The effect of environmental change on yields and nutritional quality of vegetables and legumes:

A systematic review and meta-analysis

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Abstract

Environmental changes threaten agricultural production, food security and health. Previous reviews suggest that environmental changes will substantially affect future yields of starchy staples. No comprehensive global analysis has been conducted on the impacts of environmental change on(non-staple) vegetables and legumes that are important constituents of healthy diets. We systematically searched for articles published between 1975 and 2016 on the effect of ambient temperature, tropospheric carbon dioxide(CO2) and ozone(O3) concentrations, water availability and salinization on the yields and nutritional quality of vegetables and legumes. We estimated the mean effects of standardised environmental changes using observed exposure-response relationships and conducted meta-analysis where possible. We identified 174 relevant papers(1540 experiments). The mean[95%confidence interval] reported yield changes(all vegetables and legume groups combined) were +22.0%[+11.6 to+32.5] for 250ppm increase in CO2 concentration; -8.9% [-15.6 to-2.2] for 25% increase in O3 concentration;-34.7%[-44.6 to-24.9] for 50% reduction in water availability; and -2.3%[-3.7 to -0.9] for 25% increase in salinity. In papers with baseline temperatures >20°C, exposure to 4°C increase in temperature reduced mean yields(-31.5%[-41.4 to-21.5]). The impacts on nutritional quality of vegetables and legumes were mixed. In a business-as-usual scenario, predicted changes in environmental exposures would lead to reductions in the yields of non-staple vegetables and legumes. Where adaptation possibilities are limited this may substantially change their global availability, affordability and consumption in the mid-to long-term. Our results stress the importance for prioritising agricultural developments–such as access to new varieties, improved management and mechanisation–to minimise potential reductions in vegetable and legume yields and associated negative health effects.

Significance Statement

Environmental changes including climate change, air pollution, water scarcity and salinization, threaten global agricultural production, food security and health. There is evidence that environmental change will reduce the yields of starchy staple crops but impacts on(non-staple) vegetables and legumes – that are important constituents of healthy diets – remain largely unknown. We systematically reviewed the available published evidence from experimental studies on the impact of environmental change on yields and nutritional quality of(non-staple) vegetables and legumes and found that environmental change would have a negative impact on yields without suitable responses from the agricultural sector. An enhanced understanding of the scale of environmental impacts on agricultural production is essential for the development of effective strategies to protect global population health.

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Introduction

Environmental changes, including climate change, land degradation, water scarcity, and biodiversity loss – that are predicted to become more profound in the 21st century – pose significant challenges to global agriculture, food security and nutrition. The majority of past research on environmental change and agriculture has focused on staple crop yields such as cereals. There is general consensus across projected climate scenarios, that predicted future changes in temperature and rainfall will lead to significant reductions in the yields of many staple crops important for human populations, particularly in (sub-)tropical areas (1). Some research has also explored the impact of changing environmental exposures on the nutrient content of staple crops (e.g. (2-4)).

In contrast, there has been comparatively little emphasis on the impact of environmental change on nutritionally important (non-staple) vegetables and legumes, which appear to be relatively sensitive to environmental changes. For example, tomatoes and beans have lower failure point temperatures (the ambient temperature at which growth stops) than staple crops and are more vulnerable to heat stress (5). Furthermore, several vegetables and legumes are particularly vulnerable to develop visual injury (and hence marketability) due to environmental stress, notably small bleached spots due to high O_3 exposure (6), with legumes, leafy vegetables and *Solanaceae* (including tomatoes) among the most sensitive crops (7). To-date there has been no overarching review of the global evidence of the impact of changing environmental exposures on the yields and nutritional quality of (non-staple) vegetables and legumes.

Micronutrient deficiencies are a significant public health concern affecting an estimated 2 billion people worldwide (8). Ensuring sufficient dietary intake of vegetables and fruit has been identified as critical in efforts to prevent and mitigate micronutrient deficiencies as well as tackle non-communicable diseases (NCDs) such as cardiovascular disease (9, 10). According to the Global Burden of Disease Study, 1.5 million deaths per year globally are attributable to low vegetable consumption (11). Worldwide per capita consumption of vegetables and fruit is 20-50% below the minimum daily recommended level although large regional differences exist (12). An understanding of the impact of potential changes in the availability of vegetables and legumes resulting from future changes in environmental exposures is important for both agricultural and public health policy planning. We present the results of a systematic review of the available published evidence on the impacts of changes in environmental exposures – in a standardised business-as-usual setting (i.e. no changes in agricultural practices, technologies etc.) – on the yield and the nutritional quality of (non-staple) vegetables and legumes. Our review focuses on experimental studies conducted in field and greenhouse settings and excludes desk-based modelling studies.

Results

Screening

The initial database searches yielded 73,613 titles. After screening titles, abstracts and reading full texts, 237 papers (included one paper identified through consulting experts in the field and one paper identified by reference screening) were found to be relevant and were assessed for quality. Sixty-three papers (27%) did not meet the four quality criteria and were excluded from further analysis. A total of 174 papers (1540 experiments) were included in the final analysis of which 148 reported on yields and 49 reported on nutritional quality (23 papers reported on both) (SI Appendix). Twenty-four papers (216 experiments) reported confidence limits and were available for inclusion in meta-analyses (Figure 1). Eighty-six papers reported on field studies and 89 on greenhouse studies (one paper reported on both). Each paper comprised one or more experiments (comparison of yield and/or nutritional quality between baseline and exposed crops); covered one or multiple environmental exposures; and evaluated one or multiple crop types.

Geographical locations

Experiments described in the included papers were conducted in 40 different countries (Figure 2), with the majority conducted in Southern Europe, North America and Southern Asia. Of the 86 field studies, 25 were conducted in tropical countries, 36 in sub-tropical countries, 24 in temperate countries and 1 in a boreal country.

Impact of single environmental exposures

Ambient temperature

We included 13 papers (30 experiments; 1 field study; 12 greenhouse studies) assessing the impact of ambient temperature change; all papers reported on yield changes (SI Appendix). The effect of a standardised 4°C increase in temperature was mixed (mean yield change: -4.9% [95% CI: -47.6 to 37.8]). There was clear heterogeneity of effect depending on baseline temperature (SI Appendix): experiments with a baseline temperature above 20°C (n=18) showed a mean yield change of -31.5% [95% CI: -41.4 to -21.5] whereas experiments with a baseline temperature equal to or below 20°C (12 experiments) showed a mean yield change of +34.9% [95% CI: -47.9 to +117.6]. None of the included papers reported uncertainty estimates and no meta-analysis could be performed. None of the included papers reported the impact of raised ambient temperature on nutritional quality of vegetables or legumes.

Carbon dioxide (CO_2)

We included 44 papers reporting on the impact of changing atmospheric CO_2 levels (201 experiments; 14 field studies; 30 greenhouse studies). Yield changes (35 papers; 80 experiments) resulting from a standardised 250ppm increase in CO_2 concentration were positive (mean yield change: +22.0% [95% CI: +11.6 to +32.5]) (Figure 3a). This finding was supported by meta-analysis of the available data (7 papers; 18 experiments), which suggested an overall positive impact on yields (pooled effect size: +13.6% [95% CI: +9.7 to +17.5]) that appear greater for legumes than leafy vegetables (pooled effect size: +28.1% [95% CI: +21.3 to +34.8] and +7.1% [95% CI: +0.3 to +13.8] respectively) (Figure 3b). Heterogeneity across papers was 'mild' for legumes and 'moderate' for leafy vegetables; and the corresponding funnel plots suggested some publication bias (SI Appendix). Marginal yield increases per standardised increase of 250ppm CO_2 exposure appeared to be substantially attenuated when the evaluated range of CO_2 concentrations (exposure – baseline) exceeded 400ppm (SI Appendix).

Nine papers (102 experiments; 3 field studies; 6 greenhouse studies) reported the impacts of increased CO_2 on nutritional quality of vegetables (SI Appendix) and due to limited data, analysis was restricted to leafy vegetables. A standardised 250ppm increase in CO_2 concentration had no overall impact on mean concentrations of nutritional quality parameters in leafy vegetables. These findings were supported by meta-analyses that could be performed for iron (3 papers; 7 experiments), vitamin C (3 papers; 5 experiments), flavonoids (3 papers; 5 experiments) and antioxidants (3 papers; 6 experiments). The available evidence suggests that a standardised 250ppm increase in CO_2

levels had no impact on iron, vitamin C, and flavonoid concentrations (pooled effect = +17.0% [95% CI: -18.3 to +52.2]; pooled effect = +3.2% [95% CI: -12.6 to +19.1]; pooled effect = +3.8% [95% CI: -23.3 to +31.0] respectively). However, meta-analysis suggested an increase in antioxidant concentrations (pooled effect = +27.5% [95% CI: +1.18 to +53.9]). Heterogeneity across papers was 'severe' for all quality parameters and the corresponding funnel plots suggested some publication bias, especially related to the results on iron and antioxidants (SI Appendix).

Ozone (O_3)

We identified 21 papers that reported on the impact of tropospheric ozone concentration (122 experiments; 15 field studies; 6 greenhouse studies). Yield changes (18 papers; 76 experiments) resulting from a standardised 25% increase in O_3 were negative (mean yield change: -8.9% [95% CI: -15.6 to -2.2]) (Figure 4a). This finding was supported by the meta-analysis of the available data reporting measures of uncertainty (3 papers; 15 experiments; legumes only) which suggested substantial yield decreases (pooled effect size = -18.7% [95% CI: -25.7 to -11.7]); heterogeneity across papers was severe (Figure 4b); and the corresponding funnel plot suggested minor publication bias (SI Appendix).

Scatter plots of the available evidence suggested that the (negative) incremental effect of the standardised increased O_3 concentration on yields was greatly reduced when the evaluated range of exposure (between experimental and baseline group) exceeded 25ppb (SI Appendix).

Four papers (39 experiments; 4 field studies) reported the impacts of changed O_3 concentrations on the nutritional quality on leafy vegetables (37 experiments) and *Solanaceae* (2 experiments). The amount of evidence available is relatively limited and the overall effect of 25% increases in O_3 concentrations on leafy vegetables were mixed and varied largely by quality parameter (SI Appendix). Available evidence consistently suggested that higher O_3 concentrations would increase vitamin C concentrations in leafy vegetables (2 paper; 13 experiments), but no pooled analysis could be performed.

Water availability

We identified 65 papers (511 experiments; 41 field studies; 25 greenhouse studies; one combined field and greenhouse study) that reported on the effect of reduced water availability. Yield changes (55 papers; 334 experiments) resulting from 50% reduction in water availability were negative (mean yield change: -34.7% [95% CI: -44.6 to -24.9]) (Figure 5). None of the included papers reported uncertainty estimates.

Fifteen papers (177 experiments; 8 field studies; 7 greenhouse studies) reported on the effect of water stress on nutritional quality. The overall effects were mixed and varied substantially by crop group; leafy vegetables appeared to be positively affected; while the effects on legumes were largely null (SI Appendix). The impacts on *Solanaceae* were mixed, with positive changes reported for vitamin C concentrations (8 papers; 18 experiments: mean concentration change: +37.6% [95%CI: +11.7 to +63.5]), but no significant changes reported in mean concentrations of carotenoids and antioxidants (5 papers; 28 experiments: mean concentration change: +51.2% [95%CI: -88.8 to +192.7] and 4 papers; 10 experiments: mean concentration change: +8.22 [95%CI: -38.0 to +54.4], respectively). Meta-analysis evaluating the impact of water stress on vitamin C concentrations in *Solanaceae* supported the findings in the crude analysis (4 papers; 10 experiments: pooled effect: +28.5% [95%CI: +15.3 to +41.7]) (SI Appendix). Heterogeneity across papers was 'severe' and the corresponding funnel plot suggested possible publication bias (SI Appendix).

Water salinity

We identified 45 papers (465 experiments; 18 field studies; 27 greenhouse studies) on the effect of water salinity. Yield changes (36 papers; 200 experiments) resulting from a 25% increase in salinity of irrigation water were negative (mean yield change: -2.3%; 95% CI: -3.7 to -0.9 [Figure 6]). None of the included papers reported uncertainty estimates.

Thirteen papers (252 experiments; 8 field studies; 5 greenhouse studies) reported the impacts of increased water salinity on nutritional quality of leafy vegetables and *Solanaceae*. The overall effect was mixed with no dominant direction; only in *Solanaceae* carotenoid concentrations appeared to be predominantly positively affected by increased salinity (SI Appendix).

Combined impact of multiple environmental exposures

Fifteen papers (50 experiments) assessed the combined impact of changes in environmental exposures on vegetable or legume yields. All papers evaluated the impact of raised tropospheric CO_2 concentrations in combination with a change in another environmental exposure. There was little methodological standardisation across papers and analysis was limited to reporting the direction of impact on yield in the included papers (SI Appendix). Experiments that included combined environmental stressors (including 15 experiments on the combined impact of raised CO_2 concentration and temperature) largely resulted in null or negative impacts on yields. Two papers (24 experiments) assessed the effect of raised tropospheric CO_2 and O_3 concentrations on nutritional quality and reported significantly decreased concentrations of zinc, iron, calcium and magnesium in root vegetables: due to the limited number of papers, no pooled analysis could be performed.

Discussion

Results in context

Our systematic review is the first to synthesise the available published evidence from experimental studies on the impact of critical changes in environmental exposures on yields and nutritional quality of legumes and non-staple vegetables under a business as usual scenario. The available evidence base is relatively large but fragmented and heterogeneous, however some consistent results were found. Our review suggests that – in the absence of adaptation strategies – increasing ambient temperature in (sub-) tropical areas, tropospheric O_3 and water salinity and decreasing water availability would all negatively affect vegetable and legume yields. As has previously been demonstrated for other crop types, our review also identified that increasing CO_2 concentrations will have a positive impact on vegetable and legume yields, although these increases might be substantially attenuated in the presence of other environmental stressors (namely raised tropospheric O_3 and increased ambient temperatures) and may level off at CO_2 concentration increases above baseline of greater than 400ppm. The suggested reductions in positive yields impacts resulting from raised CO_2 concentrations in the presence of other environmental exposures may be particularly important in future impact assessments, given that several of the evaluated environmental exposures – most notably increases in CO_2 concentrations and in ambient temperature – are likely to occur concomitantly in the future. A relatively limited evidence-base further suggested that environmental changes may also affect the nutritional quality of vegetables and legumes although findings are heterogeneous.

Previous reviews identified that – in the absence of appropriate adaptation strategies – increasing ambient temperature will affect major staple crop yields and that these impacts will differ by climatic zone with yield declines in tropical zones and some yield increases in temperate zones (13-17). While we were not able to disaggregate our estimates by climatic zone due to data limitations, our findings on non-staple vegetables and legumes similarly show that when baseline temperatures are high (above 20°C) increases in ambient temperature resulted in substantial declines in yields. These yield declines were not evident at low baseline temperatures where some yield increases were reported. Our work extends previous reviews by assessing the impact on yields of changes in multiple environmental exposures both individually and in combination. A previous review identified the presence of negative impacts of increased tropospheric CO_2 concentrations on the nutritional quality (zinc and iron concentrations) of staple crops (2). This phenomenon – also referred to as the "dilution effect" (18), is hypothesised to be related to reduced canopy transpiration or changes in metabolite or enzyme concentrations whereby concentrations of micronutrients in the edible product decline (e.g.(19)). Furthermore, it has been associated with increased photosynthesis resulting in larger crops, but unaltered (and hence diluted) micronutrient content (e.g.(2)). Here, we report the available evidence of the effect of different environmental exposures on nutritional quality and found that the direction and scale of impact varied by environmental exposure and crop type.

Strengths & Limitations

Our review has several strengths. We conducted a thorough and systematic search of the published literature in multiple languages using seven databases and screened papers for important markers of research quality. We included only experimental studies (not modelled analyses) and standardised the environmental impacts in our analysis. We presented the totality of available data in dot plots and calculated crude mean impacts to give an indication of the direction of effect and where possible we conducted meta-analysis. We identified studies conducted on five continents, but few included papers were conducted in Central and South America, Africa and Southeast Asia.

Our review has some limitations related largely to the design, methods and reporting of included papers and our standardisation and pooling of results. Many included papers were primarily designed to investigate mechanisms to enhance the yields and quality of vegetables and legumes, or to explore exposure-resistant varieties: changes in environmental exposure levels were therefore not always within realistic ranges of environmental change. Differences in study objectives also limited the representativeness of vegetable and legume cultivars under investigation. For example, to explore salinization adaptation strategies agricultural researchers often conducted research on salt-tolerant cultivars. Similarly, studies investigating the impact of reduced water availability mimicked water stress by applying a substantial but stable reduction in watering throughout all phenological stages of plant growth, yet sensitivity of vegetables and legumes to reduced water availability varies by growth stages. Experimental crop variety selection may also have changed over the study period (from 1975 onwards), and this might have affected the yield response of crops to environmental exposures.

Due to the variety of study methods, evaluated ranges, crop types and outcome measures, only linear relationships between environmental exposures and outcomes were conducted. To explore critical potential non-linear trends, threshold analysis was performed for ambient temperature, and tropospheric CO_2 and O_3 concentrations: for temperature, this enabled a stratified analysis for experiments with lower and higher baseline temperatures. Ideally further regional analysis would have been conducted to explore differences in impact on yield by climatic zone, but this was not possible due to data scarcity. The comparative analysis and pooling of results required standardisation of environmental change exposure levels. We used the IPCC AR5 forecasts to guide this standardisation, but some changes evaluated are large and likely to relate to longer-term impacts.

The possibilities for meta-analysis were relatively limited since only a small percentage of papers (14%) reported precision estimates; nonetheless it was used – where possible – to support crude analysis carried out on all studies. The representativeness of papers included in the meta-analysis is unclear, and the reduced study numbers restricted weighted analysis of the effect of each environmental exposure on vegetable and legume yields and nutritional quality. The funnel plots corresponding to the various meta-analyses conducted in this review show evidence that some results might be prone to publication bias (SI Appendix).

A number of papers, especially those published more than a decade ago, considered baseline levels of CO_2 below current atmospheric levels (400 – 410 ppm, (20)). Finally, several papers could not be included due to reporting issues that limited possible data extraction.

Possible health effects and wider impacts

The identified challenges for non-staple vegetable and legume production should be considered within the wider context of global public health. As worldwide vegetable consumption levels are already below recommended guidelines (21), the potential health impacts of further reductions in non-staple vegetable and legume consumption might be substantial: low vegetable consumption could increase risk of several non-communicable diseases, such as coronary heart disease and strokes, and the risk of different types of cancers (11, 22, 23). As the primary source of some essential nutrients, such as fibre, folate, and several vitamins, reduced non-staple vegetable and legume consumption could also lead to nutrient deficiencies that may be hard to overcome through substitution with other foods. Adequate consumption of non-staple vegetables and legumes is a fundamental recommendation in all national and international food-based dietary guidelines (24). Ensuring sufficient availability of, and access to, vegetables and legumes therefore represents an urgent global nutrition and public health challenge.

The ability of nations to respond to changing environmental conditions will be an important determinant of population health and economic impacts. Negative impacts are most likely to occur in poorly functioning markets and among poor rural and urban populations where environmental changes may both directly and indirectly affect the availability, affordability and consumption of vegetables and legumes. In addition to exposures evaluated in this review, yields could be affected by an increased frequency of extreme events – such as floods, cyclones and heat waves – that are more difficult to overcome by adaptation strategies.

Several additional challenges could occur: the increased visible bruising of vegetables – caused by raised tropospheric O_3 concentration – may reduce market value and could lead to lost agricultural revenue (25). Heat stress could also affect producers directly and could cause reduced labour productivity (26), further compounding the effects of increasing temperature on crop yields. The identified impacts of environmental exposures may complicate a shift towards more sustainable and healthy diets, which are typically characterised by high consumption of vegetables and legumes.

Conclusions

Improved reporting of methodological details and study results from agricultural experiments is essential to tackle the gaps in the evidence base identified in this review. Ideally, a standardised list of environmental impacts, both single and in combination, would be used in these experiments and this would enable much greater harmonisation of data and comparison of findings in formal meta-analysis. Clear reporting of sample sizes, effect sizes and uncertainty intervals are critical elements for comprehensive pooled analysis and these were frequently missing for the current analysis.

Despite inherent limitations of conducting systematic reviews in this field, our analysis identifies the potential for substantial impacts from environmental change on global non-staple vegetable and pulse legume yields. Our findings also demonstrate the value of connecting research in the environment, food system and health sectors to identify previously unquantified challenges for agricultural production and food systems to deliver diverse and healthy diets for all in the future.

Methods

Literature Search Strategy

This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (27). We sought to identify all field and greenhouse studies published between 1st January 1975 and 30th September 2016 (including online ahead of print publications) that examined the relationship between a single or combination of environmental exposures and yields and/or nutritional quality of vegetables[1] and legumes. Our exposures were changes in the following five major environmental factors: ambient temperature; tropospheric carbon dioxide (CO_2) concentration; tropospheric ozone (O_3) concentration; water availability, and; water salinity. Our primary outcomes were change (baseline versus exposure) in: 1) *vegetable or legume yield* defined as a percentage (%), and; 2) *nutritional quality* defined as the concentration of nutritionally-relevant substances in vegetables and legumes (28). We included all nutritionally-relevant substances reported in included papers namely: fibre, flavonoids, ascorbic acid (vitamin C), carotenoids, phenolic compounds, antioxidants (including antioxidant activity), vitamin E, zinc, potassium, calcium, iron, magnesium and manganese.

Seven databases were searched between 17th October and 30th November 2016: OvidSP Medline, OvidSP Embase, EBSCO GreenFILE, Web of Science Core Collection, Scopus, Ovid SP CAB Abstracts and OvidSP AGRIS. The search was conducted separately for yield and nutritional quality of vegetables and legumes using search terms for each environmental exposure and the 20 most common, non-staple vegetables and legumes based on global food supplies estimated in FAO food balance sheets (12). Search strategies were paired with a second systematic review evaluating the impact of environmental change on fruit (to be published separately). The search strategy (SI Appendix) was first developed in OvidSP Medline and adjusted as necessary for other databases. The search strategy was complimented with examining reference lists of included papers and contacting subject experts (n=4).

Selection criteria & data extraction

[1] For this review on vegetables and legumes, we also included crops such as tomatoes, cucumbers, peppers, avocados, courgettes, pumpkins and aubergines that are typically consumed as vegetables.

We included experimental studies conducted in greenhouse or field settings and excluded modelling studies. Papers were included if written in English, French, Spanish, German or Dutch. Titles were screened for relevance by two reviewers (PS, FB). Relevant abstracts were assessed for inclusion by two reviewers (PS, FB) and any disagreements resolved in discussion with a third reviewer (HT).

Data extraction was performed by a single reviewer (PS, FB or HT) and a random sample of 10% were checked by a second reviewer (PS, FB or HT). Extracted data included: location; publication year; experiment year; study design (greenhouse or field study); air temperature (minimum, maximum, average); baseline and experimental levels of the environmental exposure under study; crop type and cultivar; yields at baseline and under experimental conditions, and; nutritional quality parameters at baseline and under experimental conditions.

Study quality

Papers were assessed for quality using a modified checklist derived from the Critical Appraisal Skills Programme (CASP) for randomised controlled trials (SI Appendix (29)). Criteria relating to randomisation and blinding were removed from the checklist as they were very infrequently used in the assessed papers. Study quality was assessed by two reviewers (PS, FB) and included in the review if they met the following four quality criteria: 1. clear description of study design; 2. clear description of methods; 3. appropriate comparison group; 4. rigorous and clearly described analysis. Only papers that reported precision estimates of measured effects (i.e. confidence intervals and/or standard deviations) were included in meta-analyses.

Quantitative data synthesis

Included papers were grouped by environmental exposure and further subdivided by vegetable or legume group: *Solanaceae* (including tomato, aubergine and pepper); root vegetables; leafy vegetables; *Cucurbitaceae* (including cucumber and courgette); and legumes (*Fabaceae*). Due to the varied nature of ambient conditions under which experiments were conducted, greenhouse and field studies were combined in analysis. Sensitivity analysis identified that the direction and scale of study findings were similar in the two study designs.

Outcomes from individual experiments – described in included papers – were standardised to a fixed change in environmental exposure level (Table 1) guided by two factors: 1) the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC-AR5) forecasts for mid- to late 21st century for each exposure (30, 31), and 2) the range of exposures evaluated in the included papers (SI Appendix). For tropospheric O_3, salinity and water availability, the standardised difference was defined as a percentage change from baseline, and for tropospheric CO_2 and ambient temperature an absolute increase was used to accommodate papers that reported "ambient" as baseline value without providing actual temperatures. For salinity, we evaluated papers that specifically assessed water salinity (not soil salinity), either through flooding, saline ground water or saline irrigation water. For experiments evaluating multiple environmental exposures, we included actual reported changes in our analysis.

The reported impacts of standardised changes in environmental exposures on vegetable and legume yields and nutritional quality from all included papers were displayed visually in dot plots, and crude summary impact estimates ("mean changes") with 95% confidence intervals were calculated. The Huber (sandwich) estimate of variance (32) was used to adjust for the clustered nature of the data using each paper as cluster unit. Data from papers that provided estimates of precision (13.8% of all included papers) were used to calculate pooled effects using meta-analysis. The results of meta-analyses were used as a sensitivity mechanism to check and further quantify the crude summary data but were not used as stand-alone results due to the low percentage of papers that could be included. A minimum number of three papers was required for pooled analysis. We performed random-effects meta-analysis to account for assumed between-study heterogeneity in true effects.

For each environmental exposure, initial analysis was performed combining all crop groups. Further exploratory analysis by crop group was conducted if a minimum of three papers were available for a specific crop group. Potential environmental "tipping points" were analysed by visual examination of scatter plots in which evaluated ranges and baseline conditions were displayed against yield or nutritional quality effects of the standardised exposure. Three apparent tipping points were explored: ambient baseline temperature above 20°C; tropospheric CO_2 concentration increases above 400ppm from baseline, and; tropospheric O_3 concentration increases above 25ppb from baseline.

Risk of publication bias was assessed by visual inspection of funnel plots of the meta-analysis and by performing an Egger test (33). Heterogeneity across papers in each funnel plot was assessed with the I^2 statistic and labelled mild, moderate, and severe in terms of heterogeneity (with cut-off values <25%, ≥25%-≤50%, and >50% respectively). Crude summary impact estimates were conducted for papers reporting the combined effect of multiple environmental exposures with the aim of examining the direction of interaction between multiple environmental exposures. Analyses were performed for all vegetables and legumes combined and for each crop group. Each nutritional indicator was analysed separately for each crop group and environmental exposure.

All data and coding will be made available through the LSHTM data repository (LSHTM Data Compass).

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Figure Legends

Figure 1: PRISMA chart showing the number of papers in each search stage. *Combined with systematic review on fruits – the systematic review on fruits to be published elsewhere. **Two papers analysed both fruits and vegetables/legumes.

Figure 2: Overview of field and greenhouse studies per country. Field studies are divided into those assessing the impact of environmental changes on: nutritional quality (blue), yield changes (green), or both (yellow)

Figure 3: Dot plot (a) and forest plot (b) showing the available experimental evidence of yield changes in vegetables and legumes resulting from a standardised increase of 250ppm CO_2 concentration (further details of forest plot in SI Appendix)

Figure 4: Dot plot (a) and forest plot (b) showing the available experimental evidence of yield changes in vegetables and legumes resulting from a standardised 25% increase in O_3 concentration (further details of forest plot in SI Appendix)

Figure 5: Dot plot showing the available experimental evidence of yield changes in vegetables and legumes resulting from a standardised 50% reduction in water availability

Figure 6: Dot plot showing the available experimental evidence of yield changes in vegetables and legumes resulting from a standardised 25% increase in water salinity