et al* 2013, Park *et al* 2019) (table 1).

Carbon dioxide (CO₂), for example, may have a negative effect on the nutritional content of several crops such as wheat, potatoes, rice, and peas (Porter *et al* 2014). For example, concentrations of

iron and zinc in wheat and rice are more likely to be reduced due to increased greenhouse gas emissions (Myers *et al* 2014). Higher CO₂ associated with climate change is hypothesised to lead to micronutrient deficiencies (Müller *et al* 2014, Myers *et al* 2014, 2015, Smith, *et al*, 2017).

2.2. Review Approach

A systematic mapping review approach was employed as per the ROSES Reporting Standards for Systematic Evidence Synthesis (Haddaway *et al* 2018) to assess the association of any climatic/meteorological factors with macronutrients and micronutrients in edible products. We included articles from 1st January 2013, based on the publication date of the keystone IPCC report on climate change (IPCC 2013) to 30th June 2019.

The geographical scope of the review is global, with no restriction by geographical area (population). To be eligible for inclusion, articles were required to include at least one paragraph describing a climate-related variable within analyses, including measures of weather, meteorological variability (temperature or precipitation), season, climate, or climate change (exposure). Articles were also required to explicitly describe and include measures of food nutrient content (outcome), specifically micronutrients or macronutrients that are causes of nutritional deficiencies globally according to WHO (2019). The review comprises all types and categories of food. We included empirical papers in order to focus on place-based data in real world contexts; experimental and modelling studies were thus excluded.

Table 1. Climate variables used to assess the impact of climate on nutritional content of foods.

Climate variables	Definition	Impact on foods
<i>Change in CO₂</i>	Carbon dioxide concentrations in the atmosphere	Changes in CO ₂ have been associated with decreased availability and production of foods (IPCC 2019). Fanzo <i>et al</i> (2018) postulate that climate change and increasing levels of carbon dioxide could significantly reduce the availability of critical nutrients in foods products, including protein, iron and zinc.
<i>General seasonal variability</i>	Inter-seasonal variability (variability among one season and the next one). It includes any intra-annual seasonal categorization, including for example 4 seasons (winter, spring, summer, autumn), 2 seasons (dry, wet), or monsoonal seasons	Shifting seasonal means and increased seasonal variability will impact food production, pests and diseases in crops and livestock (Fanzo <i>et al</i> 2018). This has the potential to include impacts on the nutrient quality of foods due to accelerated development under warmer conditions (Bisbis <i>et al</i> 2018)
<i>Precipitation variability</i>	The quantity and variability over time of precipitation (e.g. rain, snow); extremes are associated with flooding or droughts	Precipitation change and increased variability can decrease land productivity and soil quality (Vermeulen <i>et al</i> 2012). Particularly, poor soil quality restricts crop productivity and nutritional quality, particularly micronutrients (Hertwich <i>et al</i> 2010).
<i>Sunlight variability</i>	Quantity and temporal variability of sunshine	Droughts will impact agriculture, especially by decreasing crop yields, livestock productivity and fisheries (FAO and USAI 2017). An experimental study (Hummel <i>et al</i> 2018) showed that the nutritional quality (especially micronutrients) of different type of beans were reduced under drought stress.
<i>Sea level rise</i>	Rise of sea levels along coasts, associated with thermal expansion of ocean waters and glacial melting	Through sea level rise, there will be an increasing of groundwater salinization affecting the quantity and quality of water with consequences on crops and plants quality (Adams 1989). Further, it will pose new transportation challenges for foods (Wakeland <i>et al</i> 2012). If the food supply chain is interrupted, this can have consequences on the nutritional value of foods during processing (Hawkes and Ruel 2012).
<i>Temperature variability</i>	Change in average or variability of temperature overtime	Food insecurity is projected to increase with global warming (IPCC 2018). Higher temperatures and decreased water availability impact negatively on food quality and safety, and increase food spoilage and waste (Vermeulen <i>et al</i> 2012).

2.3. Searches

Keyword searches were conducted in Scopus®, Web of Science™, and PubMed®. A search string was created for PubMed® and then adapted for the other databases on consultation with team members and a research librarian. The PubMed® MeSH database was consulted to generate indexing terms for ‘climate

change’ and ‘season’ and the terms were adapted from Bryson and Scheelbeek (Scheelbeek *et al* 2018, Bryson *et al* 2020). Search terms for nutrients were adapted from WHO and FAO (WHO 2013, 2019, FAO 2013). After adapting the search string, Scopus® and Web of Science™ were searched in June 2019 (table 2). Additionally, a reference checking was performed

Table 2. Results from each database of the final search string on studies exploring impact of climate on nutritional content of foods included in the review.

Database	Search String
Web of Science	TITLE: (climat* OR greenhouse OR temperature OR “extreme weather“ OR heatwave* OR heat-wave* OR “heat wave“ OR “extreme cold“ OR flood* OR “storm surge“ OR landslide* OR windstorm* OR cyclone* OR humidit* OR drought* OR “quality W/1 water“ OR “availability W/1 water“ OR biodivers* OR “health of the planet“ OR UV OR season* OR rain* OR precipitation* OR drought) AND TITLE: (micronutrient* OR macronutrient* OR nutrient* OR nutrition* OR nutritious OR vitamin* OR mineral OR iron OR zinc OR calcium OR beta-carotene OR “beta carotene“ OR betacarotene OR folate* OR “folic acid“ OR “folic-acid“ OR folicacid* OR “amino acid“ OR “amino-acid“ OR aminoacid* OR iodine OR phosphorus OR phosphorous OR magnesium OR fat OR fats OR protein OR proteins OR carbohydrate OR carbohydrates) AND TOPIC: (*nutri* OR food*) Refined by: DOCUMENT TYPES: (ARTICLE)
Scopus	TITLE (climat* OR greenhouse OR temperature OR “extreme weather“ OR heatwave* OR heat-wave* OR “heat wave“ OR “extreme cold“ OR flood* OR “storm surge“ OR landslide* OR windstorm* OR cyclone* OR humidit* OR drought* OR “quality W/1 water“ OR “availability W/1 water“ OR biodivers* OR “health of the planet“ OR uv OR season* OR rain* OR precipitation* OR drought) AND TITLE (micronutrient* OR macronutrient* OR nutrient* OR nutrition* OR nutritious OR vitamin* OR mineral OR iron OR zinc OR calcium OR beta-carotene OR “beta carotene“ OR betacarotene OR folate* OR “folic acid“ OR “folic-acid“ OR folicacid* OR “amino acid“ OR “amino-acid“ OR aminoacid* OR iodine OR phosphorus OR phosphorous OR magnesium OR fat OR fats OR protein OR proteins OR carbohydrate OR carbohydrates) AND TITLE-ABS-KEY (*nutri* OR food*) AND (LIMIT-TO (DOCTYPE, “ar”))
PubMed	((climat* OR greenhouse OR temperature OR “extreme weather“ OR heatwave* OR heat-wave* OR “heat wave“ OR “extreme cold“ OR flood* OR “storm surge“ OR landslide* OR windstorm* OR cyclone* OR humidit* OR drought* OR “quality W/1 water“ OR “availability W/1 water“ OR biodivers* OR “health of the planet“ OR UV OR season* OR rain* OR precipitation* OR drought)) AND (micronutrient* OR macronutrient* OR nutrient* OR nutrition* OR nutritious OR vitamin* OR mineral OR iron OR zinc OR calcium OR beta-carotene OR “beta carotene“ OR betacarotene OR folate* OR “folic acid“ OR “folic-acid“ OR folicacid* OR “amino acid“ OR “amino-acid“ OR aminoacid* OR iodine OR phosphorus OR phosphorous OR magnesium OR fat OR fats OR protein OR proteins OR carbohydrate OR carbohydrates)

on articles included for the review. A similar search methodology was used in other systematic map and reviews (Phalkey *et al* 2015, Bishop-Williams *et al* 2017, Bryson *et al* 2020). The search was updated until November 2019, but no new articles were found relevant for the review. The reference management software EndNote® was used to extract and collect the search results. No restrictions on language were applied; however, all search terms were in English, restricting the review to articles indexed in English (i.e. title and abstract translated if full text was non-English).

2.4. Article Screening

Articles were screened using predefined selection criteria (table 3), screening first by title and abstract, and then by full text. To ensure quality of screening and conduct consistency checking, a second reviewer screened a sample (10%) of articles.

2.5. Data Extraction and Analysis

Results were exported to Excel® for coding and analysis. Descriptive information was extracted, including title, name of journal, author(s), year of publication, country of origin, type of food studied, food category, type of micronutrient(s) and/or macronutrient(s), climate variable or proxy studied, scale of temporal comparison, theorised mechanism for climate impact, and main findings in terms of climate-nutrient associations. The foods found in the articles were grouped into 10 main categories following FAO/WHO Food Standards (FAO 2020): cereals, vegetables, fruits, legumes, dairy, meat, fish, eggs, bee products, and tea. Macronutrients and micronutrients analysed by the studies included carbohydrates, proteins, lipids, iron, vitamin A, zinc, iodine and vitamin D. These specific nutrients were chosen for analysis as they are the most common drivers of nutrient deficiency causing malnutrition globally (WHO 2019).

Table 3. Inclusion and exclusion criteria on studies exploring impact of climate on nutritional content of foods included in the review.

Inclusion criteria	Exclusion criteria
(1) Empirical papers of studies conducted in real world settings.	(1) Experimental studies in laboratory or greenhouse, model-based studies.
(2) Analyses include a climate variable or a proxy variable of climatic variability (e.g. extreme event, season)—at least one paragraph.	(2) Contain less than a paragraph describing the climate variable or proxy, or no relevant variable analysed.
(3) Analysed the association of a climate variable (or proxy) with a variable measuring nutrient content (food quality).	(3) Describes associations with availability/quantity of food rather than quality (nutrient content).

Climate factors were analysed into 6 key groups based on an *a priori* review of the literature: change in CO₂, general seasonal variability, precipitation variability, sunlight variability, sea level rise, and temperature variability (table 3). The analytic focus of articles as months, seasons, years, and decades was categorized to reflect the temporal resolution of comparisons of change in climate (proxies) and nutrient content over time.

Graphs and descriptive statistics were used to display the number of publications by: year over time, geographical area, climatic variable, methodological approach, and food category. Meta-analysis was not feasible given high heterogeneity in the variables and methods used to measure climate variability and nutrients. Counts of the number of publications were used for all combinations of food type-climate variable and nutrient type-climate variable to generate 'heat maps' indicating the frequency of publications across different food type, nutrient, and climate variable categories. Where possible, estimates of change in nutrients for contrasting climatic/meteorological conditions were extracted by calculating the difference between the extreme values, and converting the difference found in percentages. The percentage difference was calculated in nutrient content for fish, dairy, and vegetable categories. Quantitative data were extracted for three food categories only, as there were an insufficient number of studies or relevant data for extraction in other food categories. For this sub-set analysis, we used twenty articles, including fish ($n = 14$), dairy ($n = 3$) and vegetables ($n = 3$). These estimates were categorised by food category and nutrient type and results were summarised in tables as indicative estimates and ranges of nutrient

variability by environmental-climatic-weather conditions.

2.6. Assessment of Confidence of Key Findings

As this review reflects a systematic map (Haddaway et al 2018), our objective was to summarize the scope and breadth of research on the topic. We thus did not conduct formal critical appraisal of articles included in the review. However, the articles were appraised to extract information to facilitate assessment of confidence in evidence of our key review findings, focusing on adequacy and coherence of findings. In doing so, we adapt the Grade CERQual (2019) approach to assessing confidence in evidence. As per Grade CERQual, adequacy is 'an overall determination of the degree of richness and quantity of data supporting a review finding,' while coherence is 'an assessment of how clear and compelling or supportive the fit is between the data from the primary studies and a review finding that synthesizes that data.'

3. Results

The databases search retrieved 3524 articles (excluding duplicates) of which 67 were included after title and abstract screening; 14 additional articles were identified through reference checking. Following full text screening, 69 articles met the inclusion criteria, and proceeded to data extraction and analysis (figure 2).

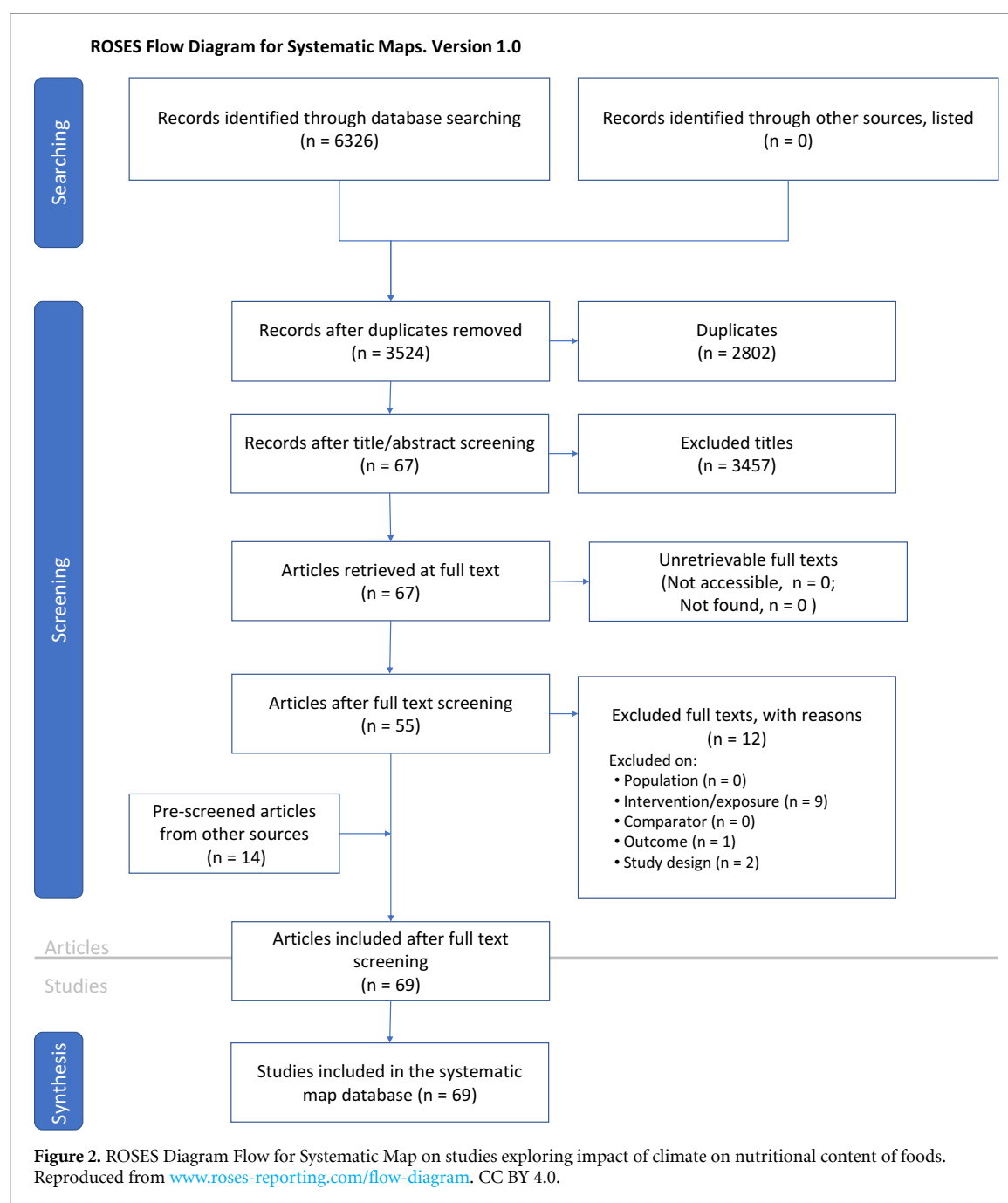
Of 69 studies included in the systematic map data analysis, over the period of publication approximately 10 papers were published per year (figure 3). All included articles ($n = 69$) are empirical and field-based, and employed quantitative methods to analyse the association of climate variability on nutrient content.

3.1. Geography of Included Studies

Studies in the systematic map spanned a range of geographic areas (figure 4). The most studied areas were South Asia, the Middle East, Europe, and the Americas. The three countries with the most articles were India ($n = 12$), Turkey ($n = 9$), and the USA ($n = 5$), which together accounted for ~ 40% of all included studies (figure 4).

3.2. Climatic Variables and Methodological Approach

From the six climate variables investigated, seasonal variability was the most frequently used exposure variable ($n = 62$). Seasonal variability included a range of categorisations, including two (rainy and dry), three (pre-monsoon, monsoon, and post-monsoon), and four (winter, spring, summer and autumn) seasons. Articles investigating data on temperature variables accounted for 11 of 69 articles, including articles on global warming, heat stress, and marine heatwaves. Furthermore, 6 of 69 articles



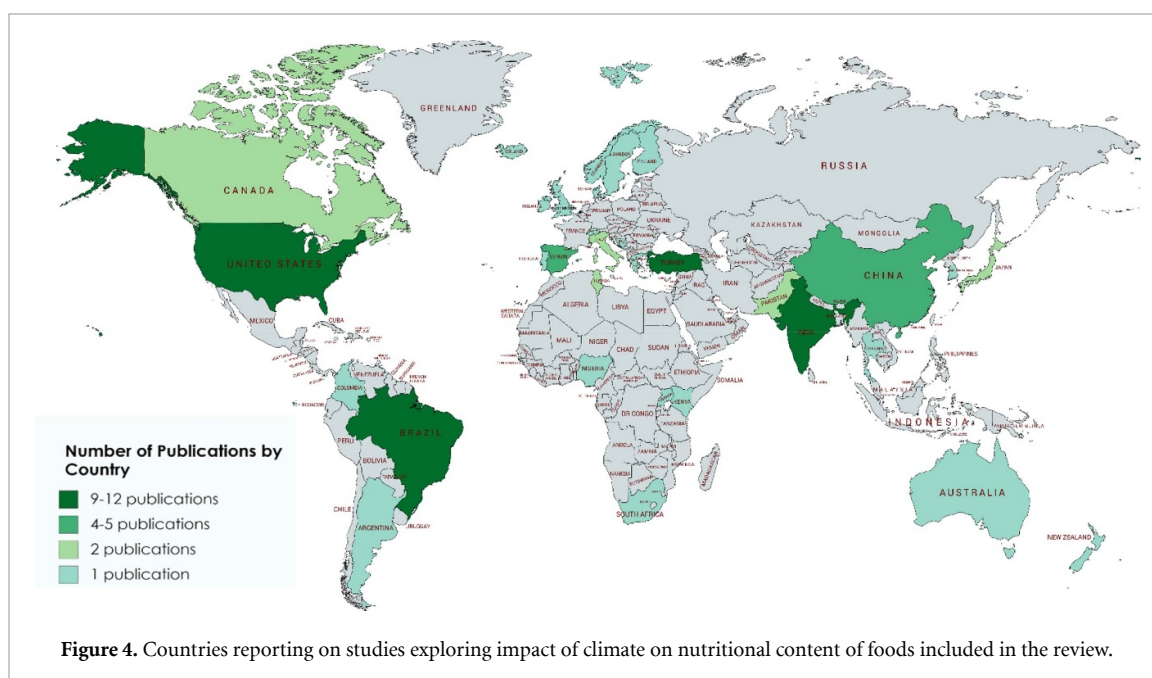
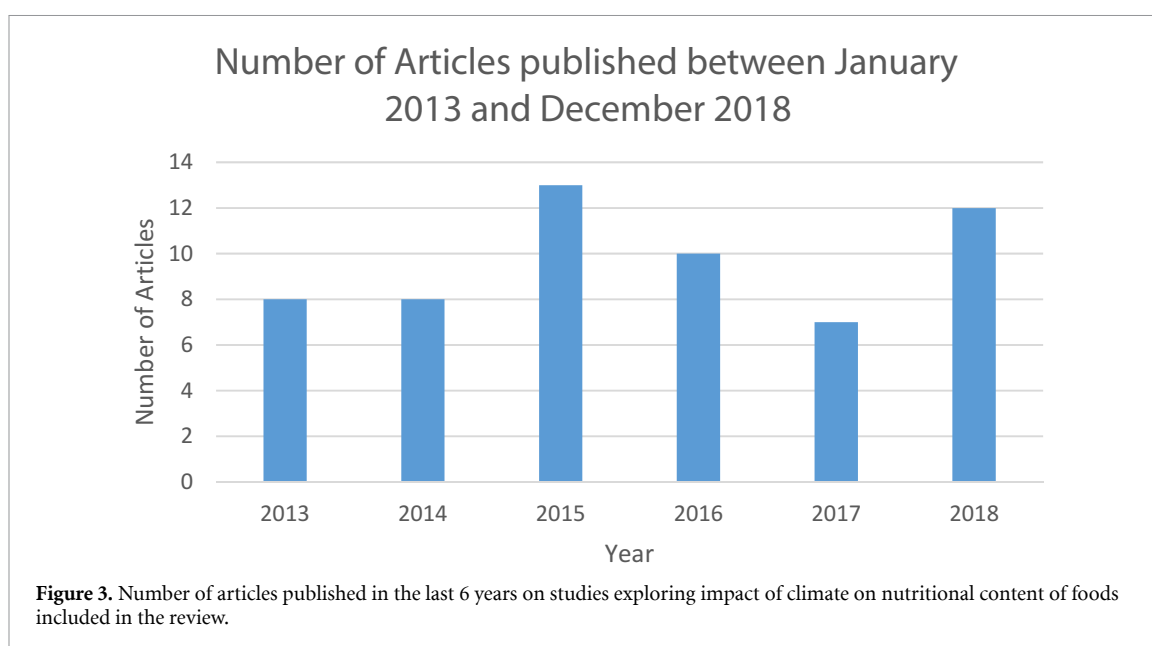
analysed precipitation variability, including floods, droughts, and rainfall intensity. Only one article referred to sunlight variability (figure 5). No articles considered variability in CO₂ or sea levels.

Analyses were conducted at a range of temporal scales (figure 6). Comparison between seasons was the most frequent (45 of 69 articles), followed by comparison between years, studying over a period of ≤ 5 years only (21 of 69 articles), and comparison between months (3 of 69 articles). Conversely, no articles analysed changing nutrients for longer than 5 years.

3.3. Food Products and Nutrients Studied

The articles explored different food products (table 4). No variety of legume or cereal was investigated,

despite comprising a key component of global diets and daily intake of carbohydrates and proteins. In the vegetables category, the majority of the research referred to seaweeds ($n = 7$), mostly consumed in Asia. Results on vegetable articles ($n = 10$) are restricted to India, China, and Japan, with no comparable evidence from other countries. Few articles on eggs ($n = 1$) and meat ($n = 3$) were published. There were no studies investigating chicken eggs or chicken meat. Generally, animal products were under-investigated, except for fish products ($n = 26$). Many different types of fish were studied worldwide, including shellfish and saltwater fish. Data on dairy products included milk and a few types of cheese ($n = 11$). Studies explored bee products and other plant based products (e.g. artemisia) not only



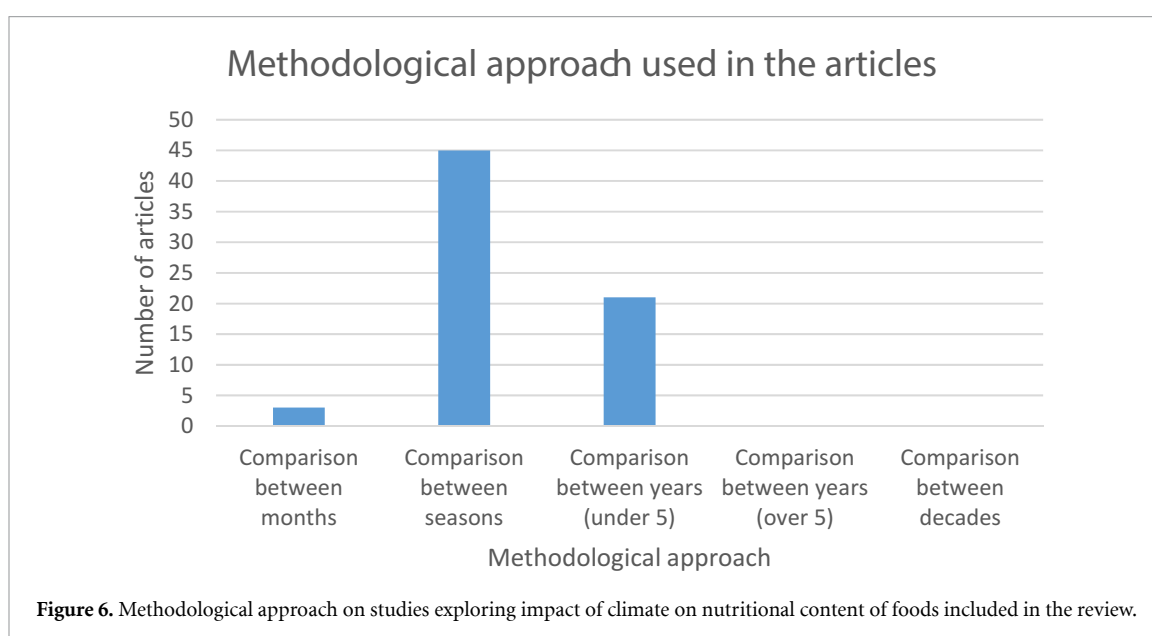
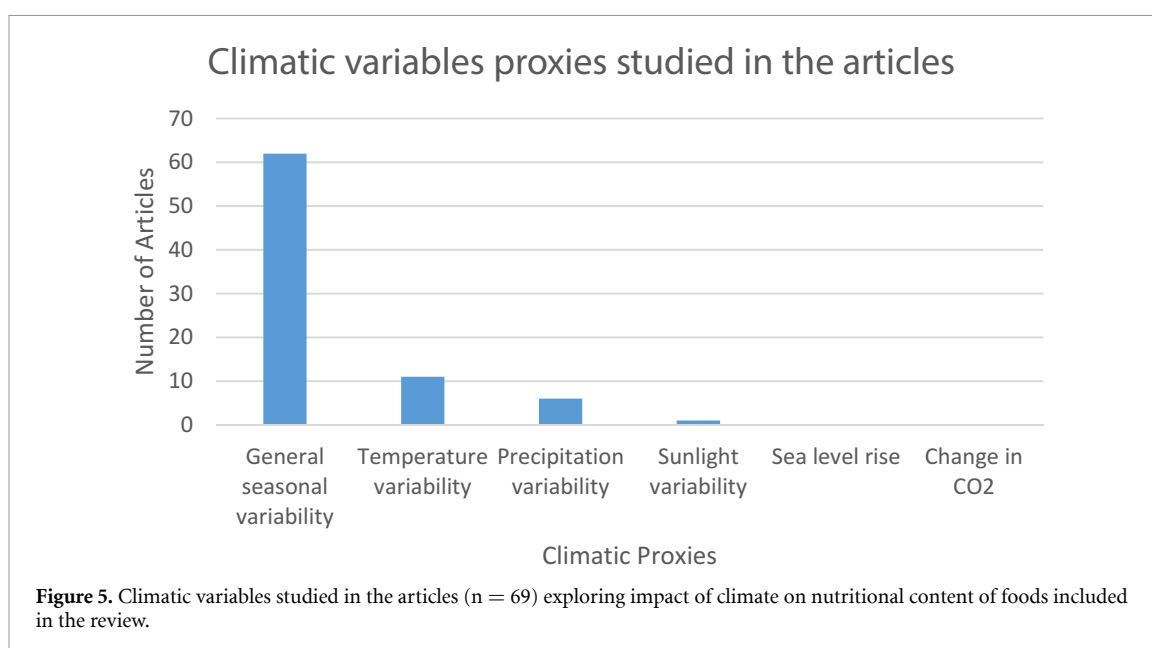
for their quality as foods, but also for their use as medicines.

3.4. Intersection of Climatic Factors and Food/Nutrients examined

There are limited data available on the change in percentages of nutritional content in foods in relation to different climatic variables (tables 5 and 6). The effect of general seasonal variability on food products was the most commonly studied, followed by the links between dairy, vegetables, and fruits with season. The number of articles published on the relationship between legumes and climatic variables is low. Frequently explored nutrients were lipids and proteins, while micronutrients were less studied (iron, zinc, vitamin A, vitamin D and iodine)

(table 6). Although proteins were the most studied, predominantly the literature explored the relationship between proteins and seasonal variability. This related to comparison of rainy and dry (Kumar *et al* 2015), summer and winter (Emre *et al* 2015) or pre- and post-monsoon (Nguyen *et al* 2017) depending on the location. Temperature, precipitation and sunlight variability were overall less studied in relation to nutrients.

We expected a greater volume of evidence on cereal products as there are many models for crops in the literature (Jägermeyr and Frieler 2018, Lobell *et al* 2008, 2011, Lesk *et al* 2016). Despite this, we did not retrieve empirical studies on nutrients in wheat or rice, and generally the number of papers studying the effect of climate proxies on nutrients in other



cereals was very limited, as shown in the heat maps (table 5).

Seven of 10 studies on vegetables referred to edible seaweeds, but these results are unlikely to be generalizable to other vegetables. The category of fish was the most studied, however there is no available evidence on the effect of sea level rise on macronutrients and micronutrients in fish. Conversely, there is research on the impact of environmental changes on aquaculture and quantity of marine flora and fauna (Phillips and Perez-Ramirez 2017).

All reviewed papers reported an association between climate-related variables (season, precipitation, temperature, or sunlight variability) and changes in food nutritional content. However, the magnitude and the direction of the change varied according to the food category or nutrients analysed,

the climatic variables considered, and also in relation to the animal or plant species studied, the nature of the food product (e.g. organic or not organic), and the geographical area where the research was conducted. In the case of fish, macronutrients varied more between seasons than micronutrients, and this was particularly pronounced for proteins and lipids. While some reported changes were low between seasons (e.g. variation in carbohydrates in prawns and crabs in India; variation in iron and zinc in *Liza aurata* fish in Tunisia), other estimates indicated potentially large percentage changes in nutrient content. Percentage change in lipid content, for example, included estimates of 6% (change in lipid content in sardinella in India over pre-monsoon, monsoon and post-monsoon period with an increase during monsoon season), 9% (change in lipid content of *Colossoma*

Table 4. Food categories and types studied in the articles exploring impact of climate on nutritional content of foods included in the review.

Food Category	Food type
Legume	Lentil, Bean, Lupin, Soybean
Cereal	Maize grain, Cassava
Vegetable	Caper, Seaweeds, Pepper, Squash, Broccoli, Olive, Artemisia species, Lettuce, Potato, Spinach, Tomato
Fruit	Pomegranate, Guava, Grapefruit, Peach, Apple, Bilberry, Kiwi, Orange, Aonla, Ber, Banana, Matooke
Egg	Goose eggs
Fish	Shrimp, Crayfish, Prawn, Scallop, Octopus, Squid, Cuttlefish and Different types of salt water fish
Meat	Beef, Pig, Mutton
Dairy	Bovine milk, Goat milk, Different types of cheese
Bee Products	Bee pollen, Propolis (bee resin)
Tea	Different types of tea leaves, yerba mate

macropomum, *Leporinus friderici*, *Prochilodus nigricans*, *Brachyplatystoma filamentosum*, and *Brachyplatystoma flavicans* between flood and drought periods in Brazil with an increase during drought season), and 16% (change in lipid content of *Capoeta antalyensis* between summer and winter with an increase during summer), as shown in table 7. In 6 of 9 studies, lipid content was higher in summer.

There were more limited data available for dairy products, and papers that were retained for this review exclusively focused on seasonal variation. Estimates varied from a 0.6% change in the protein level of bovine milk with a decrease from spring to autumn in Australia, to a 3% change in vitamin A in goat milk with an increase from winter to summer in Spain. In the studies, protein content was greater in spring, while lipids, zinc, and vitamin A were higher in winter/autumn (table 7).

Data on changing nutrient content in vegetables was restricted to estimates in seaweeds. There was evidence of potentially high variation in carbohydrates (5–21%) and proteins (2–11%), with lower estimates of change in the case of lipids (<5%), zinc and iron (<1%). No other climatic data were used other than seasonal variability (table 7). Both studies in India present higher carbohydrate and protein content in summer, whereas lipids and iron were greater during the rainy season (table 7). No information on the effect of sunlight variability, carbon dioxide change or sea level rise on nutritional content in fish, dairy and vegetables was available.

3.5. Assessment of Confidence

A key finding in this review is a substantial research gap regarding the precision and richness of climate-related variables and causal theory within this

literature. Data describing climatic factors were generally less detailed, and sometimes poorly described ($n = 2$). Nutritional data were, in contrast, richer and more detailed.

4. Discussion

This systematic map synthesized the available published evidence from empirical studies on the impact of climatic variability on nutritional content in foods. The evidence base remains limited and fragmented, though does highlight some important trends. Firstly, this review highlights emerging evidence that climatic (and meteorological and seasonal) variables are associated with changes in the nutrient levels of edible foods. The importance of nutrient level as an indicator of climate change impact is growing in recognition, as reflected in Scheelbeek's (2018) assessment of the quality of vegetables and legumes under different climatic scenarios. The majority of studies use categorical measures of seasonality; we thus cannot infer causal mechanisms regarding what aspects of seasonal extremes drive nutrient content beyond crude hypotheses of precipitation and temperature variability.

Many articles included in this systematic map present data on general seasonal variability only (45 of 69 studies), often over a limited period, and without detailed information on climate-related variables (e.g. change in CO_2). This precludes empirical analysis of the impact of longer-term changes in climate on food nutrient content. If the quality of food were to change over time due to climate variability, the consequences are expected to include an increase of stunting and micronutrient deficiencies (Fanzo et al 2018, Willett et al 2019). However, it is difficult to understand the role of climatic factors in shifting the nutritional composition of foods and the consequences on human health (Dong et al 2018). Indeed, the literature describing the mechanisms of climate impact on nutrients lacks of information, as the empirical evidence is limited.

A key finding in this review is a substantial research gap regarding the precision and richness of climate-related variables and causal theory within this literature on nutritional composition. Indeed, the lack of detail in the description of environmental elements (e.g. description of the season with information on weather conditions or temperature) has prevented further investigation of the effects of climatic factors on nutritional content in foods. This is particularly acute in the case of a total absence of empirical (non-experimental) evidence reporting on the long-term nutritional impact of climatic variability. In addition, despite extensive literature on CO_2 change impacts on nutrients, there were negligible empirical data, with the literature dominated by experimental studies and models (Myers et al 2015, Beach et al 2019, Zhu 2018). Indeed, heatwaves and rise of global temperatures are identified as major causes

Table 5. Heat Map- Number of articles available for climatic pathway per food category published between 2013 and 2019. The intensity of the blue colour varies depending on the number of articles in literature (dark blue: > 20 publications, medium blue: 5–19 publications, light blue: < 5 publications, white: no publications).

Climatic variables	Food categories									
	Cereals	Vegetables	Fruits	Legumes	Dairy	Meat	Fish	Eggs	Bee products	Tea
General Seasonal variability	0	10	9	2	11	3	24	0	2	2
Temperature Variability	1	0	1	1	0	0	1	1	0	0
Precipitation variability	2	0	1	1	0	0	2	0	0	0
Sunlight variability	0	0	0	1	0	0	0	0	0	0
Sea level rise	0	0	0	0	0	0	0	0	0	0
Change in CO ₂	0	0	0	0	0	0	0	0	0	0

Table 6. Heat Map- Number of articles available for climatic pathway per nutrient category published between 2013 and 2019. The intensity of the blue colour varies depending on the number of articles in literature (dark blue: > 20 publications, medium blue: 5–19 publications, light blue: < 5 publications, white: no publications).

Climatic variables	Macronutrients & micronutrients									
	Carbo- hydrate	Proteins	Lipids	Iron	Zinc	Vitamin A	Vitamin D	Iodine		
General Seasonality	11	20	33	12	11	6	3	3		
Temperature variabil- ity	0	2	2	0	0	1	0	0		
Precipitation variabil- ity	0	3	0	1	0	2	0	0		
Sunlight variability	0	1	0	0	0	0	0	0		
Sea level Rise	0	0	0	0	0	0	0	0		
Carbon dioxide change	0	0	0	0	0	0	0	0		

Table 7. Examples of nutrient variability (% change) under different climatic factors for fish, dairy & vegetable categories.

FISH (shellfish included)	Carbo-hydrate	Proteins	Lipids	Iron	Zinc	Vitamin A
General seasonal variability	1% ¹	2%–16% ²	0.3%–16% ³	2% ⁴	1% ⁵	■
Temperature variability	■	5% ⁶	6% ⁷	■	■	3% ⁸
Precipitation variability	■	■	9% ⁹	■	■	■
DAIRY (milk)	Carbo-hydrate	Proteins	Lipids	Iron	Zinc	Vitamin A
General seasonal variability	■	0.6% ¹⁰	1% ¹¹	■	1% ¹²	3% ¹³
Temperature variability	■	■	■	■	■	■
Precipitation variability	■	■	■	■	■	■
VEGETABLES	Carbo-hydrate	Proteins	Lipids	Iron	Zinc	Vitamin A
General seasonal variability	5%–21% ¹⁴	2%–11% ¹⁵	0.1%–4% ¹⁶	0.1% ¹⁷	0.1–0.6% ¹⁸	■
Temperature variability	■	■	■	■	■	■
Precipitation variability	■	■	■	■	■	■

Grey cell: no data available or cannot be estimated from existing data.

of changes in food systems and human diet (Cottrell *et al* 2019, Vogel *et al* 2019). Although environmental models show that extreme climatic events will affect the nutritional content of crops such as wheat, maize, and rice (Myers *et al* 2014, Springmann *et al* 2016, Beach *et al* 2019), there remains limited empirical validation and evidence to characterize and document these changes on-the-ground. Studies assessing the impact of season variability on nutrients are mostly focused on plants often grown under environmental condition in the laboratory (Stefaniak *et al* 2019), and the analysis is usually conducted over 1–3 year (Fernandez-Escobar *et al* 1999, Nachtigall and Dechen 2006).

Additionally, there are limitations related to the design, methods and reporting of included papers. Many of the studies were primarily designed to report the quantity of macronutrients and micronutrients in food; the main objective was often not to explore environmental change, thus climatic variables were usually not well described or theorized. Furthermore, it is not possible to generalise the results on the variation of nutritional content across the food categories due to variation of the type of food, geographical location, and climatic factors considered.

Similarly, national food databases contain negligible data on variation in nutrients by season or climate. Food composition tables are resources containing nutritional information of foods for a specific country. They are not often updated, especially in settings with limited resources. Furthermore, the environmental conditions used to grow plants and crops are unknown (EuroFIR 2020). In the UK, for example, food compositional tables include differential nutritional data for summer and winter for milk, but no other foods (MCCance *et al* 2019). However, literature shows that seasons have changed in the past decades (Kirtman and Power 2013), and more information on weather parameters such as precipitation, sunlight, and temperature change are essential to study differences over time. Given evidence of temporal and seasonal variability in nutrient content, inclusion of environmental data in food databases may improve accuracy and precision when assessing nutritional intake. Consideration of differential nutrient content by season within food databases is rare. Integrating climatic conditions and recognising temporal variability in nutrient content within food databases could support prioritisation of efforts in fighting micronutrient and macronutrient deficiencies, and respond to the mandate of addressing and integrating multiple Sustainable Development Goals.

Our review has some strengths and limitations. We conducted a systematic search of published literature in three main databases without language restriction. We included empirical studies in real world settings from all continents over the past 7 years to achieve a global understanding of the observed climatic-related effects on nutrients. We presented the

totality of the available data, and where possible we calculated the variation of nutrient change due to climatic events from baseline nutritional content in foods. However, due to the variety of measurement methods and outcome results, only percentages of variations of nutritional content in foods were analysed. Some nutrients in the analysed food products (fish, milk and vegetables) have shown potential non-minor variations between different climate-related conditions. For example, proteins and lipids in fish had a variation up to 16% over different seasons, while carbohydrates in vegetables varied from 5% to 21%. A larger number of studies would be necessary to extract robust meta-analysis and synthesis of results beyond the mapping of existing evidence presented here.

We were surprised at the limited amount of literature on the effect of climatic factors on nutrients in foods. We believe that interdisciplinary work involving environmental scientists and nutritionists is just beginning. Historically, these collaborations have not occurred, environmental scientists have explored the impact of climatic factors on agriculture and food production rather than quality of food, and nutritionists have worked more on health-related topics rather than agriculture. Although collecting data during emergencies (e.g. during a drought or flood) would be particularly challenging, however, empirical research is needed to assess the climate change impact on the ground. Indeed, modelling or experimental studies may not fully represent the reality.

The ability to adapt and respond to environmental changes will be important for population health and in economic terms. The impacts of climate change are likely to be greater in areas with existing poor food security, and ensuring access to safe and nutritious food, optimal child feeding practices, and health services will be challenging (Krishnamurthy *et al* 2012). Indeed, IFPRI (2017) forecasts 4.8 million more individuals will be malnourished worldwide due to climate change impacts on food security. Improved precision and clarity on how climate change and its impacts on environmental variability will affect the nutrient content of foods is critical to preparing for, and adapting to, climate change. To date, this literature remains sparse.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Declaration of interests

JEC is Director of Dietary assessment Ltd.

ORCID iD

Sherilee L Harper  <https://orcid.org/0000-0001-7298-8765>

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