Sustainable and Equitable Increases in Fruit and Vegetable Productivity and Consumption are Needed to Achieve Global Nutrition Security

Position Paper resulting from a workshop
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Workshop Purpose:

To assemble global practice and thought leaders to create a future vision for more sustainable and resilient fruit and vegetable (F&V) food systems.

Workshop Objective:

Identify challenges and opportunities for existing and future F&V food systems. Prioritize among the leverage points for change and knowledge gaps. Outline approaches (changes in the food system itself & research needs) to sustainably provide healthy, nutritious food to a growing, more urban world population, based on the principles of diversity, equity & inclusion.

Workshop Outputs:

Position paper on needed innovations in F&V food systems.

Strawman proposal on next steps, including identification of who can implement the needed system changes and conduct the needed research.

Workshop Outcome:

A new community of practice sharing an aligned vision on more resilient and sustainable F&V food systems and a roadmap on how they can be achieved.

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ABSTRACT

Increased intake of fruits and vegetables (F&V) is recommended for most populations across the globe. However, the current state of global and regional food systems is such that F&V availability, the production required to sustain them, and consumer food choices are all severely deficient to meet this need. Given the critical state of public health and nutrition worldwide, as well as the fragility of the ecological systems and resources on which they rely, there is a great need for research, investment, and innovation in F&V systems to nourish our global population. Here, we review the challenges that must be addressed in order to expand production and consumption of F&V sustainably and on a global scale. At the conclusion of the workshop, the gathered participants drafted the "Aspen/Keystone Declaration" (see below), which announces the formation of a new "Community of Practice," whose area of work is described in this position paper. The need for this work is based on a series of premises discussed in detail at the workshop and summarized herein. To surmount these challenges, opportunities are presented for growth and innovation in F&V food systems. The paper is organized into five sections based on primary points of intervention in global F&V systems: (1) research and development, (2) information needs to better inform policy & investment, (3) production (farmers, farming practices, and supply), (4) consumption (availability, access, and demand), and (5) sustainable & equitable F&V food systems and supply chains.

The Aspen/Keystone Declaration

A new Community of Practice has formed with a shared mission to synthesize data and generate the knowledge needed to better inform actions and interventions leading to more diverse, equitable, nutritious, resilient, and sustainable global F&V food systems.

The graphic on this flyer was produced by Ellie Barber of the Aspen Global Change Institute to help summarize the desirable food system outcomes discussed at the workshop. The side-event mentioned in this flyer showcased workshop outcomes and was held alongside the 2018 Global Climate Action Summit. Prepared comments from the panelists were followed by Q&A and interactions with the 40 gathered participants.

Background & Introduction

To improve public health and nutrition, populations across the globe must consume more F&V on a daily basis.[1] However, the current state of global and regional food systems is such that both F&V availability and the production required to sustain them are severely deficient to meet this need (Miller et al., 2016; Bahadur et al., 2018). While innovations in technology and production methods can improve production efficiency and increase the yield of F&V systems, yield alone is insufficient to guarantee crop nutritional quality, system sustainability, and F&V access and demand by consumers.

Research has shown that there is tremendous variation in F&V consumption across the world; however, in general, the majority of the world's population consumes far fewer F&V than recommended by the World Health Organization (WHO) and this is related to numerous poor health outcomes (Hall, Moore, Harper et al. 2009, Casagrande, Wang, Anderson et al. 2007). One of the major leading causes for poor health and disease worldwide is poor diet (Lim et al., 2012) and accordingly six of the top nine global diseases risk factors are linked to poor dietary quality (Forouzanfar et al., 2015). Approximately 16.0 million disability adjusted life years (DALYs), and 1.7 million deaths worldwide are related to low F&V consumption (WHO, 2018). F&V are among the few food groups with positive outcomes for both undernutrition (e.g. micronutrient deficiencies) and overnutrition (e.g. cardiovascular disease, overweight and obesity). According to the United Nations State of Food Insecurity in the World 2017 report (FAO., 2017), 815 million people suffered from calorie deficit hunger in 2016. Micronutrient deficiencies afflict many more people throughout the world—estimated at over 2 billion—while roughly one-third of the global population is overweight or obese (Ng et al., 2014; WHO, 2018). Approximately one-third of women of reproductive age are anemic, mainly due to iron deficiency, and one in four children suffer from stunting due to malnutrition in the first 1000 days post-conception[2] (from the womb to two years of age) (SOFA, 2018). Consumption of sufficient F&V per day (a minimum of 400g, according to the WHO) has been consistently shown to reduce risk of many chronic diseases, including multiple gastrointestinal cancers, cardiovascular disease, and stroke (Jansen 2001;WHO 2005). A systematic review of studies relating F&V consumption to reduced rates of cancer, cardiovascular disease, and premature death (Aune et al. 2017) found that there were significant benefits to intake of up to 500 g fruit/day and 800 g vegetables/day (twice the WHO minimum recommended intake level) and that 13.4 million[3] premature deaths per year could be prevented globally by increasing population-level F&V consumption.

At the same time, because F&V production uses significant quantities of natural resources, it is imperative that their consumption is aligned with production levels to prevent the waste of natural resources. Additionally, because of their perishability, F&V are the second most wasted food product category after seafood in many countries (NRDC, 2017). When F&V are diverted to the garbage instead of eaten they contribute to increases in greenhouse gas (GHGs) emissions in the

[1] As a quick word of initial explanation, this document has not been edited to the standards of a peer-reviewed journal. Many declarative statements, such as this one, have not been referenced. But many have been, and there are more than six pages of references. This document was "crowd-sourced" by the workshop participants (all of whom volunteered their time). A more tightly edited and shorter version will be submitted to a peer-reviewed journal soon. In the meantime, this report will be made available to others (via the AGCI web-site), as the first of the tangible workshop outputs and in order to facilitate next steps (e.g. proposals).
[2] While increased F&V consumption is generally understood to be beneficial during the first 1000 days, the greater need in some regions may actually be for higher amounts of animal-based foods in the diet.
[3] It should be noted there is considerable variation in the literature on this number.

process of decomposition. Food system transformations are needed to ensure closer linkages between producers and consumers, in order to improve such alignment.

Globally, public investments in F&V systems pale in comparison to major cereal crops. The World Vegetable Center, an international agricultural research institution dedicated to research and development for vegetable crops, spends approximately $20 million/year, as compared to roughly $920 million/year by the CGIAR system, which is devoted primarily to staples and has no specific F&V component.[4] This represents a global public investment of only 3-5% in vegetable breeding and systems relative to total expenditures on staple grains and other heavily-traded commodities produced in the Global South (World Vegetable Center, 2018). It is important to note that there are strong private sector investments in F&V systems in both the Global North and the Global South, particularly in the area of hybrid and commercially-important vegetables (e.g., tomato, onion, pepper, lettuce, cucumber) and fruits (e.g., orange, apple, pineapple, mango, banana). There is also an opportunity for greater investment in additional crops that are not currently commercial targets, including regional or indigenous species and varieties.

As the global trend towards urbanization shrinks farming populations (in most areas) and increases the distance between production and consumption, ensuring continued access to locally-sourced F&V becomes more daunting. Urban and rural poor alike increasingly have greater access – through both lower price points and heightened marketing and sales – to ultra-processed, high-sugar foods produced from commodity crops than they do to fresh produce. Cumulatively, these diet-related factors contribute to the triple burden of malnutrition—combined underweight, overweight, and micronutrient deficiencies—across populations in both the Global North and Global South. Additional challenges for sustainably producing enough F&V to achieve global nutrition security include a growing global population (PRB, 2017), a degraded and contaminated resource base due to current production practices, increasing competition for freshwater resources, and a changing climate.

Given the critical state of public health and nutrition worldwide, as well as the fragility and constraints of the ecological systems and resources on which they rely, there is a great need for research, investment, and innovation in F&V systems to nourish our global population. Here, we review the challenges that must be addressed in order to expand production and consumption of F&V sustainably and on a global scale. To surmount these challenges, we subsequently present opportunities for growth and innovation in F&V systems. The paper is organized into five sections based on primary points of intervention in global F&V systems: (1) research and development, (2) information needs to better inform policy & investment, (3) production (farmers, farming practices, and supply), (4) consumption (availability, access, and demand), and (5) sustainable and equitable F&V food systems and supply chains.

[4] In noting these figures, it is acknowledged that the total global value of staples greatly exceeds those of F&V crops, thus lessening the discrepancy when considered as a ratio of investment to total crop value.

1. RESEARCH AND DEVELOPMENT

Challenges: Lack of data for empirical F&V research & modeling

Data on F&V consumption and links to health outcomes are imprecise
There appears to be consensus that the global population does not consume sufficient F&V. However, the data on which this consensus is based are challenged by the imprecision of available measurement techniques. Many challenges exist in the collection of retrospective and prospective dietary intake data, including dietary recall biases and the difficulty that people experience in accurately remembering dietary intake (Riboli and Norat, 2003, Temple and Gladwin 2003). Additionally, long-term randomized control trials (RCT) investigating F&V dietary interventions as they relate to health outcomes are lacking. Although RCT evidence would fill an essential knowledge gap that could be used to update dietary guidelines, the high cost and complexity of the study design make it prohibitive. In addition, the importance of closing gaps in knowledge about nutrient content of foods is well accepted but the rapidly changing food supply makes this a daunting task. Unfortunately, establishing causal relationships between components in F&V and biomarkers of health is nearly impossible given the interactions between diet, genetics and the environment as well as the unpredictable effects of the environment and production practices on the nutrient profiles of foods.

Siloed and disciplinary data collection and storage limit F&V analyses
Data collection and storage at the scale of food systems is frequently fragmented, complicated or challenged by barriers in data sharing and integrated analyses of processes across actors and scales. For example, the question of how F&V nutrient content affects human health is key to understanding the mechanisms behind the nutritional benefits and health outcomes affected by consuming F&V, but it has never been tested, likely because complex questions require data from multiple sources. F&V nutrient profiles are highly variable and the result of interactions with natural resources (soil, water availability), with anthropogenic inputs (variety, nutrients, pesticides), and with transformations along the value chain. The nutrients in F&V that are actually consumed, bioavailable and biologically active depend on a host of social properties, including organoleptic (sensory) qualities, availability and price, and consumer preferences.

Data are collected on many of these food system characteristics. In the United States, for example, farmers collect data on variety, nutrient applications, soil characteristics, timing of planting and harvest, and harvest mass. Purchasers track time in transit from farm to next marketing stage, time in and nature of storage (including in the home), and handling costs. The final retailer collects data on sales volume and price. USDA tracks production data and provides nutrient characteristics on some F&V. Healthcare and public health investigators collect data on health parameters and dietary intakes. The resulting data typically remain with the respective collecting organizations or are available in non-transferrable formats (e.g., missing metadata). Data systems that integrate agricultural, processing, and consumer level nutritional data (along with other relevant social and cultural indicators), as well as development of metadata and ontologies to allow linkages, are essential to conducting integrated research regarding the potential and realized benefits of F&V.

Integrated (crop/economic/LCA) modeling requires integrated and fine-scale F&V data
Siloed or nonexistent data also limit researchers' analytical capacities to learn from current production or consumption patterns, as well as to predict or optimize future F&V systems given shifting environmental conditions. To understand the potential of intensifying, expanding or relocating the production of F&V in food systems, crop models offer scenario analysis, including

considering the impact and adaptation of future climate change. Crop models integrate weather, soil, and management systems to estimate or predict crop yield; both process-based models and statistical models have been used in the past for staple crops and F&V (Lobell and Field, 2011; Rosenzweig et al., 2014). Process-based crop models simulate the dynamic behaviors of crop development and growth resulting in yield over time in interaction with weather data, atmospheric CO_2, soil water and nitrogen (N) dynamics, crop management, and crop variety characteristics. Some of these crop models include N functions allowing the quantification of protein yield. To effectively run the process-based models, detailed inputs and parameter calibrations are needed, which in many cases are missing. Statistical crop models, which have a more simplified scheme as compared with process-based crop models, still have the ability to capture most first-order impacts of soil and weather as they relate to the crop yield; statistical crop models also have the flexibility to take different amounts of input data even when data is relatively limiting (Lobell and Burke, 2010). Both crop models can be applied to quantify crop dynamics in a consistent way at a field experimental plot, a farmer's field, a region, an entire country or the entire globe to generate production and nutrition data for economic, life cycle, and supply chain modeling. Such crop models exist and have been applied in systems analyses across scales for most major staple crops, such as wheat (Chenu et al., 2017), but less so for F&V crops. There are relatively few mechanistic and statistical crop models for most F&V crops, due to more limited physiological knowledge and field experimental data to build them. The application of F&V crop models at various scales is currently also hindered by limited information on cultivar characteristics, crop management (e.g. sowing and harvest dates), and yield and nutritional measurements in the field. Unlike staple crops, statistical survey data (e.g., yield, harvest area, irrigation, fertilizer use) for F&V production is limited. Efforts to map F&V production lag behind staple crops, partly due to smaller, denser, and more diversified planting areas. This information is critical for understanding, modeling, and projection of future F&V production patterns and how these systems will change under climatic or other natural resource shifts (e.g. irrigation water availability).

Dietary shifts can lead to trade-offs between nutritional and sustainability metrics

Few studies have assessed the consequences of global dietary shifts to increased intake of F&V on multiple indicators of food nutrient intake and environmental impact. United Nations' 2030 sustainable development goals (SDGs; UN, 2015) call for policies that take a systems approach and minimize trade-offs across different economic, social, environmental goals. Springmann et al. (2018a and 2018b) recently explored the impacts of improved diets, including increased F&V consumption, on a range of health and environmental outcomes at global and national levels. Most studies have assessed the dietary change or increased F&V intake impacts on single aspects of diet quality and environmental damage (e.g. GHG emissions or water) (Hess et al., 2015; Vanham et al., 2018). This is primarily because of a lack of consensus on what indicators can holistically quantify the status of national dietary quality and environmental footprint.

Recent work by Gustafson et al. (2016) and Chaudhary et al. (2018) underscored the limits of a strictly plant-based diet high in F&V intake to resolve sustainability and dietary nutritional concerns simultaneously. They found that diets in the Global North score well on intake of essential nutrients but are associated with high environmental footprint and high in intake of nutrients of health concern (e.g. sugar, cholesterol). On the other hand, diets of the Global South score well on environmental and health-concern nutrient indicators but low on indicators quantifying the adequacy of essential nutrient intake. These findings underscored the importance of a multi-indicator approach. For example, they demonstrate that a shift from current mixed diets to more plant-based diets might improve the environmental indicator scores but can result in reduction of nutritional balance score. This is because many micronutrients such as Vitamin B12 and some

essential amino acids that are found in animal-based foods are simply absent or reduced in plant-based alternatives available in the region.

Many research gaps still exist in our understanding of how particular dietary shifts such as increasing intake of F&V might affect the nutritional and environmental outcomes in different parts of the world. On the nutrition side, more comprehensive food intake as well as nutrient composition data for all food items consumed in each country are needed. This is because studies have shown that the amount of a particular micronutrient can vary dramatically for the same food item produced in different conditions/regions. Nutrient loss occurring during storage, transport, processing and cooking of food items is not well understood. On the environmental side, although several meta-analysis and life cycle assessment databases do exist, region- and production system-specific inventories of F&V items are unavailable (e.g., GHG emissions from organic F&V in SE-Asia/Africa). Global gridded maps of which F&V are grown in which regions with what management regimes are lacking. These would be important for accurately quantifying the environmental and ecosystem services impact of F&V production systems.

Opportunities: Novel research approaches to fill F&V data gaps

Trans-disciplinary systems modeling approaches are essential for integrated F&V analyses
Systems modeling using an inter-disciplinary approach is essential to the integration of complex systems such as these because they are more than the sum of their parts and must be studied as a whole. Successful approaches demand interdisciplinary teams (Finley 2017) like AgMIP – the Agricultural Model Intercomparison and Improvement Project (Rosenzweig et al. 2013), full data inclusion, data harmonization across disciplines (Finley, Fukagawa 2018) and ontologies to relate the diverse data types (Lange 2007), and independent model validation (including nutrition or clinical trials when called for by robust evidence).

Trans-disciplinary models must include the social, ecological, and economic system components of F&V systems in their analyses. This means integrating soil characteristics and the available nutrients to the market availability of the crop as well as the environmental impacts. Modelling future scenarios facing the transformations due to climatic change and further socio-economic factors such as available infrastructure, demand from the population, and the requirements of the necessary workforce will be required. This could be an opportunity to join or incorporate current models (e.g., starting from a land use suitability tool such as CONSUS and further incorporating other models such as IMPACT, GENuS).

Build improved mechanistic & statistically-based crop simulation models for F&V crops
An opportunity exists to create F&V crop models with simple generic models like CropSyst (Stockle et al., 2003), EPIC (Williams and Singh, 1995) or a new model called SIMPLE under development at University of Florida, as well as various statistical models (e.g. Lobell and Field, 2011), building on the experience with models for main crops, the literature and F&V experts. As these F&V crop models are simpler in its structure, less data is required, compared to models for main crops. To apply these F&V crop models at country or global scale, local information on variety and crop management will need to be summarized across scales as recently done for mega-environments for wheat (Gbegbelegbe et al., 2017). Expanding the modeling into nutritional aspects like protein, iron, zinc, fiber, and vitamins will require data on these across F&V crops and crop management, and in relation to changing climate and atmospheric CO_2 concentration. Creating a database with such data and identifying the gaps could be an important initial step towards modeling nutritional aspects in F&V crops. Collecting nutritional data for the major F&V crops and the main cropping systems,

including low-input (organic and agroecological) and high-input field crops, glasshouse, and urban farming systems would be critical for modeling these systems.

Advancement in high resolution remote sensing and satellite data can fill some F&V data gaps and offer new opportunities for F&V growth monitoring, yield estimation, and mapping of planting areas (Gong et al., 2013). High resolution remote sensing in both space and time is critical to provide ground truth of F&V crop, and satellite sensors from NASA (e.g. MODIS, Landsat) and European Space Agency (e.g. Sentinel missions), private sector's sensor (e.g. Planet Labs), as well as advanced fusion algorithms (e.g. Luo et al., 2018), have provided rich data for the R&V applications. Advanced cloud computing platforms, such as Google Earth Engine, Amazon Web Service, or high-performance computing facilities at individual institutes (e.g. National Center for Supercomputing Applications at University of Illinois) have provided sophisticated platforms to handle big data and machine learning analytics. Satellite remote sensing has demonstrated huge value in monitoring and modeling row crops (Guan et al. 2017; Cai et al., 2018), but they have been less utilized for monitoring F&V. These remote sensing data platforms and their analytics can support the development of statistical models and the F&V module in process-based crop models to build powerful tools to assess climate change impacts on crops (Lobell et al. 2011). However, progress depends on the availability of F&V production data at different levels (e.g., experimental, trial, plot, field, administrative levels).

Comprehensive data collection and management are needed to verify the connection between soil conservation practices and mitigation of greenhouse gas emissions. For predictive modeling efforts on long-term temperature shifts and impacts on specialty crops, better physiological and yield models are needed, which will require more spatially explicit information within the production regions (Rosenzweig et al. 2014). Such data could come from private-public partnerships or data sharing agreements with private companies.

Greater global knowledge sharing in F&V food systems

A global knowledge sharing system could assist both public and private stakeholders to disseminate existing knowledge and identify research gaps which could be addressed to drive faster progress. For example, the use of conservation tillage systems in vegetable production is rare globally, though the practice is known to have multiple environmental benefits such as reduced erosion, increased carbon sequestration, improved water holding capacity, and nutrient buffering which leads to increased protection of water quality and crop health. As conservation systems are reported to have a higher rate of adoption in South American farming regions (e.g., Brazilian zero-till farming), even in vegetable production, dissemination of knowledge and equipment could benefit other regions in the Global North and South (Landers 1999). Another opportunity is for public and private actors (including grower groups) to identify specific data needs at various points in the marketing chain, develop standards for data collection, and identify options for facilitating access to data that can improve the performance of the value chain.

Importantly, future data collection and modeling efforts should incorporate the environmental and social impacts of direct or indirect land use change associated with F&V agricultural production, such as the conversion of habitats to annual agriculture. Land use change has implications for greenhouse gas emissions, soil quality, biodiversity loss, and matters of societal equity for affected communities (land rights and tenure, household income, economic opportunity, etc.). This should include information about consumer choice, marketing and economics as well as information about food waste. Relevant datasets and experts for each of these topics should be integrated into the shared knowledge base for F&V systems.

2. INFORMATION NEEDS TO BETTER INFORM POLICY & INVESTMENT

Challenges: Better information needed to inform policy & investment for F&V systems

Food system distorted by lack of emphasis and investment on F&V crops
As noted above, public sector investments in staple grains (e.g. in CGIAR) are far greater than those in F&V (e.g. the World Vegetable Center). A further challenge includes the siloed nature of the several relevant sectors that influence the food system. For example, agricultural investments tend to support the production and expansion of major staple grains, particularly for economic returns, while food-based dietary guidelines promote increased F&V consumption (Popkin 2011).

In the Global South, traditional and indigenous F&V lack both public and private sector investment despite their superior nutritional and economic value (Schreinemachers et al., 2018). Instead, investments tend to focus on a narrow range of exotic, commercialized F&V for export, which are generally expensive to produce and to purchase, therefore restricting access for the majority of citizens. F&V investment is below the levels needed, not just in breeding, but also in infrastructure, capacity-building, and marketing required to build value chains. Lack of government oversight can result in unsafe pesticide use and food safety concerns, which ultimately affect public health.

Lack of information hides tradeoffs among food system components
Due to the complexity of F&V food systems, "optimal" production strategies are excessively challenging to define, given all of the tradeoffs – many of which are hidden – among the many competing considerations: natural resource use, distribution, food prices, and food security outcomes. Rational policies can only be defined and pursued when high-quality information is made available to all stakeholders – including those in both the public- and private-sector. In the absence of such shared access to the underlying data and information on F&V food systems, it is not possible to design, implement, and monitor relevant policies – including trade, water, and immigration.

Opportunities: Better data informs better F&V policies and investment

How to inform a holistic and integrated policy agenda for F&V systems
Public policy has the power to influence all levels of the F&V value chain, thereby shifting F&V production and consumption patterns. Innovation and investments in the private sector also have the potential to transform F&V food systems in ways that could sustainably boost productivity and enable more equitable F&V consumption. But both successful policies and investments require accurate input. A more holistic and integrated policy agenda informed by such data could help combat global malnutrition and improve sustainable nutrition security. As an example of the opportunities for better informing policy, Ministries of Agriculture typically focus on production volume, trade (exports) and farm incomes (all on supply side), whereas Ministries of Health and Education rarely focus on malnutrition as a principal challenge to overcome (Pingali, 2015). Shared access to higher quality data and information across the public- and private-sector would enable systematic and coordinated consideration of tradeoffs that best align environmental and public health outcomes (Hawkes et al., 2012).

When policymakers are provided higher quality information on the impediments of poor nutrition on educational and health improvements, action toward nutrition security is more likely to occur. For example, China's Rural Education Action Program has made great strides in convincing

policymakers to invest in improved nutrition with evidence from years of randomized control trials on nutrition-cognitive development-education interactions (FSE, 2018). Such data have the power to break down political silos, resulting in lower health costs and improved educational achievement across global populations (Naylor 2014).

Small-scale case studies on behavioral interventions would be a logical way to test hypotheses before pursuing population-level interventions. Examples worthy of consideration include purchasing policies targeting F&V, taxes/incentives, worksite wellness programs for healthy eating, and school food procurement programs, reducing cost and increasing taste and convenience.

Data-enabled investments in F&V food systems
Better data on the full diversity of F&V species and varieties can lead to more effective investment – including crops of current commercial interest as well as wild and traditional species. In the Global South, investment in processing and packaging to preserve quality and to extend shelf life will be critical to translocating rural products to city environments. An initial step in this direction would involve the construction and maintenance of rural processing plants and distribution hubs to reduce post-harvest losses in highly perishable F&V.

Data can also inform additional points of potential intervention, such as financial inclusion programs targeting women and youth involvement in sustainable F&V production, education and advertising campaigns for dietary behavior change, institutional F&V gardens and other healthy eating programming, alongside school feeding programs and hospital menus that emphasize F&V consumption.

3. PRODUCTION (FARMERS, FARMING PRACTICES, AND SUPPLY)

Challenges: Current F&V production system properties

Current F&V production systems are environmentally unsustainable
The global food system, and particularly global F&V production, cannot be sustained in its current state, due to continuing net degradation and contamination of the resource base upon which it relies. F&V systems grown in monoculture, which are frequently located in arid / semi-arid regions, tend to demand high rates of irrigation and pesticide applications that reduce water resource availability and ecosystem biodiversity over time through numerous pathways (Shennan 2008). In addition, conventional systems can be extractive and diminish soil fertility, including soil organic carbon (C) and N fractions in organic matter (Drinkwater et al. 1998). Extremely low biodiversity environments—a single F&V species across a large farm, for instance—are known to have significantly reduced levels of important ecosystem functions, such as internal nutrient (e.g., C, N, phosphorus (P)) cycling and retention, productivity, and microbial activity and abundance (Zak et al. 2003, Wagg et al. 2014). Considering the impacts of these ecosystem functions and their associated processes on the quantity and quality of F&V produced within those systems (Iverson et al. 2014, Lester & Saftner 2011), it is essential to shift production practices to build or maintain soil nutrient pools and biotic communities to sustain F&V systems moving forward.

Increasing F&V consumption must also reduce or optimize impacts to ecosystem stability, resilience, and sociocultural wellbeing (Gustafson et al., 2016). Indeed, agriculture accounts for 70% of freshwater withdrawals (FAO, 2018a), food production is projected to drive 70% of the future loss of terrestrial biodiversity (CBD, 2014), and an estimated 45% of all F&V, roots, and

tubers are wasted (FAO, 2018b). Land use efficiency and change, greenhouse gas emissions, soil quality and degradation, water use and quality, and energy use are additional environmental sustainability metrics of interest. Variation in hydrologic, soil, and climactic conditions in F&V production, in addition to variation in agricultural management systems, can result in variable natural resource requirements, risks (the WWF Water Risk Filter, 2018) and impacts, as demonstrated for water resources via water footprint analyses, (Hess & Sutcliffe, 2018) and other tools.

F&V production is overly dependent on production in semi-arid regions with scarce water
Whilst F&V are produced in many parts of the world on small farms and home gardens, global trade in F&V is increasingly providing a richer diversity of diets and increased availability of out-of-season produce. This should be beneficial for diets in those countries that import F&V. Similarly, development of export markets can bring valuable income to producing regions, stimulating the domestic economy and boosting local food security. However, through often complex supply chains, global trade in F&V can result in the relocation of environmental impacts of F&V consumption to distant locations.

Agriculture is the main user of freshwater withdrawals worldwide (>70%) and is a consumptive water use (West et al. 2014). Large-scale commercial F&V production tends to be concentrated in locations that have low rainfall and therefore rely heavily on irrigation to achieve high, reliable yields of high-quality F&V. As high-temperature, low rainfall locations, they are often also 'water-scarce,' in that the available water resources do not meet the year-round needs of domestic water use, agriculture, and industry while maintaining ecological integrity (Hess & Sutcliffe, 2018), resulting in over-exploitation of surface and ground water resources, reduced water availability to vulnerable sectors and natural resource degradation (e.g., groundwater depletion and salinization). Reliance on stressed water resources increases the vulnerability of producing regions to water shortages during drought. Many of the world's major F&V producing regions have seen recent significant droughts (e.g., California, Israel, Spain, South Africa) and are projected to see increased risk of drought in the future. Another consideration in areas dependent on desalination is the report of reduced minerals such as magnesium in F&V raised in beds irrigated with water from desalination plants (Sharar, 2018 personal communication).

The Global South lacks production support and supply chain infrastructure
F&V production in the Global South is frequently limited by access to cost-effective nutrient inputs (through fertilizers or use of legumes, compost, and manure), high-quality seeds, and pest and disease control strategies for the growing and post-harvest periods. Agricultural labor also limits expanded production, as mechanized systems are rare, and F&V crops tend to be labor-intensive. Better understanding is needed on to degree to which increased public sector support would assist farmers in transition to F&V production from other crops, or from conventional to agroecological production. Another critical factor associated with labor in F&V production systems is the need to ensure that social equity issues (e.g. human rights, child labor, etc.) are given full consideration as both productivity and overall production levels are increased.

Opportunities: Production innovations

Enhance environmental sustainability of F&V food systems
The essential question to insure the sustainable production and consumption of F&V is how to increase F&V production while minimizing negative environmental impacts. Contrary to conventional production practices, agroecological management aims to maximize positive biotic

interactions and maintains high levels of biodiversity in space and time to attain yields and other complementary goals (Altieri 1999; Shennan 2008). Ecologically-based systems emphasize internal nutrient cycling; they manage crops to build soil nutrient pools for plant uptake and microbial immobilization (e.g., Tiemann et al. 2015) and to retain nitrogen and phosphorus by maximizing the extent and functional complementarity of living crop biomass (through carbon fixation) in space and time (Isbell et al. 2017). Ecological management's approach to nutrient supply is to couple carbon and nitrogen inputs through a variety of nutrient sources, including compost, manure, and biological nitrogen fixation by legumes, and through this coupling to pair decomposition of organic residues to primary production (Blesh & Galt 2017). This approach also serves to minimize inorganic nitrogen and phosphorus pools subject to loss from the agroecosystem by assimilating them into microbial biomass and plant tissues (McDaniel et al. 2014; Vanek 2011). Thereby, agroecological management exploits microbial processes to increase internal nutrient cycling for long-term soil fertility, productivity, and yield stability (Pretty & Bharucha 2014; Raseduzzaman & Jensen 2017).

Multiple long-term studies have found that agroecological management can increase pools of soil organic carbon (SOC) while maintaining yields comparable to conventional systems (Drinkwater et al. 1998; Marriott & Wander 2006). Specific management practices that have been shown to increase soil organic carbon and nutrient (nitrogen and phosphorus) retention in agroecosystems include increasing the number of crops in rotation (McDaniel, Grandy, et al. 2014), increasing functional trait diversity in crop rotations by adding perennials and legume cover crops (or diversified cover crop mixtures) to simplified rotations (King & Blesh 2018; Marriott & Wander 2006; De Deyn et al. 2008), and reducing or eliminating tillage (Peterson et al. 1998; Six et al. 2002). Managing diversity on F&V farms can support both short-term productivity and long-term sustainability goals.

Assuring the sustainability of F&V systems will necessitate a focus on maintaining or increasing yields of a variety of nutrient-rich foods, paired with emphasis on improving soil fertility and water quantity and quality through management, as well as breeding cultivars that can adapt to a changing climate and repair of degraded resources.

Increase resource use efficiency in F&V food systems

As a step toward sustainable F&V production, increased efficiency of nutrient use can aid in the transition from high-input conventional to low-input agroecological management systems. To increase the production of F&V per unit land, plant breeding and information-technology enabling precision management can be important contributors. Global temperature increases could create opportunities in irrigated lands at higher latitudes where the possibility of multiple crop harvests per season should be evaluated. Increasing the fraction of biological yield that is marketable is also important, including the possibility of secondary markets for the lower quality F&V that are not harvested. Adoption of precision irrigation systems, that reduce non-productive water losses, can also facilitate customized application of mineral nitrogen and other nutrients, which can dramatically reduce nitrogen pollution. These irrigation systems can also reduce greenhouse gas emissions and energy use per unit of water applied. Preliminary high-level results suggest potential reductions in certain environmental impacts for protected agriculture for some crops, but innovation and re-use of byproducts is still needed to reduce energy losses (Stoessel et al. 2012, Blanke and Burdick 2005, Atallah et al., 2014).

More research is needed on where increased production would be most likely to occur, given that supply chain infrastructure tends to co-locate with areas of high agricultural production. Also, more

research is needed on what supply chain innovations are most cost-effective for industry and producers simultaneously.

4. CONSUMPTION (AVAILABILITY, ACCESS, AND DEMAND)

Challenges: Current characteristics of F&V consumption

Health challenges due to insufficient F&V consumption

F&V are among the few food groups with positive outcomes for both undernutrition (e.g. micronutrient deficiencies) and overnutrition (e.g. cardiovascular disease, overweight and obesity). For example, a diet rich in F&V may reduce the projected incidence of colorectal cancer, currently the third most common cancer and fourth leading cause of cancer-related death worldwide (Ferlay et al., 2012). As much as 90% of all colorectal cancer incidence is attributed directly to dietary factors alone (Pericleous et al., 2013). Despite current understanding of the detriments of poor nutrition, unfavorable dietary patterns prevail as the Global South transitions towards a dependency on processed foods (Popkin et al., 2012). Increasing access to inexpensive, calorically dense convenience foods may promote inadequate F&V intake, which is inversely associated with colorectal cancer risk. Colorectal cancer incidence is predicted to increase 80% by 2035, when the Global South is predicted to bear the majority of the economic burden (Douaiher et al., 2017).

Evidence of dietary diversity change over previous decades has shown an increased diversification of national food supplies worldwide with regard to major staple cereals, oils, and sugars, but not of vegetables (Khoury et al. 2014). In addition to disease prevention, consumption of F&V contributes to and enriches diet diversity, which can provide essential micronutrients that are critical for vital body functions and provide protective effects against harmful toxins naturally found in diet (e.g., aflatoxins like AFB1) and pathological processes that lead to higher risk of cardiovascular diseases (e.g., excess caloric consumption). For example, organosulfur compounds found in garlic (e.g. Diallyl sulfide and diallyl disulfide) have been shown to provide protection against AFB1 carcinogenesis via modulation of enzymes involved in the metabolism of AFB1 (Guyonnet et al., 2002). Moreover, dietary allicin compound found in garlic have been found to have a cardio-protective effect and work with gut bacteria to inhibit the conversion of L-cartinine found in red meat into Trimethylamine N-oxide, a compound that is found to promote atherosclerosis & increase risk of cardiovascular diseases (Wuab et al., 2015).

Wide gap between consumer knowledge & consumer behavior

The primary obstacle to increasing F&V intake and to reach nutrition goals and reduce population-level disease risk is the gap between consumer knowledge and consumer behavior. The public's awareness and knowledge about the health and even environmental benefits of F&V consumption are significant. Dietary guidance has been highly consistent in emphasizing this goal. However, consumer behavior is often driven not by scientifically determined goals, but by other values. Articulating and communicating value-based messages that are motivating for a range of consumers will be key to success in meeting sustainable diet objectives.

Another significant challenge is in interpretation of and communication of complex interactions and trade-offs among various impacts (Poore and Nemecek, 2018) (Perrin et al., 2014) (Rosenbaum et al., 2015). Communication in multiple spheres will be required to consumers, producers, and policy makers, each of whom will have different information requirements and ability to interpret the

complexity of trade-offs. Potential approaches include social marketing, behavioral economics approaches, policies targeting youth (Hodder et al., 2018, Arizona Department of Education, 2018), and technology-based behavior change models (Thomson and Ravia, 2011).

Shifting consumer behavior and preferences in Global North has demand-side and sustainability impacts

An ongoing trend in the Global North is that supermarkets offer a wide assortment of fresh produce throughout the year in a wide variety of more and more prepackaged products. Consumer food preferences are far from static. For the last several years, the food industry has been navigating demographic shifts, evolving consumer preferences toward health and well-being, remarkable technology advancements that reshape consumer marketing and shopping experiences, turbulent socio-economic and political forces that further bifurcate and polarize consumers, and a rapidly changing retailer and foodservice environment. Combined, these disruptive forces have significantly impacted how consumers interact with marketing and points of purchase of food, as well as their ability and willingness to purchase food, particularly in the category of F&V and other specialty crops.

Opportunities: Innovations in F&V consumption (availability, access, and demand)

Broad engagement of all stakeholders and a comprehensive, multi-disciplinary approach

IFPRI (2017) projects that global demand for fruits and vegetables will increase by more than 80% by 2050 (relative to 2010 levels), compared to an increase of around 65% for meat and 40% for cereals and roots and tubers. Understanding the drivers of food choice and the task of inducing a shift in consumption requires engagement of social scientists, industry, farmers/producers, and government agencies. Informing healthcare providers and providing a clear rationale for why they should encourage a shift in consumption will require transdisciplinary dialogue. One size does not fit all. Recommendations should embrace regional and cultural differences. For example, the emphasis could shift towards assuring access to a variety of F&V without a focus on specific nutrients or compounds in the diet. It is also important to recognize that drivers for food manufacturers and food producers are heavily influenced by economics. It will be necessary to create incentives to assure availability and access to all communities regardless of income status.

Application of social networking and information exchange with new technologies should enable collection of the necessary data to connect disparate disciplines. It appears that these technologies should be employed to understand the drivers of choice and the barriers that consumers identify as reasons they are unable to consume foods that are presumed to lead to wellness. Rather than approaching research, production, and policy in a top-down manner; prioritizing needs of the community and engaging community members in finding solutions would be more effective.

A framework to shift consumption will need information about evolving social norms, minimizing disruption in the supply stream, selling compelling benefits and maximizing awareness of increasing F&V intake (see "shift wheel" from World Resources Institute, https://www.wri.org/resources/charts-graphs/shift-wheel-changing-consumer-purchasing). Consumer engagement will help to drive demand and industry collaborations will be necessary to understand and strengthen market signals. Systems approaches will be increasingly important: "The behavior of a system cannot be known just by knowing the elements of which the system is made." (Donella H. Meadows *Thinking in Systems*).

Strategic use of communications to connect with consumers
Today's public interest in sustainable food systems offers a unique opportunity to frame a communications strategy based on meeting consumers where they are. There is an opportunity for the broader engagement of society and a range of scientists and other disciplines to define and craft unique approaches to help the public reach sustainable diet/food system goals. While the message about increasing F&V consumption is not new, the concept of a sustainable food system is relatively novel to consumers and of significant relevance. This may open a communications strategy that will meet both human health and environmental goals.

Engaging around consumer values and emotions related to F&V consumption is another promising approach as facts alone are not enough. Given that a focus on health is not sufficient to drive behavior change, developing a better understanding of motivations like: increasing pride for meeting F&V consumption objectives, developing regular F&V consumption habits, associating produce consumption with happiness/well-being, emphasizing the importance of role modeling for parents, etc. All of these examples offer two elements of successful communications: empathy and a narrative. Additionally, a wide range of players need to collaborate on any communication strategy to effectively tell the story and deliver actionable, resonant messages.

Enable private-sector sustainability initiatives to continue to thrive
Many of the largest food companies in the world are taking measures to address sustainability in their supply chains. Investors and retail customers increasingly see sustainability efforts as key to reducing risks, such as drought or adverse weather, which can disrupt company performance. Consumers increasingly seek out products which disclose ingredient origins and production methods deemed beneficial or desirable for society and the environment. Consumers also view sustainability efforts in ingredient production as a proxy for better nutrition, even in the absence of science-based evidence.

A leader of these issues is The Sustainability Consortium (TSC, sustainabilityconsortium.org), a global membership organization whose members represent $200 Billion in annual sales. Members, including the largest food retailer in the world, Walmart, utilize science-based product category sustainability profiles and key performance indicators to assess how to more sustainably produce their products. A key finding of TSC is that for food and beverage products, the agriculture supply chain has the majority of environmental and social impact risks and opportunities. In fact, for most consumer-facing companies, "80-90% of the total end-to-end environmental and social impacts are embedded in the upstream supply chain" (TSC, 2018). In the Global North, companies have come together to address these concerns through partnerships such as the Stewardship Index for Specialty Crops (SISC) and the Sustainable Agriculture Initiative.

A case study in this effort is Campbell Soup Company's work with family farms producing its annual processing tomato crop. Using SISC metrics, the Campbell Sustainable Agriculture Program has documented approximately 20% reduction in the volume of water applied per ton of tomato produced for the company after 6 years, due to the increased utilization of drip irrigation systems on these farms (http://www.campbellcsr.com/grown/interior.html#goals).

Increase social equity in F&V consumption through food literacy
In the context of a complex food environment, consumers tend to rely on simplified mental shortcuts, referred to as "heuristic cues" to help them make decisions about personal food choices. By definition, urban consumers do not regularly interact with agriculture and often lack basic knowledge about how food is produced and why food production practices may impact human and

planetary health. They also face the challenge of having to make decisions about what to eat in an increasingly complex food system. While consumers with ample disposable income may opt to purchase foods directly from farmers who practice sustainable agriculture, the cost barrier to entry is often too high for low-income consumers.

Even when consumers can afford to participate in non-mainstream F&V food systems, such as those who participate in community-supported agriculture (CSA) shares, they do not always know what to do with the unfamiliar produce items they receive from the subscription programs, which can lead to waste (Feagan & Henderson 2009). It is therefore important to consider unbiased, science-based outreach and educational opportunities that may empower consumers to make environmentally sound food choices without compromising overall social equity. The concept of food literacy offers a potentially helpful framework to build the connection between production and consumption that helps consumers make sound food choices that works best for their lives.

Food literacy interventions can take multiple forms to meet intended audience's needs. From nutrition education programs that emphasize home gardening to food preservation workshops for food enthusiasts, this framework can enable consumers and food system advocates to help urban dwellers re-engage with the food system regardless of their baseline knowledge. Instead of taking a disease-prevention focused approach, it encourages consumers to continuously build on their existing knowledge of food and empowers consumers to take actions that contribute to building more sustainable food systems.

Reduce food waste in F&V systems

The deficit in global supply of F&V is exacerbated by the highly perishable nature of F&V leading to combined losses (post-harvest) and waste (at consumer level) of more than 50% of total production (FAO, 2018b). Greater research is needed to estimate the cost of food waste, especially for low-income households; and the environmental impacts of repurposing food waste for compost, for example. Industry innovation in packaging to reduce spoilage and alert consumers of spoilage are needed and underway. Finally, greater standardization of date labels (e.g. "use by", "best by", and "sell by") are needed to prevent consumer confusion about early spoilage of products.

5. SUSTAINABLE AND EQUITABLE F&V FOOD SYSTEMS AND SUPPLY CHAINS

Challenges and Opportunities: Systemic changes to F&V systems

The primary ultimate purpose of agriculture is to meet the human need for food and nutrition. However, nutrition is a complex concept (Raiten 2017) composed of multiple processes. These processes interact with and are impacted by the health status of the individual as well as that of the external environment. The overall food system is also highly complex (National Research Council 2015), comprising many closely-interacting components. And just as with the nutrition of an individual, the overall food system is also impacted by the external environment. Given their intrinsic complexities, simple perturbations of either system can produce unanticipated effects – even when each considered in isolation from the other. But in reality, these two systems also directly interact with each other, resulting in an infinitude of possible outcomes from even the apparently simplest of interventions: such as when fewer mothers say to their children: "Finish eating your vegetables!" or a judge orders that a river may no longer be used for F&V irrigation, due to the presence of an endangered species. Data on supply:demand ratios in the Global North and the Global South show that current system-scale data on production and individual consumption are

internally consistent (Miller et al., 2015; Schmidhuber et al., 2018; Conrad et al., 2018) and that production of F&V could theoretically increase to match the global dietary need for more F&V consumption (Siegel et al., 2014).

But many system-level challenges and questions remain, in order to ensure that higher levels of F&V productivity and consumption are accompanied by fulfillment of the key imperatives identified in this position paper – namely, that F&V food systems become more diverse, equitable, nutritious, resilient, and sustainable. For instance: How will changing climatological conditions impact the availability of F&V in various regions? In what ways will shifts in geographic production areas as a result of changing climates impact workforce availability? How can we utilize the powerful role that women play as household decision makers to encourage better nutrition, without burdening them in that role? How do we ensure greater access to farming technology, particularly for smallholder farmers? What information should be available to help individuals and societies make the necessary tradeoffs for optimal diets?

There are a wide variety of F&V food systems worldwide, ranging from large commercial operations focused on global and regional trade, to medium and small family-run F&V systems, to home gardens, to collection of wild F&V. There are countless products in the global F&V system when one includes F&V indigenous to each region. There are few, if any, breeders for the latter, and these systems are poorly defined and classified. A large share of rural households throughout the world rely on home gardens for at least some of their F&V intake, and produce from these gardens is rarely counted in agricultural statistics, as such foods do not enter the formal market.

As the global population becomes more urban, household production systems may play a smaller role, and thus traded F&V will become more important. Producers of F&V throughout the world will adjust to market opportunities, policy incentives, and resources (e.g., water) availability and cost. Experience from many parts of the Global South shows that low-income farmers often sell their high-value, highly-nutritious products and purchase lower quality, less expensive starchy staples and sugar (and some meat) with their added incomes. This trend is visible in the World Bank's Living Standards Measurement Study data and runs counter to public and private investment efforts in indigenous F&V. The nutrition security and equity dimensions of expanding F&V systems in an urbanizing world merit further study and offer substantial opportunities for innovation.

CONCLUSIONS

Fruit and vegetables (F&V) as a focal point for research and action provide tremendous opportunities to improve human nutrition, food system sustainability, and potentially equity and economic opportunity. With regard to human nutrition, F&V are clearly pivotal to preventing a range of diet-related diseases and in the overall maintenance of healthy and productive lives. With regard to sustainability, increased investment in F&V provides opportunities to (re)diversify local, regional, and global food systems, and potentially to reduce soil erosion and natural resource inputs. Having significant impacts even in backyard, or very small-scale production, they also may serve as increasingly important food sources in times when larger food systems are destabilized due to climate change, trade wars, civil strife, or other shocks. Likewise, with regard to equity and opportunity, redesigning food systems toward more F&V can open opportunities for small scale producers and more direct (short value chain) marketing, as well as a re-diversifying of major food system power brokers, if done with a concerted view toward those aims.

But all of these potential opportunities require further knowledge as well as momentum to act in much broader and more coordinated ways. The most important nutritional constituents in F&V; the best ways to preserve them in value chains and make them available for absorption; and their interactions and the interactions between them and other foods, human genetic differences, and gut, oral, and soil microbiomes all require further investigation to maximize nutritional outcomes. Agronomic, genetic resource and plant breeding, and post-harvest processing and delivery all require research with the aims of greater and more stable production and delivery of high-nutritional value F&V with the minimum use of non-renewable energy, water, fertilizer, and pesticides, minimum loss, both pre- and post-harvest, and while increasing quality control and food safety. And all of this must also be accomplished while ensuring that F&V remain or become affordable to *all* consumers. With a long-term view toward sustainable food systems, further efforts are needed to investigate, conserve, breed, and celebrate the wider diversity of F&V that still persist around the world but which are disappearing or becoming more marginalized in diets, and are certainly not contributing as much as they could to global nutrition. Finally, food systems in most regions, small and large, will require major redesign if they are to provide significantly more opportunities to disenfranchised producers, farm workers, and other actors in food systems.

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References

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosystems. Agriculture, Ecosystems and Environment, 74(1–3):19–31.

Antón, A., Torrellas, M., Núñez, M., Sevigné, E., Amores, M.J., Muñoz, P., Montero, J.I., 2014. Improvement of Agricultural Life Cycle Assessment Studies through Spatial Differentiation and New Impact Categories: Case Study on Greenhouse Tomato Production. Environ. Sci. Technol. 48:9454–9462.

Appleton, K.M., A. Hemingway, L. Saulais, C. Dinnella, E. Monteleone, et al., 2016. Increasing vegetable intakes: rationale and systematic review of published interventions Eur. J. Nutr., 55:869-896

Arizona Department of Education (AZDE), 2018. AZDE Nutrition & Health Services, Fresh Fruit and Vegetable Program. Phoenix, AZ, http://www.azed.gov/hns/sfp/ffvp/.

Arvanitoyannis, I.S., Kotsanopoulos, K. V, Veikou, A., 2014. Life Cycle Assessment (ISO 14040) Implementation in Foods of Animal and Plant Origin: Review. Crit. Rev. Food Sci. Nutr. 54:1253–1282.

Atallah, S.S., Gómez, M.I., Björkman, T., 2014. Localization effects for a fresh vegetable product supply chain: Broccoli in the eastern United States. Food Policy 49:151–159.

Aune, D., E. Giovannucci, P. Boffetta, L. T. Fadnes, N. Keum, T. Norat, D. C. Greenwood, E. Riboli, L. J. Vatten, S. Tonstad., 2017. Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality — a systematic review and dose-response meta-analysis of prospective studies. International Journal of Epidemiology, VOL:1029–1056.

Bahadur K.C. et al., 2018. When too much isn't enough: Does current food production meet global nutritional needs? PLoS ONE, 13 (10), art. no. e0205683.

Blanke, M., Burdick, B., 2005. Food (miles) for Thought - Energy Balance for Locally-grown versus Imported Apple Fruit. Environ. Sci. Pollut. Res. - Int. 12:125–127.

Blesh, J. & Galt, R.E., 2017. Chapter 4: Transitions to Agroecological Nutrient Management Practices in the USA Corn Belt. In Agroecological Practices for Sustainable Agriculture. pp. 85–126.

Burney, J. A., & Naylor, R. L. 2011. Smallholder irrigation as a poverty alleviation tool in the Sub-Saharan Africa. World Development, 40(1):110-123.

Burney, J., Woltering, L., Burke, M., Naylor, R., & Pasternak, D., 2010. Solar-powered drip irrigation enhances food security in the Sudano-Sahel. PNAS, 107(5):1848-1853.

Cai, Y., Guan, K., Peng, J., Wang, S., Seifert, C., Wardlow, B., Li, Z. 2018. A high-performance and in-season classification system of field-level crop types using time-series Landsat data and a machine learning approach, Remote Sensing of Environment.

CBD, 2014. Secretariat of the Convention on Biological Diversity. Global Biodiversity Outlook 4. Montréal, 155 pages.

Cerutti, A.K., Beccaro, G.L., Bosco, S., De Luca, A.I., Falcone, G., Fiore, A., Iofrida, N., Lo Giudice, A., Strano, A., 2015. Life Cycle Assessment in the Fruit Sector, in: Notarnicola, B., Salomone, R., Petti, L., Renzulli, P.A., Roma, R., Cerutti, A.K. (Eds.), Life Cycle Assessment in the Agri-Food Sector. Springer International Publishing, Cham, pp. 333–388.

Chaudhary, A.; Gustafson, D.; Mathys, 2018. A. Multi-indicator sustainability assessment of global food systems. Nat. Commun. 9:848.

Chenu, K. et al., 2017. Contribution of crop models to adaptation in wheat. Trends in Plant Science, 22(6): 472-490.

City of Santa Monica, 2017. Santa Monica Releases New Findings from Wellbeing Index. https://www.santamonica.gov/press/2017/09/14/santa-monica-releases-new-findings-from-wellbeing-index.

Conrad, Z; Johnson, LK; Peters, CJ, et al. 2018. Capacity of the US food system to accommodate improved diet quality: A biophysical model projecting to 2030. Current Developments in Nutrition 2: nzy007-nzy.

Conrad, Z; Niles, MT; Neher, DA, et al. 2018. Relationship between food waste, diet quality, and environmental sustainability. Plos One 13: e0195405.

CONSUS (ref: https://www.sciencedirect.com/science/article/pii/S0168169917307615).

De Deyn, G.B., Cornelissen, J.H.C. & Bardgett, R.D., 2008. Plant functional traits and soil carbon sequestration in contrasting biomes. Ecology Letters, 11, pp.516–531.

Del Gobbo, LC; Khatibzadeh, S; Imamura, F, et al. 2015. Assessing global dietary habits: A comparison of national estimates from the fao and the global dietary database. American Journal of Clinical Nutrition 101: 1038-46.

Dietary Guidelines Advisory Committee. 2010. Report of the dietary guidelines advisory committee on the dietary guidelines for Americans, 2010, to the Secretary of Agriculture and the Secretary of Health and Human Services, Agricultural Research Service.

Drinkwater, L.E., Wagoner, P. & Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature, 396, pp.262–265.

FAO, 2018a. AQUASTAT: FAO's Global Water Information System. http://www.fao.org/nr/water/aquastat/main/index.stm.

FAO, 2018b. SAVE FOOD: Global Initiative on Food Loss and Waste Reduction, http://www.fao.org/save-food/resources/keyfindings/infographics/fruit/en/.

FAO, IFAD, UNICEF, WFP and WHO, 2017. The State of Food Security and Nutrition in the World 2017. Building resilience for peace and food security. Rome, FAO. http://www.fao.org/3/a-I7695e.pdf.

Faour-Klingnbiel & Todd, 2018. A Review on the Rising Prevalence of International Standards: Threats or Opportunities for the Agri-Food Produce Sector in Developing Countries, with a Focus on Examples from the MENA Region, Foods 7(3):33.

Finley J.W., D. Dimick, E. Marshall, G.C. Nelson, J.R. Mein, D.I. Gustafson. 2017. Nutritional sustainability: Aligning priorities in nutrition and public health with agricultural production. Advances in Nutrition. 8(5):780-8.

Finley J.W. and Fukagawa N.K. 2018 (in review). Integrated Data Across Multiple and Diverse Disciplines are Essential for Developing a Sustainable Food System, JSWC.

Forouzanfar MH, Alexander L, Anderson HR, Bachman VF, Biryukov S, Brauer M, et al. 2015. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013. The Lancet, 386(10010):2287-323.

FSE (Center for Food Security & the Environment), 2018. Rural Education Action Program, Stanford University, Stanford, CA. https://reap.fsi.stanford.edu/.

Gbegbelegbe, S. et al., 2017. Baseline simulation for global wheat production with CIMMYT mega-environment specific cultivars. Field Crops Research, 202: 122-135.

Gong, P., Wang, J., Yu, L. Le, Zhao, Y. Y. Y. Y., Liang, L., Niu, Z., et al. 2013. Finer resolution observation and monitoring of global land cover: first mapping results with Landsat TM and ETM+ data. International Journal of Remote Sensing, 34(7):2607–2654.

Guan, K., Wu, J., Kimball, J., Anderson, M., Li, B., Lobell, D, 2017. The shared and unique values of optical, fluorescence, thermal and microwave satellite data for estimating large-scale crop yields, Remote Sensing of Environment., 199, 333-349.

Gustafson, D.; Gutman, A.; Leet, W.; Drewnowski, A.; Fanzo, J.; Ingram, J. 2016. Seven Food System Metrics of Sustainable Nutrition Security. Sustainability, 8:196.

Guyonnet, Denis; Christine Belloir; Marc Suschetet; Marie-Hélène; SiessAnne-Marie Le Bon, 2002. Mechanisms of protection against aflatoxin B1genotoxicity in rats treated by organosulfur compounds from garlic , Carcinogenesis, 23(8):1335–1341.

Hauschild, M., 2006. Spatial Differentiation in Life Cycle Impact Assessment: A decade of method development to increase the environmental realism of LCIA. Int. J. Life Cycle Assess. 11, 11–13.

Hawkes, C., Friel, S., Lobstein, T. and Lang, T., 2012. Linking agricultural policies with obesity and noncommunicable diseases: A new perspective for a globalising world, Food Policy, 37:343–353.

Heller, M.C., Keoleian, G.A., Willett, W.C., 2013. Toward a Life Cycle-Based, Diet-level Framework for Food Environmental Impact and Nutritional Quality Assessment: A Critical Review. Environ. Sci. Technol. 47, 12632–12647.

Hess, T.M., Andersson, U., Mena, C. and Williams, A., 2015. The impact of healthier dietary scenarios on the global blue water scarcity footprint of food consumption in the UK. Food Policy, 50:1-10.

Hess, T.M. and Sutcliffe, C., 2018. The exposure of a fresh fruit and vegetable supply chain to global water-related risks. Water International. 43(6):746-761.

Hodder et al., 2018. Interventions for increasing eating of fruit and vegetables in children aged five years and under, Cochrane, https://www.cochrane.org/CD008552/VASC_interventions-increasing-eating-fruit-and-vegetables-children-aged-five-years-and-under.

Ingwersen, W.W., 2012. Life cycle assessment of fresh pineapple from Costa Rica. J. Clean. Prod. 35, 152–163.

International Food Policy Research Institute (IFPRI) 2017, 2017 Global Food Policy Report, pp 110-118. Washington, DC: International Food Policy Research Institute. http://www.ifpri.org/publication/2017-global-food-policy-report.

International Food Policy Research Institute (IFPRI) 2018. Global Food Policy Report (http://www.ifpri.org/publication/2018-global-food-policy-report), with IMPACT projections starting on p. 124 – presents IFPRI's latest IMPACT baseline projections to 2030 and 2050, by region, for key indicators and for major food groups (including F&V on p. 128).

IPES, 2015. Overcoming Barriers to Food Systems Reform.

Isbell, F. et al., 2017. Benefits of increasing plant diversity in sustainable agroecosystems. Journal of Ecology, 105, pp.871–879.

Iverson, A.L. et al., 2014. Do polycultures promote win-wins or trade-offs in agricultural ecosystem services? A meta-analysis. Journal of Applied Ecology, 51, pp.1593–1602.

Jansen, M. C. J. F. 2001. Fruits and vegetables and the risk of epithelial cancer.

Joint WHO/FAO Expert Consultation. 2003. Diet, nutrition, and the prevention of chronic diseases. Geneva: World Health Organization, Report No.: 92 4 120916 X.

Jones et al., 2016. Toward a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science, Agricultural Systems, 155:269-288.

King, A.E. & Blesh, J., 2018. Crop rotations for increased soil carbon: perenniality as a guiding principle. Ecological Applications, 28(1), pp.249–261.

Khoury, C. K. et al. 2014. Increasing homogeneity in global food supplies and the implications for food security. Proc. Natl. Acad. Sci. U. S. A. 111, 4001–4006.

Lange, M. C., Lemay, D. G., & German, J. B., 2007. A multi-ontology framework to guide agriculture and food towards diet and health. Journal of the Science of Food and Agriculture, 87(8), 1427-1434. Malik V.S., W.C. Willett, F.B. Hu. Global obesity: trends, risk factors and policy implications. Nature Reviews Endocrinology. 2013 Jan;9(1):13.

Lester, G.E. & Saftner, R.A., 2011. Organically versus Conventionally Grown Produce: Common Production Inputs, Nutritional Quality, and Nitrogen Delivery between the Two Systems. Journal of Agricultural and Food Chemistry, 59, pp.10401–10406.

Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, et al. 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010 Lancet 380(9859):2224-60.

Lobell, D.B., Burke, M.B. (eds.) 2010. Climate Change and Food Security. Springer. http://www.springerlink.com/content/978-90-481-2952-2

Lobell D.B., Field C.B., 2011. California perennial crops in a changing climate Clim. Change 109 317–33 Online: http://link.springer.com/10.1007/s10584-011-0303-6

Lobell, D. B., Schlenker, W., Costa-Roberts, J., 2011. Climate Trends and Global Crop Production Since 1980. Science 333, 616-620.

Luo, Y., Guan, K., Peng, J., 2018. STAIR: A generic and fully-automated method to fuse multiple sources of optical satellite data to generate a high-resolution, daily and cloud-/gap-free surface reflectance product, Remote Sensing of Environment, 214, 87-99.

Macdiarmid, J. (2016). University of Aberdeen- PLOS One 2018; Appetite.

Marriott, E.E. & Wander, M.M., 2006. Total and Labile Soil Organic Matter in Organic and Conventional Farming Systems. Soil Science Society of America Journal, 70, pp.950–959.

McDaniel, M.D., Grandy, A.S., et al., 2014. Crop rotation complexity regulates the decomposition of high and low quality residues. Soil Biology and Biochemistry, 78:243–254.

McDaniel, M.D., Tiemann, L.K. & Grandy, A.S., 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecological Applications, 24(3), pp.560–570.

Menter, J., 2012. Helping U.S. Farmers Increase Production and Protect the Land https://e360.yale.edu/features/helping_us_farmers_increase_production_and_protect_the_land.

Milà i Canals, L., Cowell, S.J., Sim, S., Basson, L., 2007. Comparing domestic versus imported apples: A focus on energy use. Environ. Sci. Pollut. Res. - Int. 14, 338–344.

Miller et al., 2015. The United States food supply is not consistent with dietary guidance: evidence from an evaluation using the Healthy Eating Index-2010, J Acad Nutr Diet., 115(1):95-100.

National Academies of Sciences, Engineering, and Medicine. 2018. Science Breakthroughs to Advance Food and Agricultural Research by 2030. Washington, DC: The National Academies Press.

National Research Council. 2015. A framework for assessing effects of the food system. National Academies Press, Washington, DC.

National Resources Defense Council, 2017. Wasted: How America is Losing Up to 40 Percent of its Food from Farm to Fork to Landfill. https://www.nrdc.org/sites/default/files/wasted-2017-report.pdf

Naylor, 2014. The Evolving Sphere of Food Security, Oxford U Press.

Ng, M. et al. 2014. Global, regional, and national prevalence of overweight and obesity in children and adults during 1980-2013: a systematic analysis for the Global Burden of Disease Study 2013. Lancet 384, 766-781.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. J. Clean. Prod. 140, 399–409.

Perrin, A., Basset-Mens, C., Gabrielle, B., 2014. Life cycle assessment of vegetable products: A review focusing on cropping systems diversity and the estimation of field emissions. Int. J. Life Cycle Assess. 19, 1247–1263.

Peterson, G.A., Halvorson, A.D., Havlin, J.L., Jones, O., Lyon, D.J. and Tanaka, D.L., 1998. Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil and Tillage Research, 47(3-4):207-218.

Pingali, P., 2015, Agricultural policy and nutrition outcomes – getting beyond the preoccupation of staple grains, J. Food Security (https://link.springer.com/content/pdf/10.1007%2Fs12571-015-0461-x.pdf).

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360:987 LP-992.

Popkin, B.M., 2011. Agricultural policies, food and public health, EMBO Reports, 12(1):11-18.

PRB, 2017. 2017 World Population Data, https://www.prb.org/2017-world-population-data-sheet/.

Pretty, J. & Bharucha, Z.P., 2014. Sustainable intensification in agricultural systems. Annals of Botany, 114, pp.1571–1596.

Raiten D.J., A.M. Aimone. 2017. The intersection of climate/environment, food, nutrition and health: crisis and opportunity. Curr Opin Biotechnol. 44:52-62.

Raseduzzaman, M. & Jensen, E.S., 2017. Does intercropping enhance yield stability in arable crop production ? A meta-analysis. European Journal of Agronomy, 91:25–33.

Röös, E., Karlsson, H., Witthöft, C., Sundberg, C., 2015. Evaluating the sustainability of diets–combining environmental and nutritional aspects. Environ. Sci. Policy 47, 157–166.

Rosegrant et al. 2017. Quantitative foresight modeling to inform the CGIAR research portfolio (http://www.ifpri.org/publication/foresight-modeling-agricultural-research) – examines how baseline projections could change under different agricultural investment scenarios to 2050.

Rosenbaum, R.K., Anton, A., Bengoa, X., Bjørn, A., Brain, R., Bulle, C., Cosme, N., Dijkman, T.J., Fantke, P., Felix, M., Geoghegan, T.S., Gottesbüren, B., Hammer, C., Humbert, S., Jolliet, O., Juraske, R., Lewis, F., Maxime, D., Nemecek, T., Payet, J., Räsänen, K., Roux, P., Schau, E.M., Sourisseau, S., van Zelm, R., von Streit, B., Wallman, M., 2015. The Glasgow consensus on the delineation between pesticide emission inventory and impact assessment for LCA. Int. J. Life Cycle Assess. 20:765–776.

Rosenzweig, C. et al. 2013. The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. Agricultural and Forest Meteorology 170, 166-182.

Rosenzweig, C. et al. 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proceedings of the National Academy of Sciences of the United States of America 111, 3268-3273.

Schmidhuber et al., 2018. The Global Nutrient Database: availability of macronutrients and micronutrients in 195 countries from 1980 to 2013. Lancet Planet Health 2018; 2: e353–68.

Schreinemachers, P., Simmons, E.B., Wopereis, M.C.S, 2018. Tapping the economic and nutritional power of vegetables, Global Food Security, 16:36-45.

Shackleton, C.M., M.W. Pasquini, A.W. Drescher (Eds.), 2009. African Indigenous Vegetables in Urban Agriculture, Earthscan, London & Sterling, VA, pp. 105-143

Shennan, C., 2008. Biotic interactions, ecological knowledge and agriculture. Philosophical Transactions of the Royal Society B, 363, pp.717–739.

Siegel KR, Ali MK, Srinivasiah A, Nugent RA, Narayan KMV, 2014. Do We Produce Enough Fruits and Vegetables to Meet Global Health Need? PLoS ONE 9(8): e104059.

Six, J., Feller, C., Denef, K., Ogle, S., de Moraes Sa, J.C. and Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils-Effects of no-tillage. Agronomie, 22(7-8), pp.755-775.

Smith MR, Micha R, Golden CD, Mozaffarian D, Meyers SS., 2016. Global Expanded Nutrient Supply (GENus) model: A new method for estimating the global dietary supply of nutrients. PLoS ONE 11(1): e0146976.

Springmann et al., 2016. Global and regional health effects of future food production under climate change: a modelling study, The Lancet 387:1937-1946 (https://www.thelancet.com/journals/lancet/article/PIIS0140-67361501156-3/abstract) –

examines how changes in food production and diet induced by climate change will affect human health to 2050.

Springmann et al., 2017. Mitigation potential and global health impacts from emissions pricing of food commodities, Nature Climate Change 7:69-74.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., G. Tilman, D., Rockström, J. and Willett, W., 2018. Options for keeping the food system within environmental limits, Nature 562:519–525.

Springmann, M., Wiebe, K., Mason-D'Croz, D., Rayner, M. and Scarborough, P., 2018, Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail, Lancet Planetary Health 10(2).

Steenwerth et al. Agriculture & Food Security 2014, 3:11, Climate-smart agriculture global research agenda: scientific basis for action. http://www.agricultureandfoodsecurity.com/content/3/1/11.

Stockle, C.O., Donatelli, M. and Nelson, R., 2003. CropSyst, a cropping systems simulation model. European Journal of Agronomy, 18(3-4): 289-307.

Stoessel, F., Juraske, R., Pfister, S., Hellweg, S., 2012. Life cycle inventory and carbon and water foodprint of fruits and vegetables: Application to a swiss retailer. Environ. Sci. Technol. 46, 3253–3262.

The Sustainability Consortium (TSC), 2018. https://www.sustainabilityconsortium.org/impact/impact-report/.

Thomson, C.A., Ravia, J., 2011. A Systematic Review of Behavioral Interventions to Promote Intake of Fruit and Vegetables, J. Academy of Nutrition and Dietetics, 111(10):1523–1535.

Tiemann, L.K. et al., 2015. Crop rotational diversity enhances belowground communities and functions in an agroecosystem. Ecology Letters, 18, pp.761–771.

Traill, W.B., M. Mazzocchi, B. Shankar, D. Hallam, 2014. Importance of government policies and other influences in transforming global diets Nutr. Rev., 72:591-604

Tuomisto HL et al: Wellcome Open Research 2017, 2:21, last update 15 Feb 2018

UC Davis, 2017. Aligning the Food System to Meet Dietary Needs: Fruits and Vegetables, https://horticulture.ucdavis.edu/event/nutrition-2017.

United Nations, 2015. Transforming Our World: The 2030 Agenda for Sustainable Development; United Nations Divison for Sustainable Development, Department of Economic and Social Affairs: New York, NY, USA.

Vanek, S.J., 2011. Legume-Phosphorus Synergies in Mountain Agroecosystems: field nutrient balances, soil fertility gradients, and effects on legume attributes and nutrient cycling in the Bolivian Andes. Cornell University.

Vanham, D., Comero, S., Gawlik, B.M., Bidoglio, G., 2018. The water footprint of different diets within European sub-national geographical entities, Nature Sustainability, 1(9):518-525.

Wagg, C. et al., 2014. Soil biodiversity and soil community composition determine ecosystem multifunctionality. Proceedings of the National Academy of Sciences, 111(14), pp.5266–5270.

West, P. C. et al. 2014. Leverage points for improving global food security and the environment. Science 345, 325-328.

Wildavsky, Aaron. But Is It True: A Citizen's Guide to Environmental Health and Safety Issues

Williams, J.R. and Singh, V.P., 1995. The EPIC model. Computer models of watershed hydrology.: 909-1000.

World Health Organization, 2018. Promoting fruit and vegetable consumption around the world, http://www.who.int/dietphysicalactivity/fruit/en/.

World Vegetable Center, 2018. https://avrdc.org/download/publications/annualreports/Annual_Report_2017_web2.pdf and https://worldveg.tind.io/record/57792/files/World Vegetable Center Strategy 2017-2025.pdf?version=1.

Wuab, Wei-Kai; Suraphan Panyoda, Chi-Tang Hoc, Ching-Hua Kuod Ming-Shiang Wu, Lee-YanSheena, 2015. Dietary allicin reduces transformation of L-carnitine to TMAO through impact on gut microbiota, Journal of functional foods, 15.

WWF, 2018. The Water Risk Filter. World Wildlife Fund. http://waterriskfilter.panda.org/.

Yang, R.Y., G.B. Keding, 2009. Nutritional contributions of important African indigenous vegetables

Zak, D.R. et al., 2003. Plant diversity, soil microbial communities, and ecosystem function: Are there any links? Ecology, 84(8), pp.2042–2050.