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LETTER

Mitigating sustainability tradeoffs as global fruit and vegetable systems expand to meet dietary recommendations

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Abstract

Recent analyses indicate that global fruit and vegetable (F&V) production will need to increase by 50%–150% by 2050 in order to achieve sustainable and healthy diets for 10 billion people. Although global production of F&V has grown by 50% during the last two decades alone, simply scaling up current systems of F&V production, supply chains, and consumption will inevitably worsen environmental and socioeconomic tradeoffs. This article examines three examples of important F&V—avocados, leafy greens, and tomatoes—to assess the global challenge of meeting dietary recommendations at affordable prices to consumers while sustaining producer livelihoods and minimizing environmental damage. These three cases highlight key characteristics of F&V systems that make the challenge of sustainable expansion especially difficult: knowledge-, input-, and labor-intensive production, high rates of food loss and waste, and low affordability to consumers relative to less nutrient-dense food groups. Our analysis shows that only by investing in innovations that increase diversity, integrate technology, and improve equity will truly sustainable expansion of F&V systems be possible.

1. The call for fruits and vegetables: current and future challenges

Dietary recommendations worldwide emphasize greater consumption of fruits and vegetables (F&Vs) as part of an overall dietary pattern to reduce the risk of diet-related chronic diseases including cardiovascular disease, several types of cancer, and metabolic disorders (Lim et al 2012, Willett et al 2019, Springmann et al 2020). Yet, average global F&V consumption hovers at one-half of recommended intakes for vegetables and one-fourth for fruits, with lower intakes in low-income countries and in rural populations (Miller et al 2016). Projecting further increases in F&V in future diets, the recent high-profile analysis by the EAT-Lancet Commission estimates that increases of 50%–150% in global F&V production will be required to feed a healthy diet to the expected 10 billion people in 2050 (Willett et al 2019). While there have been numerous critiques of the EAT-Lancet Commission’s report and its growth projections for different food groups (Hirvonen et al 2021).
the recommendation to increase dietary intakes of F&V beyond current rates is nearly universal among national and international dietary guidelines and sustainable diet assessments (Drewnowski et al 2020, Springmann et al 2020). In light of the discrepancy between recommended and actual dietary intake levels, as well as the importance of F&V for achieving the UN Sustainable Development Goals (SDGs), the FAO has declared 2021 the ‘International Year of Fruits and Vegetables’ (FAO 2020).

Global expansion of F&V systems implies unique sustainability challenges relative to other commodities. F&V represent a highly diverse array of crop species and varieties grown under variable social and ecological conditions across the globe. Production of F&V has already increased by 50% globally in the past two decades, with growth concentrated in East and Central Asia, and small-scale farmers are responsible for more than half of F&V production across geographies (Herrero et al 2017, FAO 2020). Increased consumption is expected in emerging economies where diet diversification is occurring, although maintaining affordability for consumers will be difficult (Mason-d’Croz et al 2019). Additional demand could strain F&V producers already facing the challenges of high resource requirements, pest pressure, biophysical changes, and low institutional support (Myers et al 2017, Schreinemachers et al 2018). Among all food groups, F&Vs generate the highest levels of pre- and post-harvest loss and waste, estimated at 35%–55% across all geographies (Gustavsson et al 2011, FAO 2019).

Recent developments in sustainable food systems emphasize strategies to reduce post-harvest losses and waste in regions with underdeveloped supply chains and physical and information infrastructure (Cattaneo et al 2020, Stathers et al 2020). Data remain limited for F&V relative to cereal crops, however, and most interventions to date have focused on the farm-level rather than integrating assessments across other domains of the food system, including supply chains and consumers (Stathers et al 2020). A suite of complementary review articles in 2020 assessed available evidence on pathways toward sustainable food systems, including incentives for adoption of sustainable practices (Piñeiro et al 2020), the role of farmer organizations (Bizikova et al 2020), agricultural training and skill building (Maïga et al 2020), and supply chain linkages for small-scale producers (Liverpool-Tasie et al 2020). While broader food system innovations can also apply to F&V, recent articles caution that technological solutions must address social and environmental tradeoffs; complex issues in the food system will require coordinated, bundled solutions rather than silver bullets to achieve the SDGs (Barrett et al 2020, Herrero et al 2020a).

This article is a first attempt to enumerate the socioeconomic and environmental tradeoffs associated with F&V production, supply chains, and consumption and to propose cross-cutting pathways toward sustainable expansion of this food group in line with dietary recommendations.

During a three-day multidisciplinary workshop in 2018, nearly 40 scholars convened with the goal of envisioning future sustainable and resilient F&V systems (Chaudhary et al 2018). Over the next year, key themes from the workshop were refined through regular working group meetings with a subset of participants and other experts in the field. These targeted discussions led our author group to coalesce around three cross-cutting pathways toward the sustainable expansion of global F&V systems, the complexity of which we chose to demonstrate with three case studies. The three F&V examples presented below were selected to cover the widest range of crop types (a perennial, an annual fruit, an annual vegetable) and socioeconomic and environmental tradeoffs associated with F&Vs. Given the increasing importance and vulnerability of F&V systems, we asked: **how can F&V systems scale up to meet dietary recommendations at affordable prices to consumers, while sustaining producer livelihoods and minimizing natural resource depletion and environmental damage?**

While global consumption across all F&V remains low, select F&V have scaled up to meet rising demand. In this perspective, we first highlight the sustainability tradeoffs associated with production, supply chains, and consumption of three distinct F&V systems that have successfully scaled up—avocados, leafy greens, and tomatoes (figures 1 and 2). We then present emerging innovations with potential to mitigate these tradeoffs and support sustainable expansion of F&V systems (figure 3). To conclude, we emphasize key research gaps and areas for growth to inform cross-sector investment and policy as F&V systems expand to meet dietary recommendations.

The three examples were selected to bring to light and synthesize nuances in what ‘sustainability’ means for complex, adaptive food systems (Nesheim et al 2015, Tuomisto 2019). The global discourse on sustainable diets requires increased attention to socioeconomic and environmental tradeoffs and investment strategies to mitigate these tradeoffs and prompt truly sustainable expansion of F&V.

### 2. Scaling up avocados

Avocados are a prominent F&V scaling success. In the United States, annual consumption has risen by over 400% since the 1980s, reaching 7.5 pounds per person in 2017–2018 (USDA 2019b). In conjunction, global harvested area nearly doubled from 2000 to 2017 (FAOSTAT 2019).
Figure 1. Mitigating sustainability tradeoffs in fruit & vegetable (F&V) systems will require cross-cutting innovations across domains of production, supply chains, and consumption.

Figure 2. Environmental footprints for three fruits and vegetables (F&V; avocados, leafy greens, and tomatoes) that have scaled up production to meet rising demand. Crop impacts are shown here using three different functional units: mass, calories, and nutrient density. Data shown above is available from: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/63AIAL.

2.1. Water
Tradeoffs. Mexico, Peru, Colombia, and Chile collectively produce nearly half of all avocados, but yields in their drier regions are restricted by infrastructural, management, and climatic factors (Cavallo and Powell 2019, FAOSTAT 2019). Water availability in arid regions is expected to decrease due to diverse factors including climate change and competing demands, potentially leading to crop failure and preventing further expansion in important avocado production areas (Ribot et al. 1996). Modern commercial avocado varieties (e.g. Hass) tend to be more productive under well-watered conditions, but are susceptible to water stress (Carr 2013).
Mitigation. Improvements to varietal drought-tolerance and irrigation efficiency for semi-arid zones could improve productivity while reducing environmental impact. Farmers in regions with appropriate climate and environmental characteristics might consider introducing this perennial crop in rotations. Locating orchards based on environmental-suitability assessments could increase tree cover in areas currently under extensive grazing or other unsustainable land uses (Ramírez-Gil et al. 2018).

2.2. Trade
Tradeoffs. Postharvest losses of avocados tend to be high in low-income countries due to poor infrastructure (Cavallo and Powell 2019), as well as stringent export quality standards (Bill et al. 2014, Jensen et al. 2014).

Mitigation. Improvements in physical and information infrastructure (e.g., postharvest storage training programs, refrigeration, and other preservation technologies) are necessary to benefit F&V productivity and reduce losses. For example, investments in paved roads, electricity, and clean water can have disproportionate benefits for production efficiency (Cavallo and Powell 2019). Similarly, improved information infrastructure (e.g., blockchain) has potential to optimize coordination between actors in avocado supply chains (Kamilaris et al. 2019). Combined, such investments can improve the efficiency and quality of traded F&V (Jensen et al. 2014).

2.3. Land use
Tradeoffs. With US consumption increasing by 10% annually (USDA 2019b), there has been significant expansion in avocado acreage in emerging economies. In 2016, the US was the top global importer, with Mexico its main supplier (FAOSTAT 2019). This increase has partially driven Mexican deforestation, particularly in temperate forest regions such as Michoacán (Bravo-Espinosa et al. 2014). Subsequent high-input management of avocados has been associated with contamination of waterways, losses in biodiversity and ecosystem functioning, soil compaction and fertility declines, and over time, reduced yields (Mangiafico et al. 2009, Bravo-Espinosa et al. 2014).

Mitigation. Producers could avoid environmental degradation by implementing sustainable nutrient and pest management practices, as they have with other export crops (e.g., rainforest-certified coffee). However, except for organic avocados, current markets lack such direct labeling incentives. For Michoacán, adjacent to the Monarch Butterfly Biosphere Reserve in Mexico (Vidal et al. 2013), ‘monarch-certified avocados’ may appeal to some American consumers. Likewise, smallholder farmers grow avocados in home gardens and agroforests, which provide essential ecosystem services such as pollination (Garibaldi et al. 2016). Linking these diversified production systems to global markets, while challenging, could provide economic growth and support sustainable production (Liverpool-Tasie et al. 2020).

3. Scaling up leafy greens
A growing appetite for convenience has driven increases in the ready-to-eat salad industry in high-income countries (Ragaert et al. 2004, Baseline et al. 2017). The success of leafy greens demonstrates that slight shifts in processing and distribution can modify the availability and affordability of F&V to stimulate consumer demand (Pollard et al. 2002).

3.1. Food safety and urbanization
Tradeoffs. Increased consumption of pre-washed, ready-to-eat leafy greens is linked to outbreaks of food-borne Escherichia coli O157, norovirus, and Salmonella due to the lack of bacterial or viral inactivation steps post-processing (Bouwknegt et al. 2015). Leafy greens may become contaminated with enteric bacterial or viral pathogens during crop production (via irrigation water, manure-based fertilizer, wildlife, or hand harvesting) or post-harvest rinsing, but urban consumers are largely unaware of risks.

Mitigation. Geographically re-distributing production systems through urban agriculture could reduce the potential to spread contaminated leafy greens to large numbers of consumers from a single processing facility. Rapid investment in urban and peri-urban leafy green production is underway, including vertical, glasshouse, and closed-loop aquaponic or fertigation systems (Eigenbrod and Gruda 2015). Such systems could reduce introduction or multiplication of contaminants, limit food loss, and contribute to local diets and economies (de Zeeuw et al. 2011), although current high costs mean they primarily supply high-end restaurants rather than lower-income individuals.

3.2. Shelf-life
Tradeoffs. Consumption of fresh leafy greens is limited by shelf-life and, in emerging economies, by underdeveloped cold chains (Pollard et al. 2002). In high-income countries, preservation techniques including flash-freezing or canning can increase F&V shelf-life and affordability (Miller and Knudson 2014). While preserving F&V can reduce food loss and waste, it is regularly overlooked in research and policy recommendations for sustainable diets in favor of initiatives directed at fresh F&V (Martindale 2017).

Mitigation. Traditional preparation of leafy greens in many low-income countries involves cooking (Uusiku et al. 2010), opening possibilities to process raw vegetables to increase shelf-life and access. Freeze-dried and canned products have very long shelf-lives.
and high potential to supply F&Vs that would otherwise be perishable without refrigeration. Complementing the convenience of fresh-cut leafy greens, these types of processing reduce food waste and transform fresh produce into a more affordable, yet still nutritious form (Usiku et al 2010, Miller and Knudson 2014). Steps to maintain or improve flavor while minimizing added sugars and salts will be necessary to support consumer demand for processed F&V.

3.3. Price

Tradeoffs. Price is a main determinant of F&V purchasing among low-income groups (Sacks et al 2015). A recent global study on the cost of the EAT-Lancet Commission’s healthy reference diet (Willett et al 2019), revealed that the least expensive iteration of their recommended diet would cost a median of US$2.84 per day (in 2011), a price affordable to many in higher income countries but out of reach for at least 1.58 billion people worldwide (Hirvonen et al 2019). F&V were the costliest food group in the reference diet, making up an estimated 31.2% of the total budget.

Mitigation. Supply chain improvements such as processing can reduce prices to increase consumer access, but a multi-pronged approach is often needed to increase F&V consumption. Numerous direct-to-consumer initiatives (e.g. nutrition classes, subsidized F&V, and healthy meal programs in schools) are now being implemented in both high- and low-income countries to increase consumption of F&V among economically disadvantaged populations (Pem and Jeewon 2015, Sacks et al 2015). Further innovations in consumer education and supply-side interventions will be needed to reduce the price of high-value leafy greens to increase demand in low-income groups (Schreinemachers et al 2018).

4. Scaling up tomatoes

The production and consumption of tomatoes are both highly globalized. Due to the popularity of processed tomato products, tomatoes are the second-most consumed vegetable in the US and many comparable countries, as well as an important source of nutrients, such as lycopene and Vitamin A, in global diets (Willcox et al 2003).

4.1. Pest management

Tradeoffs. With a host of tomato-specific diseases and pests, pesticide use in production systems can be high. Because tomatoes are also a labor- and management-intensive crop, high insecticide and herbicide application rates lead to high exposure rates for farm workers and ecosystems (Geiger et al 2010, von Osten et al 2010). Pesticide exposure is a primary occupational health concern in tomato and other F&V production systems globally (Spencer et al 1991, Boedeker et al 2020), and inappropriate use of pesticides can lead to environmental contamination and cascading effects (Yamamuro et al 2019).

Mitigation. Integrated pest management (IPM) coupled with precision agricultural techniques could reduce human and environmental exposure to pesticides. IPM involves coordinated efforts to control pest populations with regular monitoring, biological control agents (Ehler 2006), integration of non-chemical tactics such as push–pull strategies, crop rotation, and diversification, and judicious use of pesticides only when needed to reduce pest pressure (Cook et al 2007). IPM in tomatoes has been shown to be equally or more effective for both yields and economic returns than calendar-based or chemicals-standard application rates (Trumble et al 1994, Pretty and Bharucha 2015). Integrated methods also offer benefits for populations of natural enemies of tomato pests, which can further reduce the need for pesticides and the potential for human exposure (Picanço et al 2007).

4.2. Perishability

Tradeoffs. Fresh tomatoes, like many F&V, are subject to high degrees of post-harvest loss and retail and consumer waste (Parfitt et al 2010, FAO 2019). Perishability and loss exacerbate the gap between current and expected availability and recommended intake levels of F&V (Mason-d’Croz et al 2019), posing a major challenge to sustainable expansion. To reduce F&V losses, suppliers rely on cold chain technology and packaging along the supply chain, both of which increase energy use.

Mitigation. Both traditional and novel food preservation techniques (canning, freezing, and freeze-drying) can increase shelf-life, preserve nutrients, and decrease post-harvest losses (Usiku et al 2010, Miller and Knudson 2014). In countries like the US, most tomatoes (>90% in 2015) are used in processed products such as pasta sauce and ketchup (Guan et al 2017). For fresh tomatoes, edible coatings derived from mineral and plant compounds are gaining popularity to control perishability in supply chains (Herrero et al 2020b). Recent studies find that edible coatings can reduce F&V postharvest loss without compromising nutritional quality (Vignesh and Nair 2019).

4.3. Flavor and nutrients

Tradeoffs. The chemical composition and flavor profiles of tomatoes are highly variable, which can impact consumption, especially of fresh tomatoes. For example, the amount and chemical form of carotenoids such as lycopene in tomatoes are influenced by many factors (e.g. cultivar, production system, location, season, post-harvest processes) (Klein and Perry 1982, Shi and Le Maguer 2000, Mitchell et al 2007, Klee and Giovannoni 2011), and tomatoes can vary by more than 16-fold in nutrients like vitamin
A (USDA 2019a). Breeding for productivity, hardiness, and shelf-life has led to varietals with altered composition of the chemicals responsible for flavor (Tieman et al 2017). These compounds, including many different types of volatile aldehydes and alcohols, are known to influence consumer preferences and consumption patterns (Vogel et al 2010).

Mitigation. Fresh tomato consumption may increase with the development of varieties with preferable flavor profiles and enhanced nutrient content (Klee and Tieman 2018). Strategic use of genetic diversity in new breeds could enhance tomato flavor and nutritional quality—without sacrificing yields or increasing perishability (Tieman et al 2017). Pairing novel tomato cultivars with controlled environments, such as greenhouse systems, can also offer consistent yield and quality enhancements (Kubota et al 2006). Further research on energy- and water-efficiency and IPM in indoor agriculture is needed to increase the sustainability of this option for consistently high flavor and nutrient profiles.

5. Conclusions

F&V are gaining public attention through the SDGs and other global initiatives such as the FAO’s International Year of Fruits and Vegetables (FAO 2020). While expansion of F&V systems is a prerequisite of sustainable diets according to reports like that of the EAT-Lancet Commission (Willett et al 2019), simply scaling up current, flawed systems of F&V production, supply chains, and consumption will inevitably worsen environmental and socioeconomic tradeoffs. Only by addressing these tradeoffs through investment in research and development of innovative, multi-dimensional mitigation strategies, such as those outlined in figure 3, will expansion of truly sustainable F&V systems be possible. Extending lessons from avocados, leafy greens, and tomatoes to broader F&V systems, we identified the pathways shown below for private entrepreneurial innovation and public sector investments to mitigate tradeoffs and sustainably expand F&V systems. In so doing, we acknowledge that each of these cross-cutting pathways will require careful study and evaluation using practical, statistically tested, and theoretically sound methodologies, the details of which are beyond the scope of this paper.

5.1. Increase diversity

Relative to other commodities, F&V constitute a highly diverse food group. However, approaches to expanding supply to date have involved limited crop varieties typically bred for enhanced productivity (Cassidy et al 2013) and grown in intensive, monocultural systems that demand high pesticide, water, and nutrient inputs (Foley et al 2005, Kremen and Merenlender 2018). Lack of investment in diversified F&V limits sustainable expansion of these systems (deLonge et al 2016). Increased support could enable development of cultivars adapted to diverse climate conditions (Mason-d'Creo et al 2019), with improved nutritional and flavor profiles (Ebert 2020), and suited to cultivation in diversified cropping systems (Kremen and Merenlender 2018, Tamburini et al 2020), where applicable. Beyond production, increasing the diversity of processing options for F&V could improve supply chain efficiency and reduce losses (Martindale 2017, Stathers et al 2020), potentially increasing availability and affordability for consumers. Scaling up efficient, diversified F&V systems necessitates a suite of innovations; we recommend several areas for increased research and public and private investment below:

(a) Breeding multiple varieties of F&V could balance nutrient content, flavor, shelf-life, resource use efficiency, productivity, and crop and genetic diversity and increase resilience to changing environments. Novel varieties could be adapted to increasingly variable climatic conditions (Acevedo et al 2020) and should allow farmers to reduce external inputs to F&V systems while improving flavor and maintaining nutritional quality to meet consumer preferences (Ebert 2020). Participatory research, extension services, and supportive farmer networks will likely be necessary to support producer uptake of new varieties of F&V (Acevedo et al 2020, Bizikova et al 2020).

(b) Implementing F&V systems in appropriate ecological conditions and within diversified agricultural landscapes could attract pollinators, maximize productivity and quality, and increase the efficiency of resource use (Aizen et al 2019, Tamburini et al 2020).

(c) Improving the palatability and nutrient density of F&V through breeding with wild relatives could increase consumer demand (Ebert 2014). Developing new varieties and management practices for productive, equitable, and sustainable F&V systems will require investment capital not currently available for F&V.

5.2. Integrate technology

Scaling up increasingly diversified F&V systems will require technological innovations. Technologies can be integrated across supply chains (Herrero et al 2020b), though innovations in this sector must evaluate both direct and indirect socioeconomic and environmental effects rather than aiming for a one-size-fits-all solution (Barrett et al 2020, Herrero et al 2020a). In the production domain, technology can support the breeding and cultivation of diverse crop varieties (Schreinemachers et al 2018), mechanization and monitoring of diverse cropping systems (e.g. sensors for real-time monitoring in orchards), urbanizing and re-localizing production of perishable
Figure 3. Innovations in fruit and vegetable (F&V) systems can address current sustainability tradeoffs, but future challenges remain. Drawing from the examples of avocados, leafy greens, and tomatoes, we highlight generalizable innovations that could support sustainable expansion of F&V systems to meet dietary recommendations.

F&V, reducing exposure to pesticides, and modeling environmentally suitable conditions for F&V production (figure 3). With increased accessibility and transparency, blockchain and other digital technologies could support ‘smart’ and equitable management of supply chains (Kamilaris et al 2019, Mehrabi et al 2020). For consumers, food science technology can play a role in making F&V consumption more convenient and affordable through both traditional and novel forms of food preservation, and educational platforms such as mobile applications could increase consumer knowledge and intake of F&V (Appleton et al 2019). Further opportunities to integrate technology in F&V systems include the following:

(a) Incorporating precision agricultural techniques and IPM into multi-crop systems could reduce pesticide contamination and facilitate the efficient use of resources (Pretty and Bharucha 2015, Herrero et al 2020a).
(b) Enhancing physical and information infrastructure could facilitate regional distribution of F&V supply. Shorter, urban supply chains, improved use of cold chain and processing technologies
that preserve quality and nutrients, and tracking systems such as blockchain could all be used to reduce post-harvest and consumer losses (Martindale 2017, Barrett et al 2020, Stathers et al 2020). Exploring public-private partnerships could stimulate innovations in processing, preservation, and supply chain technologies.

(c) Linking small-scale producers of F&Vs in emerging economies, as well as farmer networks and organizations (Bizikova et al 2020), to integrated supply chains could facilitate both local and international trade of highly perishable F&V and improve farmer outcomes (Liverpool-Tasie et al 2020). Additionally, improving access to information about F&V sustainability through transparent certification schemes and shorter supply chains could boost consumption (Barrett et al 2020).

5.3. Improve equity

F&V systems can be knowledge-, input-, and labor-intensive relative to other food types, which limits the participation of some groups in their production, processing, and consumption (FAO 2020). Furthermore, F&V systems can negatively impact farm workers through exposure to pesticides and other occupational hazards during production (Boedeker et al 2020) and affect low-income consumers through lack of access and affordability (Darmon and Drewnowski 2015). Thus, efforts to sustainably expand F&V systems must intentionally address equity issues such that innovations in diversity and technology are accessible to all, from producers to consumers. Promising avenues for research and investment in equity in F&V systems are outlined below:

(a) Increasing investment and research in sustainable F&V could inform policies that improve the relative risk-return factors for F&V producers and alleviate affordability barriers for low-income F&V consumers. Engaging stakeholders in co-production of policy-oriented research is likely to enable both improved equity and outcomes for F&V consumption (Barrett et al 2020).

(b) Adopting a multi-level and multi-sector approach to F&V education and testing the efficacy of multiple incentives across the food system could increase consumer demand for F&V. Both education and market-based incentives are necessary to bring consumers closer to meeting F&V dietary recommendations (FAO 2020).

(c) Building capacity and investing in increased F&V in school lunches and other institutional procurement programs are promising avenues for structuring F&V demand and changing consumption habits (Sidaner et al 2012, Wittman and Blesh 2015). Concurrently, developing produce with improved flavor in fresh and preserved forms (e.g. Klee and Tieman 2018) could increase demand for F&V in current and future generations.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.7910/DVN/63AIAI.

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Author contributions

DG, JF, and AES conceptualized the original paper, with later contributions from all authors. AES wrote the manuscript, with input and revisions from all authors. DG, AES, and CP designed and generated content for figures. All authors read and approved the final manuscript.

Conflict of interest

The authors claim no competing interests related to this manuscript.

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