

Capacity of the US Food System to Accommodate Improved Diet Quality: A Biophysical Model Projecting to 2030

Zach Conrad,¹ LuAnn K Johnson,¹ Christian J Peters,² and Lisa Jahns¹

¹Grand Forks Human Nutrition Research Center, US Department of Agriculture, Agricultural Research Service, Grand Forks, ND and ²Friedman School of Nutrition Science and Policy, Tufts University, Boston, MA

Abstract

Background: Increasing Americans' diet quality will require changes to the food supply. Due to the complex nature of the food system, this is not as straightforward as simply increasing the production of healthy foods and decreasing the production of unhealthy foods. Little is known about whether the US food system can produce enough food, given finite agricultural resources, to support shifts toward healthier eating patterns.

Objective: The aim of this study was to model the capacity of the US food system to accommodate a shift toward a healthier diet by 2030.

Methods: A biophysical simulation model estimated the proportion of the US population that could be fed a given diet based on food system constraints, currently and projected to 2030. The model accepted data inputs on food intake, crop yields, and population size. Linear and nonlinear regression models were used to estimate projected food intake and crop yields based on recent historical data (1980–2014). Diet quality was estimated using the Healthy Eating Index-2015.

Results: The US agricultural system can produce enough food to feed 146% of the population by 2030. A greater proportion of the population can be fed a high-quality diet than a low-quality diet (178% compared to 119%). To accommodate increased diet quality, substantial increases in cropland acreage would be needed for fruits ($P < 0.001$), vegetables ($P = 0.002$), legumes ($P = 0.002$), and nuts ($P = 0.007$); and decreased cropland acreage would be needed for grains ($P = 0.002$) and sweeteners ($P < 0.001$).

Conclusions: The US can produce more than enough food to accommodate a shift toward a healthier diet pattern, but even moderate shifts in diet quality would require major transitions in cropland use. The success of this transition is dependent on several factors, like individuals' ease of entry into the agricultural sector, producers' ability to shift production to other crops, and modifications to the food supply chain. *Curr Dev Nutr* 2018;2:nzy007.

Introduction

Americans' diet quality remains low (1, 2) despite routine issuance of dietary guidance (3–10). Suboptimal diet is the leading cause of mortality in the US, accounting for >650,000 deaths/y (11). Only ~8% of Americans meet daily dietary recommendations for fruits and vegetables, and 60–70% exceed recommendations for empty calories like saturated fat and added sugars (2).

Some modest improvements have become evident over the past decade, however (1, 2). Americans have increased their intake of whole grains, whole fruit, dark green vegetables, some red and orange vegetables, and nuts and seeds, and decreased their intake of sugar-sweetened beverages (1, 2). Aune et al. (12) demonstrated that even a 300 g/d increase in fruit and vegetable intake can decrease the risk of all-cause mortality by ~20%, so these dietary shifts represent a laudable public health achievement. Yet further improvements in diet quality are still needed in order to fully address the high prevalence of nutrition-related chronic disease in this country.



Keywords: diet quality, food system, model, carrying capacity, Healthy Eating Index-2015, sustainability

© 2018 Conrad et al. Published by Oxford University Press on behalf of the American Society for Nutrition. This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits noncommercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re-use, please contact journals.permissions@oup.com.

Manuscript received October 26, 2017. Initial review completed December 28, 2017. Revision accepted January 16, 2018. Published online January 29, 2018. Supported in part by the US Department of Agriculture, Agricultural Research Service, 3062-51000-051-00D.

ZC, LKJ, CJP, and LJ, no conflicts of interest.

Supplemental Tables 1 and 2 and Figures 1 and 2 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at <https://academic.oup.com/cdn/>.

Address correspondence to ZC (e-mail: zach.conrad@ars.usda.gov).

Abbreviations used: 24HR, 24-h recall; DGA, Dietary Guidelines for Americans; ERS, Economic Research Service; FNDDS, Food and Nutrient Database for Dietary Studies; FPED, Food Patterns Equivalents Database; FPIID, Food Patterns Ingredients Database; HEI-2015, Healthy Eating Index 2015; LAFA, Loss-Adjusted Food Availability; WWEIA, What We Eat In America.

Even small shifts in dietary intake on a population level put pressure on the food system, domestic and international, to meet changing demand (13). And if these dietary shifts continue, agricultural producers will face even greater pressure to meet changing demand. Yet predicting the agricultural response to changing consumer food preferences is not straightforward. Due to a myriad of complexities in the food system, a change in consumer food demand does not necessarily require a commensurate change in agricultural production. For example, as food flows through the food system, and transitions from being an agricultural commodity to an edible consumer good, it goes through a number of structural modifications that alter its mass, nutritional profile, and end use (14). Furthermore, because distinct foods with divergent consumer preferences and nutritional profiles are often produced on the same cropland (indeed, different foods are often produced from the same crop), a change in consumer preference for a given food can change the supply of another food (and the associated cropland acreage) in unexpected ways (13, 14). And, finite cropland limits production of many crops, especially because not all cropland is suitable for the production of all types of crops. Although food imports are essential for minimizing temporal fluctuations in food availability and price (15, 16), the US is one of the world's leading agricultural economies (17) and produces most of the food that its citizens consume (18, 19), so shifting food demand in the US would likely have major implications for domestic agricultural output and land use. Yet little is known about the nature and extent of these changes.

Previous research examining land use changes associated with diet shifts has compared food availability data [i.e., USDA Loss-Adjusted Food Availability (LAFA) data series] to hypothetical diets. Buzby et al. (20) estimated that if Americans followed the 2005 Dietary Guidelines for Americans (DGA) for fruit, vegetables, and whole grains, cropland would need to increase by 1.5%. Using a biophysical simulation model, Peters et al. (13) demonstrated that a shift toward a diet pattern (accounting for all major food groups) commensurate with the 2010 DGA would require ~15% less (37.2 million acres) cropland than the current diet, and could feed 16% more people. To the best of our knowledge, no research has examined potential changes in carrying capacity and agricultural land use in the US associated with incremental shifts toward healthier diet patterns using food intake data from nationally representative dietary surveys of what people actually eat. Furthermore, given that the transition toward healthier diets on a population level would realistically occur over a period of time, there is an important need to understand how projected changes in food intake, crop yields, and population size could affect carrying capacity and land use into the future.

To address these gaps, we model the capacity of the US agricultural system to accommodate incremental shifts toward a healthier diet, and project our estimates to 2030 by accounting for estimated changes in food intake, crop yields, and population size.

Methods

US Foodprint Model

An established biophysical simulation model, known as the *US Foodprint Model* (13), was used to estimate the capacity of the US agricultural system to produce enough food to accommodate population-level shifts in diet quality. Several key input parameters of the model were

modified to accept projected (to 2030) data: food intake, crop yields, and population size. The model was further modified to produce reliable estimates of population-level variation in food intake using Monte Carlo simulations based on inter-individual variability of food intake from nationally representative dietary surveys.

The US Foodprint Model is a simulation model that represents the US as a closed food system (13). The primary input parameter is per capita intake of 22 distinct food groups (Figure 1). Embedded computations utilize additional input data on losses and waste that occur throughout the food system, the conversion of raw agricultural crops into edible food products, crop and grazing yields, livestock feed requirements, suitability of available land for agricultural uses, agricultural land area, and population size. Additional computations account for multi-use crops (i.e., crops that are used to produce multiple products from the same mass) and multi-use cropland (cropland used to produce multiple crops during different parts of the year). Further details can be found elsewhere (13).

Food intake data

Data on reported food intake for individuals >2 y of age were acquired from the What We Eat In America (WWEIA) survey, the dietary component of the NHANES, for the most recent years available at the time of the study (2011–2012) (21). WWEIA is administered by the USDA Agricultural Research Service, and NHANES is a program of the US Department of Health and Human Services' CDC. WWEIA is a continuous survey that collects food and nutrition data from a nationally representative sample of ~5000 individuals annually, published in 2-y waves (22). Participants complete a 24-h recall (24HR) administered by a trained interviewer (23), and a subset of the study population completes a subsequent 24HR by telephone. Data from the first 24HR ($n = 8389$) were used because this represents per capita intake (24).

WWEIA provides data on food intake as it was reported consumed (e.g., cake), so established supplementary databases were required to convert WWEIA foods into the food groups used by the US Foodprint Model (e.g., grain, egg, sweetener; see Figure 1). The Food Patterns Equivalents Database (FPED; 2011–2012) (25) provides food intake data from WWEIA converted into food groups, and those with a categorization scheme that aligned with the food groups in the US Foodprint Model were therefore acquired directly from FPED. For all others, the Food and Nutrient Database for Dietary Studies (FNDDS; 2011–2012) (26) was used to disaggregate WWEIA foods into their component ingredients (e.g., the butter in baked goods) and their units were converted (when necessary) to align with the US Foodprint Model using the Food Patterns Ingredients Database (FPID; 2011–2012) (27). But unlike FPED, FNDDS and FPID do not provide data on the amount of each food group consumed, only the disaggregation of WWEIA foods into component ingredients (FNDDS) and unit conversions (FPID), so the final step was to multiply these data by the amount consumed as reported in WWEIA.

Data on recent historical (1980–2014) annual availability of foods and food groups were acquired from the USDA LAFA data series (28). LAFA is maintained by the USDA Economic Research Service (ERS) and provides estimates of the annual per capita availability of food, which is a proxy for food intake. ERS collects data on supply (production, imports, and end-of-year stocks), exports, and losses (portions not harvested, nonedible portions, and uneaten food) of >200

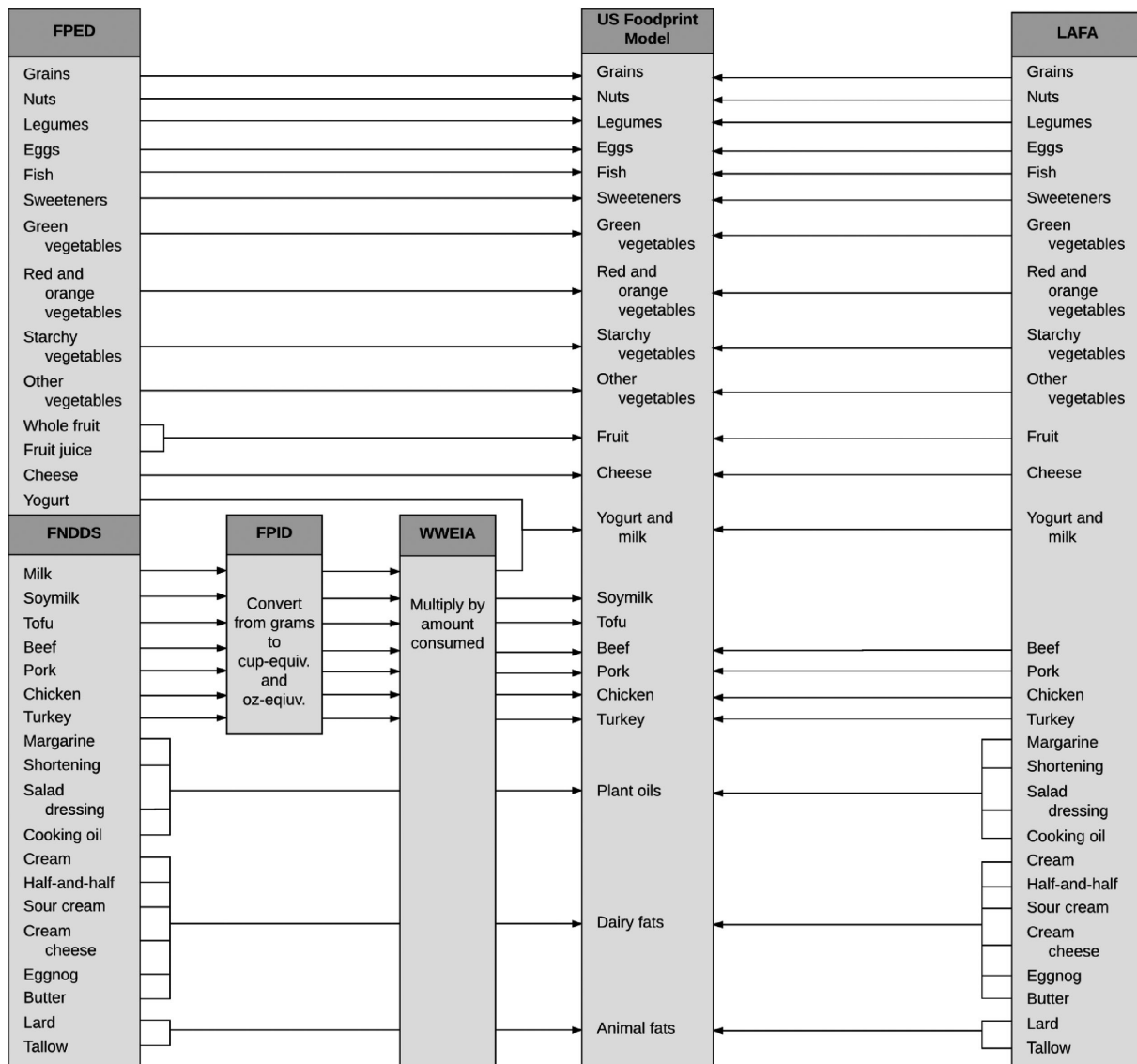


FIGURE 1 Food intake data sources. equiv., equivalents; FNDDS, Food and Nutrient Database for Dietary Studies (2011–2012); FPED, Food Patterns Equivalents Database (2011–2012); FPID, Food Patterns Ingredients Database (2011–2012); LAFA, Loss-Adjusted Food Availability data series (1980–2014); oz, ounce; WWEIA, What We Eat In America (2011–2012).

individual foods from a variety of government and nongovernment sources, and remaining data gaps are addressed by statistical imputation (19). Food availability data are ultimately computed by ERS staff based on the difference between supply and disappearance of individual foods, and the remainder is divided by the US population and adjusted for food losses that occur throughout the food system (19). LAFA presents food availability data for predefined food groups as well as individual foods, and we recategorized some foods to align with the food group input parameters of the US Foodprint Model (Figure 1). Data on per capita availability of food groups ($n = 13$) were collected for grains, fruit (including juice), fluid milk (including yogurt), cheese (excluding cream cheese), legumes, nuts, beef, pork, chicken, turkey, eggs, sweeteners, and seafood; and data on individual foods ($n = 68$) were collected and recategorized as green vegetables, red and orange

vegetables, starchy vegetables, other vegetables, plant oils, dairy fats, and animal fats—resulting in 20 food groups.

Diet quality assessment

Diet quality for each individual in WWEIA (2011–2012) was assessed using the Healthy Eating Index-2015 (HEI-2015) (29), which provides a measure of compliance with the 2015–2020 DGA (3). The HEI-2015 includes 13 components, 9 of which assess adequacy (total fruit, whole fruit, total vegetables, greens and beans, whole grains, dairy, total protein foods, seafood and plant proteins, and unsaturated:saturated fats) and 4 of which assess moderation (refined grains, sodium, added sugars, and saturated fats). Each component has its own scoring standards that range from 0–5 or 0–10. All consumption amounts are standardized to 1000 kcal. Moderation components are reverse scored so that

ultimately greater scores are favorable for each component. The component scores were summed to compute the overall HEI-2015 score, with a maximum score of 100. Individuals providing dietary data in WWEIA were grouped by quintile of HEI-2015 score, where quintile 1 represents the lowest diet quality and quintile 5 represents the highest diet quality. Mean HEI-2015 scores for each quintile were computed using the population-ratio method (30).

Crop yield data

Data on recent historical (1980–2015) annual crop yields ($n = 155$) were acquired from USDA Agricultural Surveys, maintained by the National Agricultural Statistics Service (31). Crop yields represent the harvested weight per acre of land. Data are collected primarily by telephone surveys with producers and by in situ yield measurements in all states for all major crops. Producers are selected based on the size of their operation, with larger producers having a higher likelihood of being selected to participate in the survey. Approximately 65,000–81,000 producers are surveyed for each crop annually (32).

Projected food intake, crop yields, and population size

Data on food intake and crop yields were projected to 2030 using linear and nonlinear (sigmoidal and hyperbolic) regression models. Food groups and crops with insufficient data (<10 data years) were not included in the projection estimates, resulting in 20 food groups and 103 crops for analysis. Data on food intake and yield were plotted against time and visually inspected to initially determine the regression function (linear, sigmoidal, or hyperbolic). Final determination of function was made based on successful convergence of each model's maximum likelihood algorithm. In select cases for which data did not fit a linear or nonlinear function, projected estimates were set to the mean of all observations. LAFA does not measure food intake at the individual level so it lacks data on interindividual variability. To address this limitation, and to account for known differences in dietary data collection programs, projected food group estimates from LAFA were adjusted by the difference from WWEIA intake estimates for each diet quality quintile (Supplemental Figure 1). Current and projected food intake by HEI-2015 quintile are presented in Supplemental Table 1, and current and projected crop yields are presented in Supplemental Table 2. Current (2015) and projected (2030) population estimates were acquired from the US Census Bureau (33).

Modeling scenarios and statistical analysis

Carrying capacity and land use of the US food system were represented by 6 modeling scenarios and 3 additional sensitivity analyses (Table 1). Scenario 1 represented current conditions: no change in diet quality, crop yields, and population size. Scenarios 2a–e represented incremental population-level shifts in diet quality and projected changes in food intake, crop yields, and population size. To examine the sensitivity of the model outputs to the projected data inputs, we conducted 3 sensitivity analyses. Scenario 3a represented projected food intake and current crop yields and population size; Scenario 3b represented current food intake, projected crop yields, and current population size; and Scenario 3c represented current food intake and crop yields, and projected population size.

For each modeling scenario, data are presented as the percentage of the population fed (i.e., carrying capacity) and amount of agricultural land use (acreage) by crop category: all crops, fruits, vegetables, grains, legumes, nuts, feed grains and oilseeds, sweeteners, hay, and pasture. Measures of variation were estimated using Monte Carlo simulations with 1000 draws. Differences between scenarios were tested at $P < 0.05$ using 2-tailed z tests with Bonferroni adjustment for multiple comparisons (critical P value set to 0.008 for main analyses and 0.017 for sensitivity analyses). Tests for trends across quintiles were conducted using simple linear regressions, with $P < 0.05$. SAS 9.4 (SAS Institute; Cary, NC) was used to estimate population-ratio HEI-2015 scores using modified code and macros provided by the National Cancer Institute (34). Stata14 (StataCorp; College Station, TX) was used for data management and all other analyses. All analyses were adjusted for the complex sampling design and sample weights of WWEIA data.

Results

The US agricultural system currently produces enough food to feed 136% (95% CI: 129–144%) of its population (Figure 2). If Americans decreased their diet quality by 2030, estimated carrying capacity would decrease to 112% (103–121%; $P < 0.001$) under the lower diet quality scenario (HEI-2015 quintile 2; Figure 2) and to 119% (113–126%; $P < 0.001$) under the lowest diet quality scenario (HEI-2015 quintile 1; $P < 0.001$). No change ($P = 0.112$) in carrying capacity was observed if the US population adopted a higher quality diet (HEI-2015 quintile 4), but estimated carrying capacity increased to 173% (152–198%)

TABLE 1 Modeling scenarios

| Label | Description |
|---|---|
| 1. Current carrying capacity and land use | No change in diet quality, crop yields, or population size |
| 2. Projected carrying capacity and land use | |
| 2a. HEI-2015 ¹ quintile 1 | Population-level shift to lowest diet quality, and projected crop yields and population size |
| 2b. HEI-2015 quintile 2 | Population-level shift to lower diet quality, and projected crop yields and population size |
| 2c. HEI-2015 quintile 3 | Median diet quality, and projected crop yields and population size |
| 2d. HEI-2015 quintile 4 | Population-level shift to higher diet quality, and projected crop yields and population size |
| 2e. HEI-2015 quintile 5 | Population-level shift to highest diet quality, and projected crop yields and population size |
| 3. Sensitivity analyses | |
| 3a. Model 1 | Projected food intake, and current crop yields and population size |
| 3b. Model 2 | Current food intake, projected crop yields, and current population size |
| 3c. Model 3 | Current food intake and crop yields, and projected population size |

¹HEI-2015, Healthy Eating Index 2015.

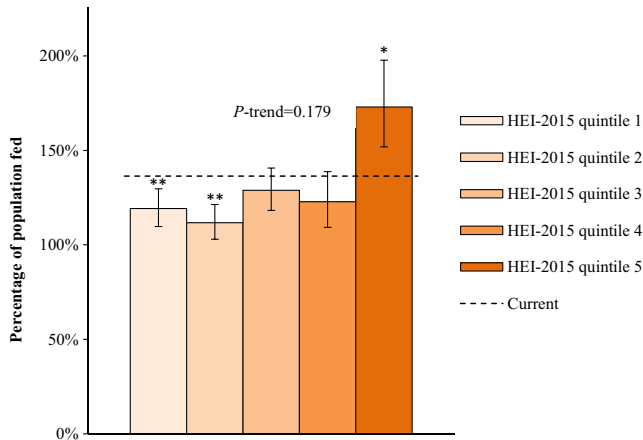


FIGURE 2 Percentage of US population potentially fed with domestically produced food, current and projected to 2030 by HEI-2015 quintile. *P*-trends represent linear trend over the 5 quintiles, weighted by the inverse of the SEs of the means. HEI-2015 mean scores (out of 100): quintile 1 = 33, quintile 2 = 46, quintile 3 = 57, quintile 4 = 68, quintile 5 = 84. *Significantly different than current at $P < 0.05$ (Bonferroni adjusted). **Significantly different than current at $P < 0.001$. HEI-2015, Healthy Eating Index 2015.

under the highest diet quality scenario (HEI-2015 quintile 5). No linear relation was observed between carrying capacity and diet quality ($P = 0.179$).

Figure 3 displays current and projected cropland acreage by diet quality and crop type. A linear relation was not observed between total cropland acreage and diet quality ($P = 0.299$; **Figure 3A**), although linear relations were observed for individual crop types. Increased diet quality was linearly associated with increased cropland acreage for fruits ($P < 0.001$; **Figure 3B**), vegetables ($P = 0.002$; **Figure 3C**), legumes ($P = 0.002$; **Figure 3D**), and nuts ($P = 0.007$; **Figure 3F**); and associated with decreased cropland acreage for grains ($P = 0.002$; **Figure 3D**) and sweeteners ($P < 0.001$; **Figure 3H**).

Sensitivity analyses demonstrated that projected food intake had a positive effect on carrying capacity ($P < 0.01$) and projected population size had a negative effect on carrying capacity ($P < 0.01$; **Supplementary Figure 2A**); no effect was observed for projected crop yields ($P = 0.203$). Projected food intake had a negative effect on cropland area ($P < 0.01$), and no effect was observed for projected crop yields ($P = 0.021$) and projected population size ($P = 0.191$; **Supplementary Figure 2B**).

Discussion

This is the first study, to the best of our knowledge, to use a biophysical simulation model to investigate the capacity of the US agricultural system to accommodate incremental shifts toward a healthier diet, accounting for projected changes in food intake, crop yields, and population size to 2030. We used a novel approach to project food intake by combining data from several distinct, nationally representative dietary datasets, which allowed for the incorporation of notable advantages unique to each dataset. This study is also the first, to the best of

our knowledge, to utilize the HEI-2015, which represents the most up-to-date approach for measuring diet quality. We demonstrated that the healthiest diets require less agricultural land than the least healthy diets. However, incremental improvements in diet quality would require substantial changes to the amount of agricultural land used to produce fruits, vegetables, grains, legumes, nuts, and sweeteners.

Peters et al. (13) estimated that a population-wide adoption of an omnivorous diet pattern commensurate with the DGA-2010 would increase the carrying capacity by 16% (from 130% to 151%). In the present study we observed a similar response but of greater magnitude: 27% increase in carrying capacity from the current scenario (136%) to the projected highest diet quality (HEI-2015 quintile 5: 173%). We explored these differences using post hoc model simulations and observed that disparities in the amount of individual food groups used to represent the healthy diet scenarios substantially explained the divergent results. In other words, there is more than one way to eat a healthy diet, with varied implications for food production. This also highlights the important difference between using hypothetical and empirical data to derive diet patterns.

Buzby et al. (20) estimated agricultural land use changes associated with population-wide adoption of DGA-2005 and observed a 117% increase in land area for fruit production, 44% increase in land area for vegetable production, and 23% reduction in land area for grain production. These estimates are moderately different (higher for fruits and vegetables and lower for grains) than in the present study, likely due to several key differences in methodology. Unlike the approach used by Buzby et al., the US Foodprint Model, used in the present study, accounts for agricultural land area that was used for dual cropping purposes, where multiple crops may be grown on the same land parcel during different parts of the year. Additionally, in order to reflect actual farm management decisions, the US Foodprint Model restricts crop production on lands used for grazing due to inherent differences in soil suitability that would prevent adequate crop yields on grazing land (13).

The US agricultural system exceeds the capacity to accommodate shifts toward a healthier diet. Indeed, from a biological perspective, a greater proportion of the population can be fed a high-quality diet than a low-quality diet. This is largely explained by lower consumption of beef (and therefore less land area being required for hay and other livestock feed) among those with the healthiest diets (quintile 5). However, high consumption of beef does not necessarily imply a low-quality diet, just a larger agricultural land requirement; indeed, we observed relatively high beef consumption among individuals in quintile 4.

On a biological basis, the present analyses demonstrate that major shifts in cropland use would be needed to accommodate even incremental shifts in diet quality, which would require increasing the acreage of fruits, vegetables, legumes, and nuts, and decreasing the acreage of grains and sweeteners. Yet successfully transitioning cropland on a major scale would depend on changes to several key nonbiophysical properties of the food system, namely availability of farm labor, farmer expertise, and supply chain infrastructure.

Given the aging farm population and declining number of younger individuals entering the farm sector (35), greater efforts will be needed to encourage younger people to become farmers and to adopt production of specialty crops like fruits, vegetables, and nuts. This may be challenging for beginning farmers who lack the prior knowledge and specialized machinery needed to successfully cultivate specialty crops.

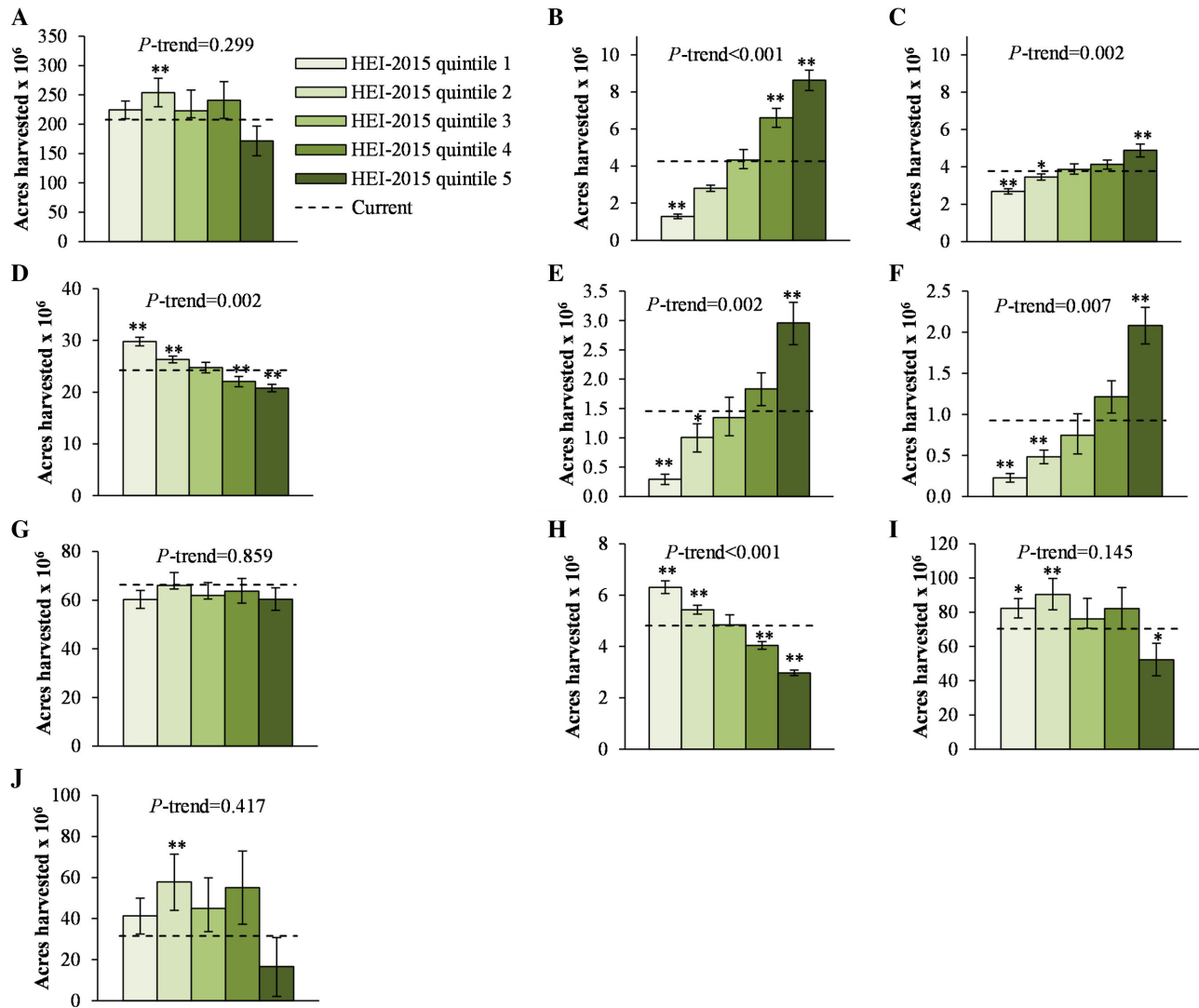


FIGURE 3 US agricultural land area, current and projected (2030), needed to accommodate shifts in dietary quality, by crop category: (A) all crops, (B) fruits, (C) vegetables, (D) grains, (E) legumes, (F) nuts, (G) feed grains and oilseeds, (H) sweeteners, (I) hay, and (J) cropland pasture. HEI-2015 mean scores (out of 100): quintile 1 = 33, quintile 2 = 46, quintile 3 = 57, quintile 4 = 68, quintile 5 = 84. *P*-trends represent linear trend over the 5 quintiles, weighted by the inverse of the SEs of the means. *Significantly different than current at *P* < 0.05 (Bonferroni adjusted). **Significantly different than current at *P* < 0.001. HEI-2015, Healthy Eating Index 2015.

This will also be challenging for existing farmers whose knowledge and farm infrastructure are geared toward production of field crops like grains, oilseeds, and forages, which have a production structure very distinct from specialty crops; this may limit willingness to transition. Successful production of specialty crops requires specialized knowledge, planning, and management, and the time needed to develop this knowledge and implement these practices could be a barrier to adoption for some producers (36). Many of these crops require specialized equipment for planting and harvesting that cannot be repurposed for other crops, and capital investment is high. Uncertainty, risk, and market volatility are prominent features of specialty crop production because of the highly perishable and seasonal nature of these crops (15, 37), which could further dissuade potential farmers. Assistance for new farmers, like the Beginning Farmer and Rancher Development

Program (38), will continue to be important to adapting to future food needs. Indeed, a greater proportion of beginning farmers are producing specialty crops compared to established farmers (39), with favorable implications for future production of these crops. Ease of entry into the agricultural sector for beginning farmers will be just as important as ease of movement across the agricultural sector for existing farmers.

Large-scale shifts in food supply (production) and demand (consumption) would also require changes in the food supply chain. Many individual foods, particularly fruits and vegetables, flow through a highly complex and specialized supply chain network comprised of distinct entities (e.g., packinghouses, third-party certifiers, storage facilities, distributors, marketers, brokers, shippers, processors, wholesalers, and retailers); and coordination across these enterprises can be

challenging because of the diversity of the handling requirements and market demands of different foods (37, 40, 41). Furthermore, these entities are often co-located with agricultural production centers (37), and the difficulties associated with relocating or replicating this infrastructure can limit the ability of food supply chains to accommodate increased supply and demand for certain foods. Several important federal programs have been implemented to address potential changes in producer demographics, cropland usage, and supply chain networks (38, 42), and these may rise in importance if Americans improve their diet quality. Developments in regional supply chains may also play a role in aligning food supply chains with food demand. For example, organizations that manage the logistics and marketing of regional food supply chains (i.e., food hubs) are growing in number, and food hub operators report opportunities for expansion (43).

The HEI-2015 is the most up-to-date measure of diet quality. Prospective cohort studies have demonstrated consistent relations between higher diet quality scores and lower risk of chronic disease in multiple US populations using the previous iteration, the HEI-2010 (44–46), so we are confident that diet quality has been effectively measured using the best tools currently available. We also incorporated >30 y of data on crop yields for >100 individual crops, representing all of the major agricultural land use categories (grains, fruits, vegetables, oilseeds, forages, and pasture), and projected our estimates to 2030 using linear and nonlinear regression models. Finally, to account for the numerous intricacies of the US food system, all data were inputted into an established biophysical simulation model that incorporated the complex interactions between the agricultural and consumer sectors as food moves from being agricultural commodities to mixed dishes consumed by millions of individuals in their homes and at restaurants.

Several limitations of this study warrant mention. The modeling approach used in this study does not explicitly account for food imports or exports, which does not reflect the globalized nature of the actual agricultural market. Yet for the purposes of this study this was a necessary model constraint because, from a biophysical perspective, carrying capacity represents the ability of a fixed geopolitical locale to support its human population based on its own resources. Although limitations on carrying capacity can be overcome with international trade, not all countries can exceed these limits simultaneously, given the planet's finite resources. Additionally, food intake projections were computed at the food level rather than at the person level, such that the model accounted for individuals changing their food intake over time but not moving across diet quality quintiles. This was a necessary constraint imposed by lack of data availability.

The carrying capacity of the US food system is influenced by several factors not accounted for in this analysis due to limited data availability. The amount of agricultural land available for cultivation has decreased by nearly 9% (39 million acres) since 1982 (47), including 14 million acres of prime farmland (48); and future reductions in cropland availability will likely further constrain carrying capacity by 2030. Additionally, the viability of US agriculture is made more uncertain by climate change projections that include reduced water availability and pesticide efficacy, which are expected to disrupt crop yield and quality, and may therefore influence compensatory agricultural amendment intensities (49). This is particularly important for specialty crops like fruits, vegetables, and tree nuts, which require relatively intensive applications of

irrigation water and other amendments. Altered precipitation patterns are also expected, with some areas more prone to runoff and leaching of agricultural chemicals, which may further reduce productivity in these areas (49).

Further research is needed to examine the benefits (e.g., increased food production) and costs (e.g., carbon emissions) associated with cultivating additional land, perhaps as a yield index that measures the amount of additional food production gained per unit of additional land cultivated. Further research is also needed to better understand how reductions in food waste can increase the amount of food available to consumers and reduce the amount of land that is used to grow uneaten food.

This study used an established biophysical simulation model, combined with projected data on food intake, crop yields, and population size, to investigate the capacity of the US food system to accommodate population-wide incremental shifts toward a healthier diet by 2030. This approach accounted for the vast complexities of the US food system by modeling the numerous interactions between the agricultural and consumer sectors. We observed that the US food system exceeds the capacity to increase the diet quality of all Americans currently and into the future, and that a greater proportion of the population can be fed a high-quality diet than a low-quality diet. Yet, importantly, even incremental shifts in diet quality would require major transitions in cropland use, toward increased production of fruits, vegetables, legumes, and nuts. The success of this transition is dependent on several factors, like individuals' ease of entry into the agricultural sector, and producers' ability to shift production to other crops. The food supply chain would need to overcome inherent challenges to adapt to shifting food supply and demand. And this transition may be at the expense of cropland used to produce grains and sweeteners, unless additional land was brought into production. Yet a comprehensive assessment of the benefits and costs of cultivating such land is not well understood, representing an area of further research need. Additional research is also needed to better understand how reductions in food waste can increase the amount of food available to consumers and reduce the amount of land that is used to grow uneaten food.

Acknowledgments

We thank Wayne Riveland for his essential contribution to model programming.

The authors' contributions were as follows—ZC: designed and conducted the research, wrote the paper, and had primary responsibility for final content; ZC and LKJ: analyzed the data and performed statistical analyses; ZC and LJ: interpreted the results; and all authors: critically revised the manuscript, and read and approved the final version.

References

1. Wang DD, Leung CW, Li Y, Ding EL, Chiuve SE, Hu FB, Willett WC. Trends in dietary quality among adults in the United States, 1999 through 2010. *JAMA Internal Medicine* 2014;174(10):1587–95.
2. Rehm CD, Peñalvo JL, Afshin A, Mozaffarian D. Dietary intake among US adults, 1999–2012. *JAMA* 2016;315(23):2542–53.
3. US Department of Health and Human Services and US Department of Agriculture. 2015–2020. *Dietary Guidelines for Americans 2015–2020*. 8th ed. Washington (DC): US Government Printing Office, 2015. Available from: <http://health.gov/dietaryguidelines/> [cited 2018 Jan 3].

4. US Department of Health and Human Services and US Department of Agriculture. Dietary Guidelines for Americans 2010. 7th ed. Washington (DC): US Government Printing Office, 2010. Available from: <http://health.gov/dietaryguidelines/> [cited 2018 Jan 3].
5. US Department of Health and Human Services and US Department of Agriculture. Dietary Guidelines for Americans 2005. 6th ed. Washington (DC): US Government Printing Office, 2005. Available from: <http://health.gov/dietaryguidelines/> [cited 2018 Jan 3].
6. US Department of Health and Human Services and US Department of Agriculture. Dietary Guidelines for Americans 2000. 5th ed. Washington (DC): US Government Printing Office, 2000. Available from: <http://health.gov/dietaryguidelines/> [cited 2018 Jan 3].
7. US Department of Health and Human Services and US Department of Agriculture. Dietary Guidelines for Americans 1995. 4th ed. Washington (DC): US Government Printing Office, 1995. Available from: <http://health.gov/dietaryguidelines/> [cited 2018 Jan 3].
8. US Department of Health and Human Services and US Department of Agriculture. Dietary Guidelines for Americans 1990. 3rd ed. Washington (DC): US Government Printing Office, 1990. Available from: <http://health.gov/dietaryguidelines/> [cited 2018 Jan 3].
9. US Department of Health and Human Services and US Department of Agriculture. Dietary Guidelines for Americans 1985. 2nd ed. Washington (DC): US Government Printing Office, 1985. Available from: <http://health.gov/dietaryguidelines/> [cited 2018 Jan 3].
10. US Department of Health and Human Services and US Department of Agriculture. Dietary Guidelines for Americans 1980. 1st ed. Washington (DC): US Government Printing Office, 1980. Available from: <http://health.gov/dietaryguidelines/> [cited 2018 Jan 3].
11. US Burden of Disease Collaborators. The state of U.S. health, 1990–2010: burden of diseases, injuries, and risk factors. *JAMA* 2013;310(6):591–606.
12. Aune D, Giovannucci E, Boffetta P, Fadnes LT, Keum N, Norat T, Greenwood DC, Riboli E, Vatten LJ, Tonstad S. 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. *Int J Epidemiol* 2017; 46(3):1029–56.
13. Peters C, Picardy J, Darrouzet-Nardi A, Wilkins J, Griffin T, Fick G. Carrying capacity of U.S. agricultural land: ten diet scenarios. *Elementa* 2016;4:116.
14. Peters CJ, Wilkins JL, Fick GW. Testing a complete-diet model for estimating the land resource requirements of food consumption and agricultural carrying capacity: the New York State example. *Renew Agric Food Syst* 2007;22(2):145–53.
15. Plattner K, Perez A, Thornsbury S. Evolving U.S. fruit markets and seasonal grower price patterns. USDA Economic Research Service. FTS-357-01. Washington (DC): US Government Printing Office, 2014. Available from: <https://www.ers.usda.gov/publications/pub-details/?pubid=37065> [cited 2018 Jan 3].
16. Huang SW. 2013. Imports contribute to year-round fresh fruit availability. USDA Economic Research Service (ERS). FTS-356-01. Washington (DC): US Government Printing Office, 2013. Available from: <https://www.ers.usda.gov/publications/pub-details/?pubid=37057> [cited 2018 Jan 3].
17. US Department of Agriculture, Economic Research Service. Agricultural total factor productivity growth indices for individual countries, 1961–2013. Washington, DC: US Government Printing Office; 2017. Available from: <https://www.ers.usda.gov/data-products/international-agricultural-productivity/> [cited 2018 Jan 4].
18. US Department of Agriculture, Foreign Agricultural Service. Global Agricultural Trade System. 2018. Available from: <https://apps.fas.usda.gov/gats/ExpressQuery1.aspx> [cited 2018 Jan 3].
19. US Department of Agriculture, Economic Research Service. Loss-Adjusted Food Availability (LAFA) data series. Washington, DC: US Government Printing Office; 2001–2014. Available from: <https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/loss-adjusted-food-availability-documentation/> [cited 2018 Jan 3].
20. Buzby JC, Wells HF, Vocke G. Possible implications for US agriculture from adoption of select dietary guidelines. USDA Economic Research Service (ERS). Economic Research Report Number 31. Washington (DC): US Government Printing Office, 2006. Available from: <https://www.ers.usda.gov/publications/pub-details/?pubid=45694> [cited 2018 Jan 3].
21. US Department of Health and Human Services, Centers for Disease Control and Prevention (CDC). National Health and Nutrition Examination Survey [Internet]. 2011–2012. Available from: www.cdc.gov/nchs/nhanes.htm [cited 2018 Jan 3].
22. US Department of Health and Human Services, Centers for Disease Control and Prevention (CDC). About the National Health and Nutrition Examination Survey [Internet]. 2017. Available from: https://www.cdc.gov/nchs/nhanes/about_nhanes.htm? [cited 2018 Jan 3].
23. Moshfegh AJ, Rhodes DG, Baer DJ, Murray T, Clemens JC, Rumpler WV, Paul DR, Sebastian RS, Kuczynski KJ, Ingwersen LA, et al. The US Department of Agriculture automated multiple-pass method reduces bias in the collection of energy intakes. *Am J Clin Nutr* 2008;88(2):324–32.
24. National Cancer Institute, National Institutes of Health. Recommendations on potential approaches to dietary assessment for different research objectives requiring group-level estimates [Internet]. Available from: <https://dietassessmentprimer.cancer.gov/approach/table.html#intake> [cited 2018 Jan 3].
25. US Department of Agriculture, Agricultural Research Service. Food Patterns Equivalents Database. 2011–2012. Available from: www.ars.usda.gov/Services/docs.htm?docid=23871 [cited 2018 Jan 3].
26. US Department of Agriculture, Agricultural Research Service. Food and Nutrient Database for Dietary Studies. 2011–2012. Available from: <https://www.ars.usda.gov/northeast-area/beltsville-md/beltsville-human-nutrition-research-center/food-surveys-research-group/docs/fndds/> [cited 2018 Jan 3].
27. US Department of Agriculture, Agricultural Research Service. Food Patterns Ingredients Database. 2011–2012. Available from: <https://www.ars.usda.gov/northeast-area/beltsville-md/beltsville-human-nutrition-research-center/food-surveys-research-group/docs/fped-overview/> [cited 2017 June 21].
28. US Department of Agriculture, Economic Research Service. Loss-Adjusted Food Availability (LAFA) data series. 1980–2015. Available from: <https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/loss-adjusted-food-availability-documentation/> [cited 2018 Jan 3].
29. National Cancer Institute, National Institutes for Health. Overview & background of the Healthy Eating Index [Internet]. Available from: <https://epi.grants.cancer.gov/heii/> [cited 2017 June 21].
30. Freedman LS, Guenther PN, Krebs-Smith SM, Kott PS. A population's mean Healthy Eating Index-2005 scores are best estimated by the score of the population ratio when one 24-hour recall is available. *J Nutr* 2008;138(9):1725–9.
31. US Department of Agriculture, National Agricultural Statistics Service. Agricultural Surveys. 1980–2015. Available from: http://www.nass.usda.gov/Quick_Stats/ [cited 2018 Jan 3].
32. US Department of Agriculture, National Agricultural Statistics Service. About NASS Agricultural Surveys. 2018. Available from: https://www.nass.usda.gov/Education_and_Outreach/Understanding_Statistics/index.php [cited 2018 Jan 3].
33. US Department of Commerce, US Census Bureau, Population Division. Projected population by single year of age, sex, race, and Hispanic origin for the United States: 2014–2060. 2018. Available from: <https://www.census.gov/data/datasets/2014/demo/popproj/2014-popproj.html> [cited 2018 Jan 3].
34. National Cancer Institute, National Institutes for Health. HEI tools for researchers [Internet]. Available from: <http://epi.grants.cancer.gov/heii/tools.html> [cited 2018 Jan 3].
35. US Department of Agriculture, Economic Research Service. Beginning farmers and age distribution of farmers [Internet]. 2017. Available from: <https://www.ers.usda.gov/topics/farm-economy/beginning-disadvantaged-farmers/beginning-farmers-and-age-distribution-of-farmers/> [cited 2018 Jan 3].
36. Johnson D, Krissof B, Young E, Hoffman L, Lucier G, Breneman V. Agronomic and economic barriers to expanding fruit and vegetable

- production. In: Eliminating fruit and vegetable planting restrictions: how would markets be affected? USDA, Economic Research Service. Economic Research Report Number 30. Washington (DC): US Government Printing Office, 2006. Available from: https://www.ers.usda.gov/webdocs/publications/45673/29906_err30fm_002.pdf [cited 2018 Jan 3].
37. Cook RL. Fundamental forces affecting U.S. fresh produce growers and marketers. *Choices: the magazine of food, farm and resource issues* [Internet]. 2011. Available from: http://go.galegroup.com/ps/i.do?id=GALE%7CA354272486&v=2.1&u=mlin_m_tufts&it=r&p=AONE&sw=w&asid=7eb7c91df6ea5a74a7c3411a2426bf18
 38. US Department of Agriculture, National Institute of Food and Agriculture. Beginning Farmer and Rancher Development Program (BFRDP) [Internet]. 2018. Available from: <https://nifa.usda.gov/funding-opportunity/beginning-farmer-and-rancher-development-program-bfrdp> [cited 2018 Jan 2].
 39. Ahearn M. Beginning farmers and ranchers at a glance. US Department of Agriculture, Economic Research Service. 2013. Economic Brief 22. Available from: <https://www.ers.usda.gov/publications/pub-details/?pubid=42876> [cited 2018 Jan 2].
 40. Beutel JA. Kiwifruit production in California [Internet]. 1990. Available from: www.sfp.ucdavis.edu/pubs/brochures/Kiwi/ [cited 2018 Jan 3].
 41. Stoddard CS, Davis RM, Cantwell MI. Sweetpotato production in California. Vegetable Production Series. University of California, Agriculture and Natural Resources. Publication 7237. 2013. Available from: <http://anrcatalog.ucanr.edu/pdf/7237.pdf> [cited 2018 Jan 3].
 42. US Department of Agriculture, Agricultural Marketing Service. Specialty Crop Multi-State Program [Internet]. 2018. Available from: <https://www.ams.usda.gov/services/grants/scmp> [cited 2018 Jan 3].
 43. Barham J, Tropp D, Enterline K, Farbman J, Fisk J, Kiraly S. Regional food hub resource guide. 2012. US Department of Agriculture, Agricultural Marketing Service. Available from: <https://www.ams.usda.gov/publications/content/regional-food-hub-resourceguide> [cited 2018 Jan 2].
 44. Liese AD, Krebs-Smith SM, Subar AF, George SM, Harmon BE, Neuhauser ML, Boushey CJ, Schap TRE, Reedy J. The dietary patterns methods project: synthesis of findings across cohorts and relevance to dietary guidance. *J Nutr* 2015;145(3):393–402.
 45. Harmon BE, Boushey CJ, Shvetsov YB, Ettienne R, Reedy J, Wilkens LR, Le Marchand L, Henderson BE, Kolonel LN. Associations of key diet-quality indexes with mortality in the multiethnic cohort: the dietary patterns methods project. *Am J Clin Nutr* 2015;101(3):587–97.
 46. Reedy J, Krebs-Smith SM, Miller PE, Liese AD, Kahle LL, Park Y, Subar AF. Higher diet quality is associated with decreased risk of all-cause, cardiovascular disease, and cancer mortality among older adults. *J Nutr* 2014;144(6):881–9.
 47. US Department of Agriculture, National Agricultural Statistics Service. Census of Agriculture. Washington (DC): US Government Printing Office, 1982–2012. Available from: <http://www.agcensus.usda.gov/> [cited 2018 Jan 2].
 48. US Department of Agriculture, Natural Resources Conservation Service. Natural resources inventory summary report. 2015. Available from: <https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/> [cited 2018 Jan 2].
 49. Hatfield JL, Boote KJ, Kimball BA, Ziska LH, Izaurralde RC, Ort D, Thomson AM, Wolfe D. Climate impacts on agriculture: implications for crop production. *Agron J* 2011;103(2):351–70.