ELEMENTA
Science of the Anthropocene

Carrying capacity of U.S. agricultural land: Ten diet scenarios

Christian J. Peters[1,*] • Jamie Picardy[2] • Amelia F. Darrouzet-Nardi[3] • Jennifer L. Wilkins[4] • Timothy S. Griffin[1] • Gary W. Fick[5]

[1]Friedman School of Nutrition Science and Policy, Tufts University, Boston, Massachusetts, United States
[2]Geography and Regional Planning, Mount Ida College, Newton, Massachusetts, United States
[3]Global Health Studies Program, Allegheny College, Meadville, Pennsylvania, United States
[4]Department of Public Health, Food Studies and Nutrition, Syracuse University, Syracuse, New York, United States
[5]Section of Soil and Crop Sciences (Emeritus), Cornell University, Ithaca, New York, United States

*Christian.Peters@tufts.edu

Abstract

Strategies for environmental sustainability and global food security must account for dietary change. Using a biophysical simulation model we calculated human carrying capacity under ten diet scenarios. The scenarios included two reference diets based on actual consumption and eight "Healthy Diet" scenarios that complied with nutritional recommendations but varied in the level of meat content. We considered the U.S. agricultural land base and accounted for losses, processing conversions, livestock feed needs, suitability of land for crops or grazing, and land productivity. Annual per capita land requirements ranged from 0.13 to 1.08 ha person^{-1} year^{-1} across the ten diet scenarios. Carrying capacity varied from 402 to 807 million persons; 1.3 to 2.6 times the 2010 U.S. population. Carrying capacity was generally higher for scenarios with less meat and highest for the lacto-vegetarian diet. However, the carrying capacity of the vegan diet was lower than two of the healthy omnivore diet scenarios. Sensitivity analysis showed that carrying capacity estimates were highly influenced by starting assumptions about the proportion of cropland available for cultivated cropping. Population level dietary change can contribute substantially to meeting future food needs, though ongoing agricultural research and sustainable management practices are still needed to assure sufficient production levels.

Domain Editor-in-Chief
Anne R. Kapuscinski, Dartmouth

Guest Editor
Ernesto Méndez, University of Vermont

Knowledge Domain
Sustainability Transitions

Article Type
Research Article

Part of an *Elementa* Forum
New Pathways to Sustainability in Agroecological Systems

Received: October 12, 2015
Accepted: June 14, 2016
Published: July 22, 2016

1. Introduction

1.1 Relationships between diet and sustainability

One of the most perplexing questions in sustainability science is, "What should we eat?" Within the food and agriculture literature, a strong case has been presented that dietary change is essential for meeting future human food needs (McMichael et al., 2007; Pelletier and Tyedmers, 2010; Godfray et al., 2010; Foley et al., 2011; Smith et al., 2013). By "dietary change," these authors refer to eating patterns that stabilize, or decrease, livestock production, keep food system environmental impacts within ecosystem limits, and more equitably distribute food to meet global nutritional goals.

This line of thinking is not new. The equation I=PAT, conceived in the 1970s, proposes that environmental impact is a function of population, affluence, and technology (Parris and Kates, 2003). Calls for considering the environmental impacts of food consumption through changes in diet were made decades ago both in popular (Lappé, 1971) and academic literature (Gussow and Clancy, 1986). However, for most of the 20th Century the predominant agricultural science paradigm focused on increasing yield and production efficiency, expanding in the 1980s and 1990s to include ecological impacts of farming but not focusing on food systems (Welch and Graham, 1999). Likewise, nutritional sciences and dietary advice over most of the past century have been guided almost exclusively by evidence on the relationships among nutrients, foods, diets and human health (King, 2007). If strategies for sustainability must address both food consumption and production, then analyses that link agriculture and nutrition are needed.

1.2 Land as a fundamental resource

The food system exerts a broad range of ecological impacts. Biodiversity loss, climate-forcing emissions, nutrient cycle disruption, and competition for land, water, and energy are all cited as reasons to contain agriculture's environmental impact (Godfray et al., 2010; Foley et al., 2011). Among these impacts, land use is central. Sparing land from conversion to agriculture may be important for protecting biodiversity (Balmford et al., 2005; Lambin and Meyfroidt, 2011). In addition, as highlighted in debates about the merits of biofuels, conversion of native grassland or forest to agriculture causes carbon emissions (Fargione et al., 2008; Searchinger et al., 2008). Both issues provide persuasive arguments against expanding land under cultivation. Yet agricultural yields are not on track to meet projected global increases in food demand (Ray et al., 2013). Potential (and probable) increased demand for bioenergy or carbon sequestration further confounds the land conversion question (Smith et al., 2013). Given all the challenges, understanding the impact of dietary patterns on land use is critically important.

1.3 Assessing impacts of diet on land use and food supplies

A variety of approaches, each with its own limitations, have been applied to determine how dietary choices influence land use. No single method is definitive. Economic models project future demands for food commodities and account for competing sectors (van Tongeren et al. 2001), but may not adequately capture supply side constraints (Heistermann et al., 2006). Life cycle assessments can allocate the environmental impact of individual foods, but the approach faces methodological challenges and data limitations to modeling complete diets (Heller et al., 2013). A variety of bio-physical approaches exist to estimate the land requirements of food consumption patterns (see, for example, Gerbens-Leenes et al., 2002; Peters et al., 2007; Wirsenius et al., 2010), yet this field is sufficiently young that comparison of the merits of each approach has not yet been assessed. Hoekstra and Wiedmann (2014) posit that "cross-fertilization" among different environmental footprint approaches will ultimately lead to more consistent frameworks. In other words, a melding of the best parts of each approach will occur over time. In the meantime, it is perhaps best to focus on what has been learned from attempts to understand the relationship between diet and land use.

Two key lessons have emerged from the literature. First, livestock products are a major contributor to land requirements associated with Western diets (van Dooren et al., 2014). Gerbens-Leenes et al. (2002) developed one of the first approaches to estimating land impacts of diet, and compared the land requirements of meeting current consumption patterns in 14 European countries and the U.S. (Gerbens-Leenes and Nonhebel, 2003). In all cases, meat, dairy, and fats accounted for the majority of land requirements. Similar patterns have been observed by subsequent studies of Sweden (Geeraert, 2013) and Germany (Meier and Christen, 2013). While studies of China (Li et al., 2013) and the Philippines (Kastner and Nonhebel, 2010) suggest that meat, dairy, and plant oils require a much smaller share of agricultural land, these patterns will likely change over time. Empirical evidence shows that consumption of meat and dairy products increases as a country's per capita income increases (Cranfield et al., 1998; Regmi et al., 2001) and that consumption patterns in middle-income countries are converging with those in higher-income countries (Regmi et al., 2008).

The second lesson is cautionary. While livestock production is the largest land user on Earth, simplistic thinking about dietary change must be avoided (Herrero and Thornton, 2013). Reviews of life cycle assessments of livestock systems and protein products show, definitively, that land use per unit of protein is generally lower with plant than animal sources (de Vries and de Boer, 2010; Nijdam et al., 2012). However, they also demonstrate a wide range among individual livestock products and among different systems producing the same livestock product. In addition to this variability in area of land required, the quality of land required differs as well. Modeling studies suggest that the largest fraction of land needs for ruminant animals are from forages and grazing lands (Wirsenius et al., 2010; Peters et al., 2014), which are often grown on non-arable land. Thus, reducing the most land-intensive products in the diet does not necessarily equate to freeing up land for cultivation. Finally, the land needs for producing animals do not always follow linear patterns, and can change rapidly when supplies of residual forage (Keyzer et al., 2005) or oilseed byproducts (Elferink et al., 2008) have been exhausted. When it comes to interpreting the land impacts of dietary change, caution is warranted.

1.4 Purpose of this analysis

The purpose of this analysis is to compare the per capita land requirements and potential carrying capacity of the land base of the continental United States (U.S.) under a diverse set of dietary scenarios. We argue that assessing human carrying capacity (persons fed per unit land area) is essential for fully understanding current and potential productivity of a land base. Estimates of carrying capacity represent the productive output of many crops grown across a heterogeneous land base in a single indicator, the number of people fed. While trade will remain essential to national food security in many countries, the purpose behind the closed system approach was to conduct a complete accounting of all land needed to meet total food needs and, thus, calculate carrying capacity.

Three aspects of this paper are novel relative to prior work. First, the study focuses at the scale of the conterminous U.S. To our knowledge, such an analysis of how dietary change might impact land use and carrying capacity has not been conducted at this scale. Second, the "Foodprint model" (described below) estimates land requirements for complete diets, accounting for three important interactions: the multiuse nature of certain grain and oilseed crops, the suitability of multiple land types to grazing, and the relationship between dairy production and beef production. Finally, the study explores how assumptions about the partitioning of agricultural land and the suitability of cropland for cultivated crops influences estimates of carrying capacity.

2. Materials and methods

2.1 Overview of the approach

A biophysical simulation model (the U.S. Foodprint Model based on Peters et al., 2007) that represents the conterminous U.S. as a closed food system was designed to calculate the per capita land requirements of human diets and the potential population fed by the agricultural land base of the continental United States. To do this, three sets of calculations were performed (Fig. 1). The first set of calculations estimated the annual, per capita food needs of the population based on daily food intake, the individual food commodities that comprise each food group, the weight of a serving of food, losses and waste that occur across the food system, and the conversion of raw agricultural commodities into processed food commodities. The second set of calculations estimated the individual land area required for each agricultural commodity in the diet based on yield data for each component crop and the feed requirements of all livestock. The third set of calculations estimated the potential carrying capacity of U.S. agricultural land, accounting for the aggregate land requirements of a complete diet, the area of land available, and the suitability of land for different agricultural uses. At key points in these calculations, marked with an asterisk in the diagram, additional calculations were performed to account for interdependencies in the food system. A description of the primary calculations and data sources is described below, and additional detail is provided in the Supplementary material.

2.2 Scenarios of food consumption

Ten distinct diet scenarios were analyzed in this study (Table 1). The scenarios focused solely on differences in food consumption patterns; parameters for food losses and waste, processing conversions, livestock feed needs, crop yields, land availability, and land suitability were held constant. The structure of the scenarios was designed to compare the land requirements and carrying capacity of nine isocaloric (equal caloric content) diets, eight of which are comparable in nutritional quality but which differ in terms of their protein sources. The tenth diet, representing current average food consumption, was included as a reference point. The relationship between the scenarios is described in more detail below.

The reference diet (Baseline) reflects contemporary food consumption patterns based on loss-adjusted food availability data from 2006–2008 (USDA Economic Research Service, 2010). The first isocaloric diet is identical to the baseline for the major food groups, but contains fewer discretionary calories in the form of added fats and sweeteners to prevent energy intake from exceeding caloric needs (Positive control, POS). The eight remaining diet scenarios generally conform to the USDA food group recommendations published in the 2010 Dietary Guidelines for Americans (U.S. Department of Agriculture and U.S. Department of

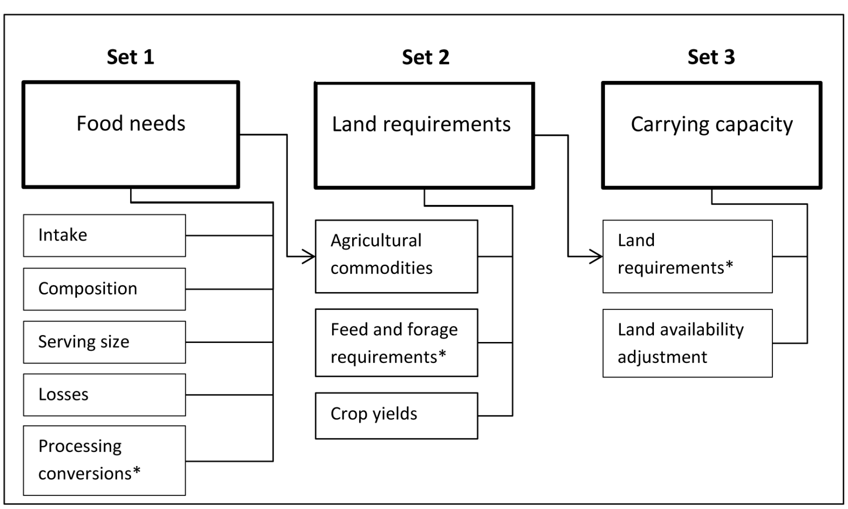

Figure 1

Flow diagram of the sets of calculations performed in the U.S. Foodprint model.

Major calculations are represented by the large boxes and the underlying data are indicated by smaller boxes beneath. Arrows indicate the flow of data from one set of calculations to another. The asterisks (*) mark points where additional calculations are made.

doi: 10.12952/journal.elementa.000116.f001

Table 1. Scenarios for the land requirements of diet analysis of the U.S.

Group	Description	Name	Symbol	Key attributes
Current consumption	Based on USDA estimates of per capita loss-adjusted food availability.	Baseline	BAS	Food intake equals loss-adjusted food availability for individual food commodities.
		Positive control	POS	As above, except intake of fats and sweeteners is reduced to make diet energy-balanced.
Healthy diet, omnivorous	Complies with 2010 Dietary Guidelines for Americans. Includes animal flesh.	100% healthy omnivorous	OMNI 100	100% of person-meals follow an omnivorous healthy diet pattern.
		80% healthy omnivorous	OMNI 80	80% of person-meals follow an omnivorous healthy diet pattern and 20% follow a ovo-lacto vegetarian healthy diet pattern.
		60% healthy omnivorous	OMNI 60	60% of person-meals follow an omnivorous healthy diet pattern and 40% follow a ovo-lacto vegetarian healthy diet pattern.
		40% healthy omnivorous	OMNI 40	40% of person-meals follow an omnivorous healthy diet pattern and 60% follow a ovo-lacto vegetarian healthy diet pattern.
		20% healthy omnivorous	OMNI 20	20% of person-meals follow an omnivorous healthy diet pattern and 80% follow a ovo-lacto vegetarian healthy diet pattern.
Healthy diet, vegetarian	Complies with 2010 Dietary Guidelines for Americans. Excludes animal flesh.	Ovolacto vegetarian	OVO	Includes both eggs and dairy products.
		Lacto vegetarian	LAC	Includes dairy products. Excludes eggs.
		Vegan	VEG	Excludes all livestock products.

doi: 10.12952/journal.elementa.000116.t001

Health and Human Services, 2010), hereafter referred to as the *dietary guidelines*. Each diet includes the weighted average recommendation for the U.S. population, based on the age-gender distribution of the population and each cohort's respective food group and caloric recommendations. The single exception is the dairy food group, which did not meet the recommended level in all diets. Dairy was selected because its recommendation is driven by dietary reference intakes for calcium, which can also be obtained from plant sources, fortified foods, or supplements, and all diets already contained adequate amounts of dietary protein.

Five of the "Healthy Diet" scenarios contained meat, and three were vegetarian. The diets containing meat (omnivore diets) represent varying degrees of transition toward plant-based sources of protein. The 100% healthy omnivorous diet represents a situation in which all Americans follow the dietary guidelines, requiring a modest (13%) reduction in protein-rich foods but retaining the current preference for meat (red meat, poultry, and fish) as the primary protein sources. The next four diets represent a transition toward vegetarian eating patterns (80%, 60%, 40%, and 20% healthy omnivorous), in which a decreasing percentage of meals follow the healthy omnivorous diet and are replaced by meals following an ovolacto-vegetarian diet. Effectively meat is substituted with additional servings of eggs, nuts, pulses, and tofu. The final three scenarios represent distinct vegetarian diet patterns: ovo-lacto vegetarian (OVO), lacto vegetarian (LAC), and vegan (VEG).

Within each of the ten diet scenarios, foods were divided into five major groups (grains, vegetables, fruits, dairy, and protein-rich foods) and two discretionary categories (added fats and sweeteners). Vegetables were further divided into subgroups as done in the dietary guidelines. In addition, the dairy and fats groups were broken into subgroups. The dairy group distinguishes fluid products (e.g. milk and yogurt) from other products (e.g. cheese and ice cream) as a heuristic way to enable the scenarios to represent dietary guidelines to choose lower fat sources of dairy. Similarly, plant sources of added fats were separated into plant oils (which are generally encouraged) and animal sources (which are recommended only in moderation). Protein rich foods were reported individually and in subgroups of similar foods (e.g. dry beans, peas, and lentils) because the literature suggests that these foods vary significantly in terms of their individual land requirements. Daily intake of the major food groups, food subgroups, and protein foods for each of the ten diet scenarios are reported in Table 2.

The macronutrient profiles of the ten diets differed in two important ways (Table 3). First, while the baseline diet represented current per capita energy intake, all other diets were balanced to meet the age-gender weighted average caloric requirements of the U.S. population, roughly 2,150 kcal person^{-1} day^{-1}. Second, the nine isocaloric diets differed in terms of total protein, fat, and carbohydrate content. Diets with higher levels of animal-based foods contained higher levels of protein and fats, and less carbohydrate, than diets that were more plant-based.

2.3 Partitioning of agricultural land

In this analysis, the term "land requirements" refers to the area of productive agricultural land needed to supply food, meaning land harvested by hand, machine, or grazing animals. Productive agricultural land was divided into two pools, cropland and grazing land. Cropland includes all land harvested for crops and arable

Table 2. Daily food intake by diet scenario[a]

Food group	Food subgroup	Unit	BAS	POS	OMNI 100	OMNI 80	OMNI 60	OMNI 40	OMNI 20	OVO	LAC	VEG
Grains	Whole and refined grains	oz	7.66	7.66	7.01	7.01	7.01	7.01	7.01	7.01	7.01	7.01
Vegetables	Total vegetables	cups										
	Dark green vegetables	cups	0.16	0.16	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
	Red and orange vegetables	cups	0.30	0.30	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
	Dry beans, lentils, and peas	cups	0.11	0.11	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
	Starchy vegetables	cups	0.46	0.46	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
	Other vegetables	cups	0.53	0.53	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Fruits	All fruit	cups	0.86	0.86	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92
Dairy	All dairy	cups										
	Cow's milk products	cups	1.68	1.68	1.68	1.77	1.85	1.94	2.02	2.11	2.25	0.00
	Fluid milk and yogurt	cups	0.68	0.68	1.43	1.50	1.58	1.65	1.72	1.79	1.92	0.00
	Cheese and other dairy	cups	1.00	1.00	0.25	0.26	0.28	0.29	0.30	0.31	0.34	0.00
	Soy milk	cups	n/a	n/a	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.89
Protein	All protein foods	meat oz equivalents	6.67	6.67	5.80	5.80	5.80	5.80	5.80	5.80	5.80	5.80
	Dry beans, lentils, and peas	meat oz equivalents	n/a	n/a	0.00	0.25	0.51	0.76	1.01	1.26	1.53	2.02
	Nuts	meat oz equivalents	0.77	0.77	0.67	0.91	1.16	1.40	1.65	1.89	2.29	2.29
	Tofu	meat oz equivalents	n/a	n/a	0.00	0.33	0.66	0.98	1.31	1.64	1.98	1.48
	Beef	meat oz equivalents	1.80	1.80	1.56	1.25	0.94	0.62	0.31	0.00	0.00	0.00
	Pork	meat oz equivalents	1.19	1.19	1.03	0.83	0.62	0.41	0.21	0.00	0.00	0.00
	Chicken	meat oz equivalents	1.51	1.51	1.31	1.05	0.79	0.53	0.26	0.00	0.00	0.00
	Turkey	meat oz equivalents	0.39	0.39	0.34	0.27	0.21	0.14	0.07	0.00	0.00	0.00
	Eggs	meat oz equivalents	0.53	0.53	0.46	0.57	0.68	0.79	0.89	1.00	0.00	0.00
	Fish	meat oz equivalents	0.48	0.48	0.42	0.33	0.25	0.17	0.08	0.00	0.00	0.00
Added fats	Plant oils	grams	64.46	28.03	28.03	28.03	28.03	28.03	28.03	28.03	28.03	28.03
	Dairy fats	grams	7.26	2.14	1.09	1.09	1.09	1.09	1.09	1.09	1.09	0.00
	Animal fat (lard and tallow)	grams allowed in diet	2.90	0.86	0.44	0.35	0.26	0.17	0.09	0.00	0.00	0.00
Sweeteners	All sweeteners	tsp	28.91	8.53	4.34	4.34	7.23	4.34	4.34	4.34	4.34	4.34

[a]Each scenario is indicated by its alphanumeric code: BAS (baseline), POS (positive control), OMNI 100 (100% healthy omnivorous), OMNI 80 (80% healthy omnivorous), OMNI 60 (60% healthy omnivorous), OMNI 40 (40% healthy omnivorous), OMNI 20 (20% healthy omnivorous), OVO (ovolacto vegetarian), LAC (lacto vegetarian), and VEG (vegan). Scenario descriptions are provided in the main text.

doi: 10.12952/journal.elementa.000116.t002

land that was used as pasture. Grazing land is unsuitable for cultivation and includes permanent pasture, rangeland, and woodland pasture. These two pools included most land that occurs on farms. However, they excluded idle cropland, woodlots not used for grazing, and land in farm roads, structures, ponds, and all other uses. The relationship between the categories used in this analysis and the standard land use categories employed by USDA is discussed in detail in the Supplementary material (Text S1, "Land availability" section).

Cropland was further partitioned to limit the percentage of the total area that can be used for cultivated crops in a given year. Scientists have long recognized that soils vary in their inherent suitability for intensive agriculture. The U.S. land capability classification system was first developed in the 1930s and refined over several decades to categorize land into grades based on their suitability for agriculture (Helms, 1997). The system distinguishes between arable land, land suitable only for grazing or forestry, and land entirely unsuited to commercial plant production. It further divides arable land into four grades (Classes I through IV). Sustainable land management on all but Class I soils (the highest grade of arable land) requires attention to crop choice or production practices, and these requirements become increasingly restrictive at each change in capability class (see USDA Natural Resources Conservation Service, 2013).

Decisions about the specific practices or crop choices will vary from farm to farm. Nonetheless, empirical data from the 2012 National Resources Inventory (U.S. Department of Agriculture, 2015) show that since 1982 large areas of cropland have been dedicated to permanent hay crops (15 to 19 million ha) or to hay crops and pasture grown in rotation with annual crops (4.3 to 8.7 million ha). Data from the Major Land Uses program (USDA Economic Research Service, 2011) show that an additional 5.2 to 27 million ha of

Table 3. Macronutrient profile of diet scenarios

Scenario name	Scenario symbol	Total energy (kcal day^{-1})	Protein (g day^{-1})	Fat (g day^{-1})	Carbohydrate (g day^{-1})
Baseline	BAS	2,844	92.1	119.8	363.1
Positive control	POS	2,153	91.9	80.9	272.6
100% healthy omnivorous	OMNI 100	2,153	88.7	73.0	296.8
80% healthy omnivorous	OMNI 80	2,153	86.5	72.5	301.4
60% healthy omnivorous	OMNI 60	2,153	84.2	72.0	306.1
40% healthy omnivorous	OMNI 40	2,153	82.0	71.5	310.8
20% healthy omnivorous	OMNI 20	2,153	78.9	71.0	315.4
Ovolacto-vegetarian	OVO	2,153	77.5	70.5	320.1
Lacto-vegetarian	LAC	2,154	75.7	69.7	325.6
Vegan	VEG	2,154	74.0	65.8	336.2

doi: 10.12952/journal.elementa.000116.t003

cropland have been used exclusively as pasture. Taken together, the area in perennial forages has ranged from 20 to 30 percent of total productive cropland (authors' calculations from USDA, 2015 and USDA Economic Research Service, 2011).

Estimating the optimum combination of annual to perennial crops on U.S. cropland to control erosion and maintain adequate soil health lies beyond the scope of this paper. A baseline estimate of the limit on cultivated crops was made based on the current proportion of cropland under cultivation. Since this assumption could potentially limit the carrying capacity of the model scenarios, a sensitivity analysis was included to examine the influence of increasing or decreasing the limit on cultivated cropland. Carrying capacity for the eight healthy diet scenarios was estimated for seven different levels of the restriction on cultivated cropland. One level was the default value, 95 out of 134 million ha of cropland (71% of the total cropland area). The other six levels represented increases or decreases in the default value in 10% increments.

2.4 Model calculations

The U.S. Foodprint model was organized as a stand-alone, spreadsheet-based model (Text S1, "Model structure" section). All calculations were performed simultaneously in Excel ® but can be understood, conceptually, as three sets of interrelated calculations. The principal calculations are described below in three sections: food needs, land requirements, and carrying capacity.

2.4.1 Food needs

Diet scenarios were structured based on intake of food groups, as shown in Table 2. The first set of calculations performed in the U.S. Foodprint model translated each of the diet scenarios into estimates of the mass of primary food commodities needed to supply each diet, as well as the equivalent quantities of agricultural commodities from which the foods are derived.

The quantity of primary food commodities (QF) required in a diet (in g person^{-1} year^{-1}) was the product of five factors (Eq. 1). Intake (I) of a food or food group (i) was defined for each of the scenarios, and expressed in servings person^{-1} day^{-1}. For composite food groups, composition (C) estimated the proportion of intake that come from individual food commodities (j) based on the relative loss-adjusted availability of these foods in the U.S. food supply for the period 2006–2008 (USDA Economic Research Service, 2010). Weight (W) of a serving converted intake from a volume basis to a mass basis (expressed in g serving^{-1}) using data on serving size from the Nutrient Database for Standard Reference, Release 23 (USDA Agricultural Research Service, 2010). Loss adjustment factors (L) accounted for spoilage, waste, inedible portions, and cooking losses using data from the USDA Loss-Adjusted Food Supply Database (USDA Economic Research Service, 2010). The constant 365 converts daily consumption to annual consumption.

$$QF_{ij} = I_i \times C_{ij} \times W_j \times L_j \times 365 \qquad (1)$$

The quantities of food required were converted into equivalent amounts of agricultural commodities (Eq. 2) to enable subsequent calculations of land requirements using crop yield data. The quantity (g person^{-1} yr^{-1}) of agricultural commodity (QA) required to supply food intake was the product of the quantity of food commodity required (QF_j) and a processing conversion (P) which converts units of primary food commodity (j) output into the equivalent amount of agricultural commodity (k) input. Processing conversion factors were obtained primarily from U.S. Department of Agriculture sources (USDA Economic Research Service, 1992 and 2010) with a few exceptions where data were not available (Text S1, Table S2). However, dairy products constituted a special case, since the amount of fluid milk required to make them depends on the aggregate requirements for milk fat and non-fat solids relative to the composition of the milk. Therefore, the model determined the aggregate milk fat and non-fat solid requirements for all dairy products included in each diet scenario, then processing conversions were calculated based on the limiting component (see Text S1, "Processing conversions for dairy products" section).

$$QA_{jk} = QF_j \times P_{jk} \tag{2}$$

2.4.2 Land requirements

The second set of calculations determined the land requirements for individual foods and for complete diets.

2.4.2.1 Individual foods. Annual per capita land requirements (LR) for individual foods were calculated (in ha yr^{-1}) based on the quantities of agricultural commodities needed to support food intake and estimates of the respective agricultural yields. For plant-based foods (Eq. 3a), the land requirement (LR) for each individual food commodity (j) equaled the quantity (QA) of agricultural commodity (k) required (in kg yr^{-1}) divided by the average U.S. yield (Y) of that commodity (in kg ha^{-1}) over the time period 2000-2010. In this equation, agricultural commodities are synonymous with crops.

$$LR_{jk} = QA_{jk} / Y_k \tag{3a}$$

Annual per capita land requirements for animal-based foods were calculated for each individual feed ingredient (Eq. 3b). The land area required (LR) for each feed ingredient (l) needed to produce an animal-based food (j) is equal to the quantity of feed crop needed divided by the associated crop yield. The quantity required of each individual feed crop equals the product of three factors: the quantity (QA) of agricultural commodity (k) required supply the food in the diet (in kg yr^{-1}), the amount of feed ingredient (l) in the ration (R) fed to livestock (in kg feed kg livestock $product^{-1}$) and a conversion factor (P) to account for any processing losses in deriving the feed ingredient from the source crop (e.g. soybean meal from soybean (*Glycine max*)). The quantity of feed crop required is divided by the yield of the crop (in kg ha^{-1}) to calculate land requirements.

$$LR_{jkl} = (QA_{jk} \times R_{kl} \times P_{kl}) / Y_l \tag{3b}$$

Yield data (in kg ha^{-1}) for harvested crops for the period 2000–2010 were based on annual surveys conducted by the USDA National Agricultural Statistics Service. Data were compiled from the QuickStats Database (USDA National Agricultural Statistics Service, 2014) and various summary reports (USDA National Agricultural Statistics Service, 2004, 2008a, 2008b, 2010a, 2010b, and 2011; USDA National Agricultural Statistics Service - California Field Office, 2011). Biomass productivity of grazing lands is not reported in USDA yields statistics, and a separate procedure was used to estimate forage yields from grazed land (see Text S1, "Grazing yields" section and Table S1). The feed needs of livestock products (beef, chicken, dairy, eggs, pork, and turkey) were obtained from a model developed by Peters et al. (2014) for the purpose of calculating feed conversion ratios and aggregate ration compositions based on contemporary production practices in the U.S. The model estimated feed needs for a simplified list of ingredients: alfalfa silage, corn grain, corn silage, grass hay, grazed forage, and soybean meal. Conversions from feed ingredients to crop ingredients were determined from various USDA sources (see Text S1, "Data sources and assumptions" section).

An important food system interaction considered at this stage was that the beef supply chain includes meat from animals that originate in the dairy system. Culled dairy animals, veal calves, and dairy calves that are raised to market weight contribute to the total beef supply. The model determined the proportion of meat that comes from beef versus dairy breeds based on the residual meat output from the dairy system and the quantities of beef and fluid milk required in each diet scenario (see Dataset S1).

2.4.2.2 Complete diets. Land requirements for complete diets were calculated for three distinct categories of land: cropland in cultivated crops, cropland in perennial forage crops, and grazing land (Eqs. 4a-4c). Cultivated cropland included all annual field crops, fruits, nuts, and vegetables. Cropland in perennial forages included hay crops and grazing on land which could be cropped but is used for pasture. Grazing land included non-arable grasslands and woodlands that can be used for grazing. Preliminary estimates of the land requirements of each diet for each category of land were calculated by summing the land requirements for individual food commodities, grouped by the appropriate land class.

$$ALR_{\text{cultivated cropland}} = \Sigma\,(LR_{jk}) + \Sigma\,(LR_{jkl}) - MUCA \tag{4a}$$

$$ALR_{\text{perennial cropland}} = \Sigma\,(LR_{jkl}) + GA_{\text{perennial cropland}} \tag{4b}$$

$$ALR_{\text{grazing}} = \Sigma\,(LR_{jkl}) - GA_{\text{grazing}} \tag{4c}$$

For cultivated cropland (Eq. 4a), aggregate land requirements (ALR) of diet (ha $person^{-1}$ yr^{-1}) were calculated by taking the sum of all land requirements (LR) for individual plant-based foods (jk) and the land requirements of ration ingredients (jkl) used in producing animal-based foods that are cultivated crops. A multi-use crop adjustment (MUCA), which accounts for the multi-use nature of oilseed crops and corn (*Zea mays*), was subtracted from this subtotal. Preliminary estimates of aggregate land requirements (ALR) for perennial cropland (Eq. 4b) and grazing land (Eq. 4c) were calculated as the sum of the land requirements of certain livestock ration ingredients, specifically, hay crops, perennial silage crops, and grazed forages. Since grazed forages can also be produced on cropland, the subtotals of the land requirements of individual ration ingredients were modified by applying a grazing adjustment (GA), to distribute grazed forage requirements across both cropland and grazing land to optimize use of available land. For details on the calculations to derive the multi-use crop adjustment and the grazing adjustment, see the Supplementary material (Text S1, “Land use adjustments” section).

2.4.3 Carrying capacity

In this study, the term “carrying capacity” refers to the number of people that could be fed from an agricultural land base. Potential carrying capacity was calculated based on per capita land requirements, the areas of cultivated cropland, perennial cropland, and grazing land available in the U.S, and the suitable uses for each pool of land. Only land that is harvested for crops or used for livestock grazing was considered available for food production. While the practice of agriculture also involves support land, such as buildings, farm roads, and irrigation ponds, such uses do not generate biomass and were therefore excluded from the estimate of available land.

Availability of cropland for cultivated crops and perennial forages was estimated from data on land use for farms, crop groups, and individual crops from the 2007 Census of Agriculture (USDA National Agricultural Statistics Service, 2009) (see Text S1, “Land availability” section). The existing ratio of cultivated to perennial forage crops was used to set an upper bound on the area of cropland considered suitable for cultivated cropping. Cultivated cropland was further multiplied by a cropping intensity factor to account for the effective area that may be harvested in a single year. All non-cropland used for grazing in 2007 was considered available grazing land. Estimates of the combined area of public and private land used for grazing in 2007 were obtained from the data set “Major Uses of Land in the U.S.” (USDA Economic Research Service, 2011). Both grassland and grazed woodlands were included.

The carrying capacity of the U.S. (persons potentially fed) under each diet scenario was calculated based on the per capita land requirements for each pool of land and the corresponding areas of land available in the U.S. (Eq. 5). In theory, the potential to meet food needs will be limited by the most scarce pool (or pools) of land. Thus, carrying capacity was calculated using a function that returns the minimum of three possible values: (a) the effective area (EA) of available cultivated cropland divided by the annual per capita land requirements (ALR) for cultivated cropland, (b) the available area (A) of cropland divided by the sum of the annual per capita land requirements (ALR) from cultivated and perennial cropland, and (c) the total area of available cropland and grazing land divided by the sum of the annual per capita land requirements (ALR) for cultivate cropland, perennial cropland, and grazing land.

$$\text{Carrying capacity} = \text{MIN}\left(EA_{\text{cultivated cropland}} / ALR_{\text{cultivated cropland}},\ A_{\text{cropland}} / (ALR_{\text{cropland}} + ALR_{\text{perennial cropland}}),\ A_{\text{total}} / (ALR_{\text{cultivated cropland}} + ALR_{\text{perennial cropland}} + ALR_{\text{grazing}})\right) \tag{5}$$

3. Results

3.1 Overview of results

The findings of this study build upon one another sequentially. Estimates of the annual per capita land requirements of complete diets are foundational and are thus presented first (section 3.2). Assumptions regarding the area of agricultural land available in each pool and the utilization of available land are discussed next (section 3.3). Carrying capacity of the U.S. agricultural land base is compared across each diet scenario in the final section (3.4).

3.2 Land requirements of diet

Total per capita requirements for agricultural land varied widely across the diet scenarios, with a factor of *eight* separating the least land intense and most land intense diets (Fig. 2). The baseline scenario had the highest total land use, 1.08 ha person^{-1} year^{-1}, followed closely by the positive control, 1.03 ha person^{-1} year^{-1}. Land requirements decreased steadily across the five healthy omnivorous diets, from 0.93 to 0.25 ha person^{-1} year^{-1}, and the total land requirements for the three vegetarian diets were all similarly low, 0.13 to 0.14 ha person^{-1} year^{-1}. However, differences in total per capita land requirements are only part of the story.

Different patterns of variation were also observed between the three pools of land. Per capita requirements for grazing land accounted for a large portion of the variation across the diets ranging from 0.10 to 0.74 ha person^{-1} year^{-1}across the seven diet scenarios that included meat. Grazing land was absent from the three vegetarian diets. Likewise, annual per capita requirements for perennial cropland ranged widely. Perennial cropland requirements were highest for the baseline and positive control diets (0.16 and 0.17 ha person^{-1} year^{-1}), and perennial cropland requirements decreased steadily as the amount of meat in the diet decreased, eventually leveling off to 0.02 ha person^{-1} year^{-1} for the ovolacto- and lacto-vegetarian diets. Perennial cropland requirements were zero in the vegan diet. In contrast, the variations in per capita requirements for cultivated land were less pronounced relative to grazing land and perennial cropland. Cultivated cropland requirements displayed a *1.5-fold* range across the diet scenarios, from a high of 0.18 ha person^{-1} year^{-1} in the baseline diet and a low of 0.12 ha person^{-1} year^{-1} in the lacto-vegetarian diet.

3.3 Utilization of available land

To calculate potential carrying capacity, all diet scenarios were restricted to the areas available within each pool of productive agricultural land. The aggregate area available for food production was estimated to be 95 million ha cultivated cropland, 134 million ha total cropland, and 299 million ha grazing land (Dataset S1). Aggregate land use in each scenario was estimated as the product of carrying capacity and the annual per capita land requirements.

Not all diets equally exploited each pool of land (Fig. 3). The five diets containing the largest quantities of meat (baseline, positive control, 100% health omnivorous, 80% healthy omnivorous, and 60% healthy omnivorous) used the entire available area, both cropland and grazing land. The five diets containing the least meat (or no meat) used the maximum allowable area of cultivated cropland and varied widely in their use of the remaining agricultural land. The 40% healthy omnivorous diet and the 20% healthy omnivorous diet used some of the available grazing land (214 and 75 million ha, respectively) and most of the cropland restricted to perennial forages (35 and 24 million ha, respectively). The ovolacto- and lacto-vegetarian diets used about half of the cropland restricted to perennial forages, while the vegan diet used none of the restricted cropland. None of the vegetarian diets used any grazing land (dairy rations were modeled with cows fed only harvested feeds and forages, see Peters et al., 2014).

Differences in land allocation were even more noticeable when land use was compared by crop group (Fig. 4). In the two diets closest to current consumption patterns (baseline and positive control), approximately 20% of the available cropland was devoted to food crops (grains, fruit, vegetables, pulses, nuts, and sweeteners) and about 80% to primarily feed and forage crops (feed grains, oilseeds, hay, and pasture). Food crops constituted an increasing share of cropland use as the amount of meat in the diet was reduced.

3.4 Potential carrying capacity

Human carrying capacity is defined here as the number of people who could be fed from the area of land available to produce the food required for each diet scenario. This number was a function of the annual per capita land requirements and the area of land available in each pool within the U.S. Potential carrying capacity of the U.S. varied substantially across the scenarios, with a factor of *two* separating the highest and lowest carrying capacities (Table 4). The baseline diet had the lowest estimated carrying capacity (402 million persons), and the lacto-vegetarian diet had the highest (807 million persons). All estimates exceeded the 2010 U.S. population (U.S. Census Bureau, 2015). Indeed, model output estimated that U.S. agricultural land has the capacity to meet the needs of a populace 1.3 to 2.6 times larger than the 2010 population, without trade.

All dietary changes increased estimated carrying capacity relative to the baseline. Reducing excess discretionary calories (positive control diet) resulted in a small increase in potential to feed people, 19 million persons (about 5% of the 2010 U.S. population). Reducing meat in the diet, as shown by the five healthy omnivorous diet scenarios, further increased carrying capacity relative to the baseline: 63 to 367 million persons (16% to 91% of the 2010 U.S. population). Switching to an entirely vegetarian diet also increased

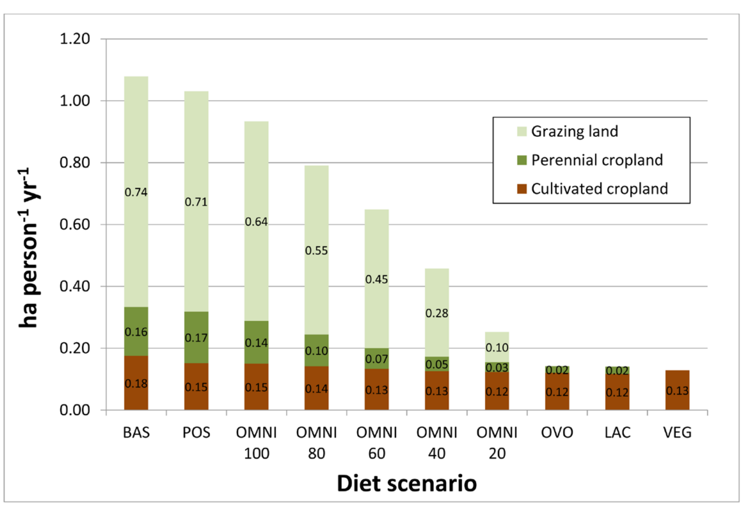

Figure 2

Annual per capita requirements for productive agricultural land by diet scenario and category of land use.

Diets are described in detail in text and Table 1.

doi: 10.12952/journal.elementa.000116.f002

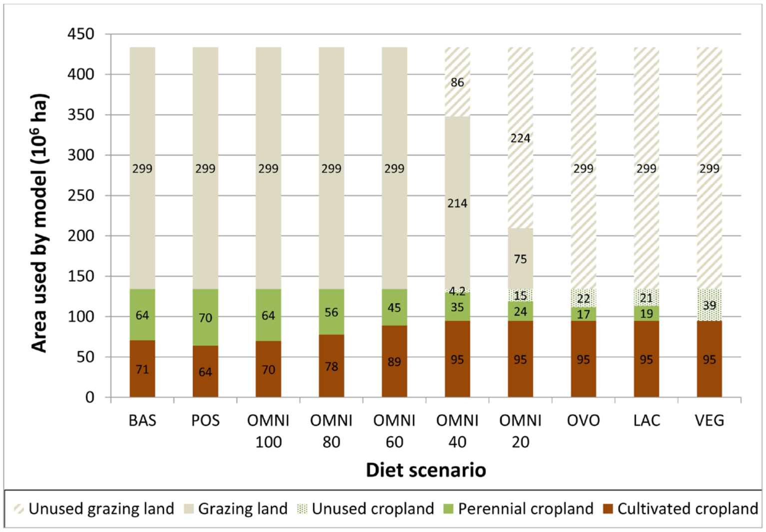

Figure 3

Utilization of the area of cropland available for food production in the United States by diet scenario.

Diets described in detail in text and Table 1.

doi: 10.12952/journal.elementa.000116.f003

carrying capacity relative to the baseline, though ovolacto- and lacto-vegetarian diets had higher carrying capacities than the vegan diet. Indeed, the carrying capacity of the vegan diet fell between the 60% omnivore and 40% omnivore diet.

A sensitivity analysis was run to demonstrate how the restriction on the area of cultivated cropland influences estimated carrying capacity (Fig. 5). Carrying capacity was shown to be highly sensitive to the starting assumptions about the proportion of land available for cultivated cropping. The differences in carrying capacity observed across the eight diets were smaller when less of the cropland is available for cultivation and larger when more land is available for cultivation. Each diet, except the vegan diet, eventually reached a plateau, indicating the point at which the proportion of land available for cultivated cropping exceeds the level needed for cultivated crops. Over the range observed, the vegan diet eventually surpasses all but the lacto-vegetarian diet. These two diets are approximately equal when 92% of cropland is considered available for cultivation.

4. Discussion

4.1 Influence of dietary patterns on agricultural land requirements

Three lessons can be gleaned from the data presented. First, requirements for grazing land must be distinguished from requirements for cropland. As shown in Fig. 2, annual per capita requirements for agricultural land exhibit a wide (eight-fold) range across scenarios. A simple comparison of the total land requirements could lead one to the erroneous conclusion that the differences in carrying capacity are similarly large.

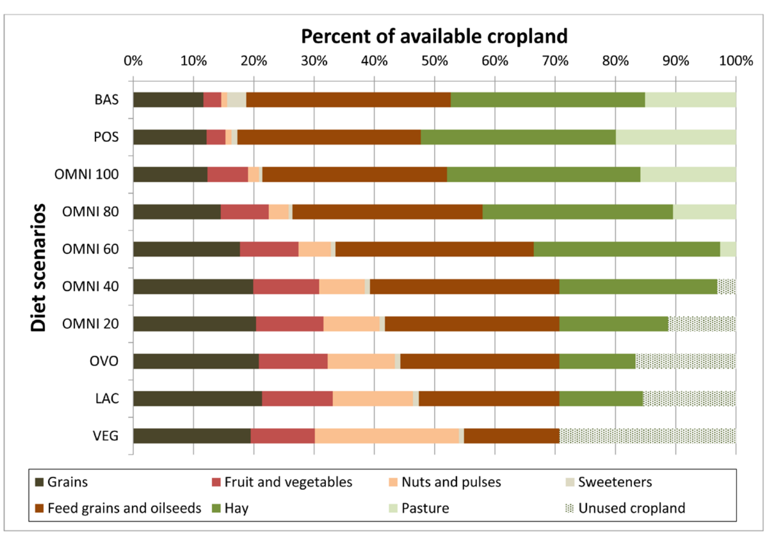

Figure 4

Distribution of cropland use by crop type.

Bars indicate the percentage of total cropland devoted to major categories of crops as defined by use within the food system. Diets described in detail in text and Table 1.

doi: 10.12952/journal.elementa.000116.f004

Table 4. Carrying capacity of the U.S. by diet scenario

Scenario	Population fed		Change from baseline	
Symbol	(10^8 persons)	(% of 2010 population)[a]	(10^8 persons)	(% of BAS population)
BAS	4.02	130%	na	na
POS	4.21	136%	0.19	5%
OMNI 100	4.67	151%	0.63	16%
OMNI 80	5.48	178%	1.46	36%
OMNI 60	6.69	217%	2.67	66%
OMNI 40	7.52	244%	3.50	87%
OMNI 20	7.69	249%	3.67	91%
OVO	7.87	255%	3.84	96%
LAC	8.07	261%	4.05	101%
VEG	7.35	238%	3.32	83%

[a]Population of the United States on April 1, 2010 according to the 2010 Census (U.S. Census Bureau, 2015).

doi: 10.12952/journal.elementa.000116.t004

However, grazing land by definition is not arable, and the estimated forage yield for this resource is quite low. Thus, the estimates of per capita land requirements are only meaningful when divided into constituent pools.

Second, diet composition greatly influences overall land footprint. As Fig. 3 illustrates, five of the diets operate under conditions in which the total footprint of agriculture does not change, even though carrying capacity differs widely. However, the 40% healthy omnivorous, the 20% healthy omnivorous, and the three vegetarian diets all have aggregate footprints smaller that the area currently used in the U.S. This finding is significant in light of recent calls to contain the footprint of agriculture (Godfray et al., 2010; Foley et al., 2011). Provision of food, while essential, is not the only important ecological service provided by land. Some of these services, such as carbon capture, may be compatible with grazing, at least in well-managed systems. Other services, such as wildlife habitat, may be impinged where domesticated species compete for biomass with wild ruminants and ungulates. Finally, the use of perennial cropland for grazing or hay production could conceivably compete with bioenergy production where biomass energy or draft animals are possible alternatives to fossil fuels.

Third, dietary changes toward the 2010 Dietary Guidelines for Americans imply very different allocations of land by crop type. Specifically, land in grains, fruits and vegetables, pulses, and nuts would need to increase relative to land in feed grains and oilseeds, hay, and cropland pasture. USDA researchers have noted the implications of compliance with the dietary guidelines (Young and Kantor, 1999; Buzby et al., 2006), and these patterns are even more striking under scenarios of reduced meat consumption. In short, scenarios that differ from the baseline represent increasingly large shifts from the status quo and would have implications well beyond land use. While such considerations lie beyond the purpose of this study, it is essential to recognize that shifts toward plant-based diets may need to be accompanied by changes in agronomic and horticultural research, extension, farm operator knowledge, infrastructure, livestock management, farm and food policy, and international trade.

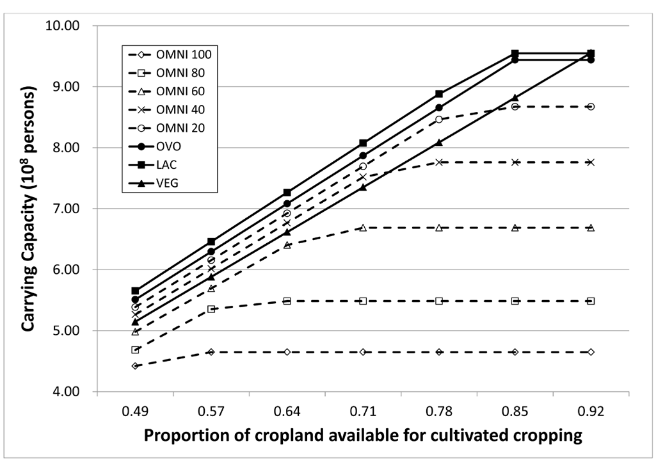

Figure 5

Sensitivity of carrying capacity to starting assumptions regarding the proportion of cropland available for cultivation.

Solid lines indicate vegetarian diet scenarios and dashed lines indicate omnivore diet scenarios. Diets are described in detail in text and Table 1. Proportion of land available for cultivated cropping covers a range around the default value used in previous model runs (0.71). See section 2.3 for more details.

doi: 10.12952/journal.elementa.000116.f005

4.2 Interpreting potential carrying capacity

In this study, carrying capacity is an estimate of the potential population that could be fed from an agricultural land base. Our use of the term deviates somewhat from its broader meaning in ecology, in which a species' population may be limited by any essential resource, not just access to food. Nonetheless, carrying capacity provides a valuable concept for measuring the potential food output of agricultural land. Our use of the concept is consistent with arguments in the literature (Peters et al., 2003; Cassidy et al., 2013) that from the standpoint of nutrition, productivity of agricultural land is more appropriately measured in people fed per unit area than by yield of individual crops. This analysis held crop yields constant across all scenarios. Thus, the reported estimates of potential carrying capacity measured only the differences imposed by changing consumption.

Seen in this light, the estimates of carrying capacity for each scenario suggest that dietary choices can greatly influence the ability of agriculture to meet human food needs. Reducing meat in the diet clearly resulted in increased carrying capacity, as evidenced by the fact that carrying capacity increased across the five healthy omnivorous diets as the amount of meat consumed decreased. Likewise, the ovolacto- and lacto-vegetarian diets had the highest estimates of carrying capacity overall. However, the influence of dietary changes are not always obvious, as shown by the fact that the relative position of the vegan diet varied depending on starting assumptions regarding the proportion of cropland available for cultivation. Similarly, removing 700 kcal person^{-1} day^{-1} from the baseline diet caused just a small jump in carrying capacity as shown in the positive control diet. It is important to bear in mind that all scenarios consistent with the Dietary Guidelines for Americans are considered nutritionally sufficient. From the standpoint of meeting human food needs, they are all equivalent. Thus, differences in carrying capacity should represent the trade-offs of food preferences rather than nutritional quality.

The absolute magnitude of the numbers is large. All estimates of carrying capacity exceed the size of the 2010 U.S. population by at least 30%. This result suggests that the U.S. has a large food security buffer, which it currently shares with other countries through trade. In addition, the differences between the scenarios suggest that the dietary changes could free up capacity to feed hundreds of millions of people around the globe. To meet global food needs in 2050, a potential of this magnitude is significant. Whether the windfall of such dietary change could be redistributed to those in need remains an important unanswered question. Nonetheless, this research suggests that U.S. agricultural land has the capacity to feed many more people than reside in the U.S. and this margin might be extended through dietary change.

4.3 Caveats and lingering questions

While this study shows that dietary change has the potential to reduce requirements for agricultural land and increase carrying capacity, the results are perhaps best treated as a foundation for further hypothesis testing. Only one version of each diet scenario was run in the analysis. More work is needed to understand the range of variability within each diet, and the sensitivity of results to changes in key parameters such as crop yields and food waste. In particular, each of the diets is represented by a single set of food preferences, and it is possible to envision variations on each diet that conform to the same structure in terms of food group servings yet differ in terms of the constituent foods. For example, diets containing meat could vary in terms of the proportion of servings from beef, pork, and poultry. Likewise, earlier work has shown that land requirements can be influenced by the amount of fat in the diet (Peters et al., 2007), and scenarios could conform to the same food group distributions but vary in terms of the calories from added fats. Quantifying the sensitivity of the model output to variability in input data is an important next step. Nonetheless, such work seems likely to confirm that dietary choices are important.

In addition to variation within scenarios, future work should refine the most appropriate boundaries for scenarios. This analysis examined multiple diets with reduced meat, since such a shift is consistent with recommended nutritional advice. However, it may also be important to examine diets in which meat consumption is greater than the baseline, since model projections of global food demand suggest that demand for livestock products in OECD countries will continue to increase, albeit slowly (Valin et al., 2014). Similarly, complete adoption of dietary guidelines by a population is highly unlikely, if not impossible, so comparison of diets that reflect a partial and imperfect transition towards healthier eating would be beneficial. Finally, the modeling of a population-wide ovolacto- or lacto-vegetarian diet leaves open the question of the fate of animals from the dairy or egg-production systems that in the current agricultural system would be raised for meat (such as dairy calves) or used as meat at the end of their productive life span (such as and culled dairy cows).

5. Conclusions

Dietary change has been proposed as part of a strategy to ensure future food security for a growing world population while addressing environmental challenges associated with agricultural production. The findings of this study support the idea that dietary change towards plant-based diets has significant potential to reduce the agricultural land requirements of U.S. consumers and increase the carrying capacity of U.S. agricultural resources. Future work is needed to determine the best way to share this productive bounty with the rest of the world, but potential for dietary change to influence land requirements and carrying capacity is clear. Diet composition matters.

This study focuses attention on some underappreciated concerns. While agricultural land is often discussed in the aggregate, our analysis shows that accounting for the partitioning of land between grazing land, cultivated cropland, and perennial cropland has a strong influence on estimates of carrying capacity. Indeed, we demonstrate that under a range of land use conditions, diets with low to modest amounts of meat outperform a vegan diet, and vegetarian diets including dairy products performed best overall. Finally, the analysis illustrates how carrying capacity can be used to measure the potential food output of agricultural land. Moreover, the model presented herein provides a basis for exploring an even wider range of diet scenarios, and to further examine which diets make most efficient use of available land.

References

Balmford A, Green RE, Scharlemann JPW. 2005. Sparing land for nature: Exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Glob Change Biol* **11**(10): 1594–1605.

Buzby JC, Wells HF, Vocke G. 2006. Possible Implications for U.S. Agriculture from Adoption of Selected Dietary Guidelines. *Economic Research Report No. 31*. Verified 16 November 2014. http://www.ers.usda.gov/publications/err-economic-research-report/err31.aspx.

Cassidy ES, West PC, Gerber JS, Foley JA. 2013. Redefining agricultural yields: From tonnes to people nourished per hectare. *Environ Res Lett* **8**: 1–8. doi: 10.1088/1748-9326/8/3/034015.

Cranfield JAL, Hertel TW, Eales JS, Preckel PV. 1998. Changes in the structure of global food demand. *Am J Agr Econ* **80**(5): 1042–1050.

de Vries M, de Boer IJM. 2010. Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock Science* **128**: 1–11.

Elferink EV, Nonhebel S, Moll HC. 2008. Feeding livestock food residue and the consequences for the environmental impact of meat. *J Cleaner Prod* **16**: 1227–1233.

Fargione J, Hill J, Tillman D, Pulaski S, Hawthorne P. 2008. Land clearing and the biofuel carbon debt. *Science* **319**: 1235–1237.

Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, et al. 2011. Solutions for a cultivated planet. *Nature* **478**(7369): 337–342.

Geeraert F. 2013. Sustainability and dietary change: The implications of Swedish food consumption patterns 1960–2006. *International Journal of Consumer Studies* **37**: 121–129.

Gerbens-Leenes PW, Nonhebel S. 2003. Consumption patterns and their effects on land required for food. *Ecol Econ* **42**(1–2): 185–199.

Gerbens-Leenes PW, Nonhebel S, Iven WPMF. 2002. A method to determine land requirements relating to food consumption patterns. *Agr Ecosys Environ* **90**(1): 47–58.

Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, et al. 2010. Food security: The challenge of feeding 9 billion people. *Science* **327**: 812–818.

Gussow JD, Clancy KL. 1986. Dietary guidelines for sustainability. *J Nutr Educ* **18**(1):1–5.

Heistermann M, Muller C, Ronneberger K. 2006. Land in sight? Achievements, deficits and potentials of continental to global scale modeling. *Agr Ecosys Environ* **114**(2–4): 141–158.

Heller MC, Keoleian GA, Willett WC. 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.

Helms D. 1997. Land capability classification: The U.S. experience. *Advances in GeoEcology* **29**: 159–175.

Herrero M, Thornton PK. 2013. Livestock and global change: Emerging issues for sustainable food systems. *P Natl Acad Sci* **110**(52): 20878–20881.

Hoekstra AY, Wiedmann TO. 2014. Humanity's unsustainable environmental footprint. *Science* **344**(6188): 1114–1117.

Kastner T, Nonhebel S. 2010. Changes in land requirements for food in the Philippines: A historical analysis. *Land Use Policy* **27**(3): 853–863.

Keyzer MA, Merbis MD, Pavel IFPW, van Wesenbeeck CFA. 2005. Diet shifts towards meat and the effects on cereal use: Can we feed the animals in 2030? *Ecol Econ* **55**: 187–202.

King JC. 2007. An Evidence-Based Approach for Establishing Dietary Guidelines. *J Nutr* **137**: 480–483.

Lambin EF, Meyfroidt P. 2011. Global land use change, economic globalization, and the looming land scarcity. *P Natl Acad Sci* **108**(9): 3465–3472.

Lappé FM. 1971. *Diet for a Small Planet*. New York, New York: Ballantine Books.

Li G, Zhao Y, Cui S. 2013. Effects of urbanization on arable land requirements in China based on food consumption patterns. *Food Security* **5**: 439–449.

McMichael AJ, Powles JW, Butler CD, Uauy R. 2007. Food, livestock production, energy, climate change, and health. *Lancet* **370**: 1253–1263.

Meier T, Christen O. 2013. Environmental impacts of dietary recommendations and dietary styles: Germany as an example. *Environ Sci Technol* **47**: 877–888.

Nijdam D, Rood T, Westhoek H. 2012. The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Policy* **37**: 760–770.

Parris TM, Kates RW. 2003. Characterizing a sustainability transition: Goals, targets, trends, and driving forces. *P Natl Acad Sci* **100**(14): 9068–9073.

Pelletier N, Tyedmers P. 2010. Forecasting potential global environmental costs of livestock production 2000–2050. *P Natl Acad Sci* **107**(43): 18371–18374.

Peters CJ, Fick GW, Wilkins JL. 2003. Cultivating better nutrition: Can the Food Pyramid help translate dietary recommendations into agricultural goals? *Agron J* **95**: 1424–1431.
Peters CJ, Picardy JA, Darrouzet-Nardi A, Griffin TS. 2014. Feed conversions, ration compositions, and land use efficiencies of major livestock products in U.S. agricultural systems. *Agr Syst* **130**: 35–43.
Peters CJ, Wilkins JL, Fick GW. 2007. Testing a complete-diet model for estimating the land resource requirements of food consumption and agricultural carrying capacity: The New York State example. *Renewable Agriculture and Food Systems* **22**(2):145–153.
Ray DK, Mueller ND, West PC, Foley JA. 2013. Yield trends are insufficient to double global crop production by 2050. *PLOS One* **8**(6): e66428.
Regmi A, Deepak MS, Seale JL Jr, Bernsteirn J. 2001. Cross-country analysis of food consumption patterns. *Changing Structure of Global Food Consumption and Trade [WRS-01-1]. U.S. Department of Agriculture, Agriculture and Trade Report*. P. 14-22. A. Regmi (ed.). Verified 24 March 2015. http://www.ers.usda.gov/publications/wrs-international-agriculture-and-trade-outlook/wrs01-1.aspx.
Regmi A, Takeshima H, Unnevehr L. 2008. Convergence in food demand and delivery: Do middle-income countries follow high-income trends? *Journal of Food Distribution Research* **39**(1): 116–122.
Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, et al. 2008. Use of U.S. croplands for biofuels increase greenhouse gases through emissions from land-use change. *Science* **319**: 1238–1240.
Smith P, Haberl H, Popp A, Erb KH, Lauk C, et al. 2013. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob Change Biol* **19**: 2285–2302.
U.S. Census Bureau. 2015. American Fact Finder [on-line]. Verified 27 May 2015. http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=PEP_2014_PEPANNRES&src=pt.
U.S. Department of Agriculture. 2015. Summary Report: 2012 National Resources Inventory. Iowa State University, Ames, Iowa: Natural Resources Conservation Service, Washington D.C. and Center for Survey Statistics and Methodology. Verified 11 March 2016. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd396218.pdf.
U.S. Department of Agriculture and U.S. Department of Health and Human Services (USDA and HHS). 2010. Dietary Guidelines for Americans, 2010. 7th Edition. Washington, DC: U.S. Government Printing Office. Verified 14 November 2014. http://www.cnpp.usda.gov/sites/default/files/dietary_guidelines_for_americans/PolicyDoc.pdf.
USDA Agricultural Research Service. 2010. Nutrient Database for Standard Reference, Release 23 [On-line]. Accessed November 2010. http://www.ars.usda.gov/ba/bhnrc/ndl.
USDA Economic Research Service (ERS). 1992. Weights, measures, and conversion factors for agricultural commodities and their products. *Agric. Handbook 697*. Washington, D.C.: USDA Economic Research Service.
USDA Economic Research Service (ERS). 2010. Loss Adjusted Food Availability Data [on-line]. Accessed October 2010. Verified 14 November 2014. http://www.ers.usda.gov/data-products/food-availability-(per-capita)-data-system/.aspx.
USDA Economic Research Service (ERS). 2011. Major Land Uses, Summary table 4: Total grazing land, by region, State, and United States, 2007. Verified 16 November 2014. http://www.ers.usda.gov/data-products/major-land-uses.aspx.
USDA National Agricultural Statistics Service (NASS). 2004. Citrus Fruit Final Estimates, 1997–2002. *Statistical Bulletin No. 997 (04)*. Verified 14 November 2014. http://usda.mannlib.cornell.edu/usda/nass/SB997/sb997.pdf.
USDA National Agricultural Statistics Service (NASS). 2008a. Citrus Fruit Final Estimates, 2003–2007. *Statistical Bulletin No. 1009*. Verified 14 November 2014. http://usda.mannlib.cornell.edu/usda/nass/SB997/sb1009.pdf.
USDA National Agricultural Statistics Service (NASS). 2008b. Noncitrus Fruit and Nuts, Final Estimates 2002–2007. *Statistical Bulletin No. 1011*. Verified 16 November 2014. http://usda.mannlib.cornell.edu/usda/nass/SB985/sb1011.pdf.
USDA National Agricultural Statistics Service (NASS). 2009. 2007 Census of Agriculture, Desktop Data Query Tool 1.02. Verified 16 November 2014. http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Desktop_Application/.
USDA National Agricultural Statistics Service (NASS). 2010a. Agricultural Statistics 2010. Washington, D.C.: Government Printing Office. Verified 16 November 2014. http://www.nass.usda.gov/Publications/Ag_Statistics/2010/2010.pdf.
USDA National Agricultural Statistics Service (NASS). 2010b. Citrus Fruit 2010 Summary. Verified 14 November 2014. http://usda.mannlib.cornell.edu/usda/nass/CitrFrui//2010s/2010/CitrFrui-09-23-2010.pdf.
USDA National Agricultural Statistics Service (NASS). 2011. Noncitrus Fruit and Nuts, 2010 Summary. Verified 16 November 2014. http://usda.mannlib.cornell.edu/usda/nass/NoncFruiNu//2010s/2011/NoncFruiNu-07-07-2011.pdf.
USDA National Agricultural Statistics Service (NASS). 2014. Quick Stats database [on-line]. Accessed September 2011. Verified 14 November 2014. http://quickstats.nass.usda.gov/.
USDA National Agricultural Statistics Service - California Field Office (NASS-CA). 2011. California Agricultural Statistics, 2010 Crop Year. Sacramento, California. Verified 16 November 2014. http://www.nass.usda.gov/Statistics_by_State/California/Publications/California_Ag_Statistics/Reports/2010cas-all.pdf.
USDA Natural Resources Conservation Service. 2013. Part 622 – Interpretive Groups. *National Soil Survey Handbook*. Verified 11 March 2016. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_054242.
Valin H, Sands RD, van der Mensbrugghe D, Nelson GC, Ahammad H, et al. 2014. The future of food demand: Understanding differences in global economic models. *Agr Econ* **45**: 51–67.
van Dooren C, Marinussen M, Blonk H, Aiking H, Vellinga P. 2014. Exploring dietary guidelines based on ecological and nutritional values: A comparison of six dietary patterns. *Food Policy* **44**: 36–46.
van Tongeren F, van Meijl H, Surry Y. 2001. Global models applied to agricultural and trade policies: A review and assessment. *Agr Ecoomics* **26**: 149–172.
Welch RM, Graham RD. 1999. A new paradigm for world agriculture: Meeting human needs. *Field Crops Res* **60**: 1–10.
Wirsenius S, Azar C, Berndes G. 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agr Syst* **103**: 621–638.
Young CE, Kantor LS. 1999. Moving toward the Food Guide Pyramid: Implications for US agriculture. *America's Eating Habits: Changes and Consequences. USDA Economic Research Service Agriculture Information Bulletin No. 750.* Washington, DC: US Government Printing Office. p. 403–423. Frazao E, ed. Verified 16 November 2014. http://www.ers.usda.gov/media/91096/aib750t_1_.pdf.

Contributions

- Design of the US Foodprint model was led by CP.
- Suggestions to model design were made by AD, TG, and JP.
- Primary responsibility for collecting data to parameterize the model was born by AD and JP.
- Design of the scenarios was led by CP with input from GF and JW, who worked with CP on an earlier version of the model, and from TG, who worked on a related analysis of livestock feed requirements.
- Writing of the manuscript and preparation of tables and figures was led by CP.
- All co-authors (AD, GF, TG, JP, and JW) read and commented on the manuscript, making suggestions on how to condense the narrative, clarify writing, frame the analysis, and interpret findings.

Acknowledgments

We thank the editors and anonymous reviewers for the time and effort they invested in reading and critiquing the original manuscript and for their insightful and constructive feedback.

Funding information

This research was supported in part by funding from the W.K. Kellogg Foundation, grant number P3008987.

Competing interests

The authors have no competing interests to declare.

Supplemental material

- **Table S1. Grazed forage yields on cropland pasture and other grazing lands (DOC)**
  doi: 10.12952/journal.elementa.s001
- **Table S2. Processing conversion parameter estimates obtained from non-standard sources (DOC)**
  doi: 10.12952/journal.elementa.000116.s002
- **Text S1. Data sources, assumptions, supporting calculations, and structure of the U.S. Foodprint model.**
  This supplemental material includes additional detail on certain calculations performed in the Methods and on the structure of the U.S. Foodprint model. Text S1 is organized in three main sections, "Data sources and assumptions," "Supporting calculations," and "Model structure." The supporting calculations section includes five subsections: disaggregation of fats, processing conversions for dairy products, grazing yields, land use adjustments, and land availability calculations. The model structure section describes the accompanying dataset.
  doi: 10.12952/journal.elementa.000116.s003
- **Dataset S1. U.S. Foodprint model**
  The U.S. Foodprint Model is the spreadsheet model used to estimate the land requirements and carrying capacity of all diet scenarios evaluated in the study.
  doi: 10.12952/journal.elementa.000116.s004

Data accessibility statement

U.S. Foodprint Model: uploaded as supporting information as a self-contained spreadsheet (.xlsx file)