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Comparing the water, energy, pesticide and fertilizer usage for the production of foods consumed by different dietary types in California

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Abstract

Objective: To compare the use of water, energy, pesticides and fertilizer to produce commodities for two dietary patterns that vary in the content of plant and animal products.
Design: A unique analysis using 'real-world' data was performed, in contrast to previous analyses which applied simulated data. Consumption data from the Adventist Health Study were used to identify two dietary patterns with a markedly different consumption of several plant and animal products. State agricultural data were collected and applied to commodity production statistics. Indices were created to allow a comparison of the resource requirements for each dietary pattern.
Setting: California, USA.
Subjects: None.
Results: The diet containing more animal products required an additional 10 252 litres of water, 9910 kJ of energy, 186 g of fertilizer and 6 g of pesticides per week in comparison to the diet containing less animal products. The greatest contribution to the difference came from the consumption of animal products, particularly beef.
Conclusions: Consuming a more plant-based diet could to an extent alleviate the negative environmental impacts related to food production. As a method to feed ourselves more sustainably, behavioural adjustments appear to be a very important tool.

Keywords
Food production
Sustainable dietary patterns

There is a direct link between dietary preference, agricultural production, resource use and environmental degradation(1–3). At the global level, agriculture accounts for 70 % of water withdrawals; in North America this figure is 38 %(4). Critical water issues exacerbated by agricultural practices include pollution of surface- and groundwater sources, over-drafting of aquifers and salinization of soils(5,6). Globally, agriculture is within the highest energy-use category(7). In the USA, food-related energy use increased from 14 % of the national energy budget in 2002 to an estimated 16 % in 2007(8), of which agricultural production is estimated to account for 14·4 %(8). Environmental impacts associated with the use of fossil fuels include acid rain, air pollution, soil and water contamination and greenhouse gas emissions. About 3 million tonnes of pesticides are applied globally every year(9), containing approximately 1600 different chemicals, with a lack of complete toxicity data(10). The environmental consequences of pesticide use include residues on food(11), surface- and groundwater contamination(12), persistence in the environment(13), damage to non-targeted species and increased resistance in pests(14,15). Global fertilizer use was about 180 million tonnes in 2012, with the USA consuming about 20 million tonnes per annum, and is forecast to increase(16). It is estimated that only about 30–50 % of the N from fertilizer application is absorbed, with the remainder entering the environment and causing numerous problems such as surface- and groundwater contamination, salinification of soils, oceanic 'dead zones', a decrease in plant species and a reduced production of biomass(10,17,18).

Food production faces serious challenges, exacerbated by a changing climate and future growth in urbanization,

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industrialization and population(19). Therefore, considered together with the need to generate fewer overall environmental impacts, a more efficient use of resources for food production is crucial(20). The production of animal products generally requires more resources and results in greater environmental degradation in comparison to plant foods, hence dietary choices have a very determining impact(21–23). While technological options offer scope for increasing the sustainability of food production, it is improbable for technology alone to deliver sufficient changes(24–26). Thus, adopting diets with a lower environmental footprint through behavioural modification is essential(24,27,28).

The research reported here aimed to explore the scope of impacts that behaviour change at the consumer level could offer by comparing the use of water, energy, pesticides and fertilizer to produce commodities for two different diets varying in the content of plant and animal products. Unlike previous analyses which have utilized simulated data(2,21,29), the present research takes a novel approach through the use of original, 'real-world', non-simulated data sets. To our knowledge, the present analysis is also the first to simultaneously quantify energy, water, pesticides and fertilizer usage for a range of food groups.

Experimental methods

Estimating the water, energy, fertilizer and pesticides used for each dietary type involved a synthesis of 'real-world' empirical data. The analysis involved a number of stages which are detailed in the following sections.

Deriving dietary consumption

The dietary data resulted from responses to a lifestyle and dietary questionnaire administered in the Adventist Health Study 1 (AHS1) cohort, which captured a sample of 34 198 individuals of whom about 50 % consumed relatively small amounts of animal products. Details regarding the AHS1 methodology have been published elsewhere and will therefore not be repeated here. The study population has a variety of dietary patterns and has been identified as a low-risk group regarding the incidence of chronic disease(30,31).

The AHS1 food survey data allowed for the identification of two dietary groups based on their consumption of meat (beef and poultry), defined as lower animal products (LAP) and higher animal products (HAP). The LAP group included all respondents who ate less than one serving of meat per week and the HAP group included all respondents who ate one or more servings of meat per week.

The AHS1 food survey data provided consumption frequencies and amounts for fifty foods. Given the wide diversity of ingredients in terms of geographic origin, complex/processed products such as doughnuts and beverages were removed as they were beyond the scope of the available commodity statistics, leaving thirty-one foods. This was further reduced to twenty-two by testing the statistical significance of differences between the number of servings for the LAP and HAP groups. Where the difference in the number of servings was less than 0·25 per week, such food items were also removed from the analysis, leaving twelve foods. The inclusion of fish was beyond the scope of the research given the lack of availability of commodity statistics. Hence, a total of eleven food groups were included in the analysis: dry fruit, canned fruit, winter fruit, seasonal fruit, citrus fruit, fruit juice, nuts, beans, eggs, chicken and beef. Weekly consumption quantities were calculated using portion size data from the Special Nutrition Sub-Study of the AHS1(32), with each food weighted according to the gender and age distribution of the AHS1 sample(33). Table 1 shows a comparison of weekly consumption across the eleven food groups and two dietary patterns.

Table 1 Food groups, food items, production commodities, and production and consumption weights for each dietary group

			Consumption (g/week)			Production (g/week)	
Food group	Representative food item	Production commodity	LAP diet group	HAP diet group	Conversion factor*	LAP diet group	HAP diet group
Eggs	Eggs	Eggs	60·24	137·51	1·68	101·20	231·02
Chicken	Chicken	Chicken	3·60	89·13	2·33	8·39	207·67
Beef	Beef	Beef	10·30	330·05	3·87	39·86	1277·29
Canned fruit	Peaches	Peaches	331·79	185·13	1·28	424·65	236·97
Winter fruit	Apples	Apples	641·67	454·62	1·26	808·50	572·82
Seasonal fruit	Watermelon	Watermelon	433·82	275·95	2·57	1114·92	708·21
Citrus fruit	Oranges	Oranges	366·21	227·57	1·60	585·94	364·11
Fruit juice	Orange juice	Oranges	714·85	732·84	2·03	1451·15	1487·67
Nuts	Almonds	Almonds	65·57	27·72	1·00	65·57	27·72
Dry fruit	Raisins	Grapes	87·78	90·25	5·19	455·58	468·40
Beans	Dried beans	Dried kidney beans	257·13	168·80	0·38	97·71	64·14

*The conversion factor transforms food consumption weights back to food production weights. Weight changes from the farm gate to the consumer's plate were included, taking into account inedible yield, waste and cooking(93,94).

Calculating environmental production costs of the eleven food items

The geographical remit for food production was limited to California given this was the area of residence of the AHS1 respondents and also in consideration of the relatively higher reliance on local produce when the consumption data were collected during the mid-1980s. In addition, California is one of the most productive states in the USA in terms of food provision.

For consistency with the time period during which the food consumption data were collected, the US Department of Agriculture Food Consumption, Prices, and Expenditures 1970–97(34) were used to identify representative food items (defined as the most frequently consumed food item from each of the eleven food groups; see Table 1). The items included were raisins, canned peaches, apples, watermelon, oranges, orange juice, almonds, dried beans, eggs, chicken and beef. Items not produced in California in any appreciable quantity were not included (for example, bananas). To calculate the environmental costs relating to production, the food consumed was converted to production weights (see Table 1 for production weights and conversion factors). The 1997 Census of Agriculture was the key source of agricultural production statistics(35). Data from the 1997 Agricultural Commissioners' Data(36) were used for production statistics for eggs. Grape production statistics were used to represent raisins. Primary data collected by other researchers were analysed and used in conjunction with the analysis of other data to produce values that were used to reliably calculate inputs of water, primary energy, fertilizer and pesticides.

Water use

Water consumption data for the production of almonds, apples, dried beans, grapes, oranges, peaches and watermelon were obtained from Cost and Return Studies (CRS) published by the University of California Cooperative Extension Service and the University of California Davis Department of Agriculture and Resource Economics(37–49).

For beef products, the water consumed by the animals (obtained from the National Academy of Science(50)) and used in the production of their feed was accounted for. Approximate daily water intakes were 66 litres for a 454 kg nursing cow; 41 litres for a pregnant wintering cow; 22 litres for a 182 kg calf; 32 litres for a 273 kg stocker; and 48 litres for a 409 kg finishing steer. An average consumption was derived by summing the requirements for each class of cattle (25 468·80 litres) and dividing by the total weight of beef produced (477·27 kg), giving a ratio of 53·36 litres/kg beef produced. Data for the production of alfalfa(51,52) and maize(53,54) used for animal feed were obtained from CRS and were added to the direct water used by the animals using a net feed consumption rate of 5·62 kg maize/kg beef and 2·66 kg alfalfa/kg beef. A feed conversion efficiency of 7·0 was assumed(10). Soya in the feed formulations for beef and poultry was excluded.

Water consumed directly by chickens grown for meat consumption is generally about twice the weight of their feed(55–57). Temperature, relative humidity, age of birds and type of watering system are also important(55,57). An estimated consumption of 0·23 kg/bird per d gives an average direct consumption of 227·12 litres water/1000 birds per d(55–57). An estimated indirect use of 227·12 litres water/1000 birds per d relating to the production facility (evaporative cooling, facility sanitation and fire protection) was included(55), giving a total of 454 litres water/1000 birds per d. The production of a 2·27 kg chicken in 49 d would require approximately 22·0 litres, therefore approximately 9·69 litres of water is required per kilogram of live weight chicken produced.

For egg production, the same average water use was assumed (227·12 litres/1000 birds per d) for direct consumption and 238·48 litres/1000 birds per d for indirect consumption (including egg washing)(55–57), giving a total water consumption of 465·60 litres/1000 birds per d. Assuming average figures (80·6 % hen-day egg production rate and a weight of 60·4 g/egg), each hen produces 48·7 g egg/d(55). Therefore, each kilogram of eggs produced requires approximately 9·65 litres of water. Table 2 shows water use data involved in the production of each food item.

Energy use

Data for the production of almonds, apples, dried beans, grapes, oranges, peaches and watermelon were obtained from CRS. Original data were reported for gasoline and diesel fuel in gallons per acre and were converted to units of joules of energy used per kilogram of commodity produced using an energy value of 34 828 427 J/litre for gasoline and 38 657 950 J/litre for diesel fuel(58). Data for the production of alfalfa and maize used for animal feed were obtained from CRS. Table 2 shows energy use data for each food item.

Fertilizer use

Average application rates for each crop produced in California were obtained from the US Department of Agriculture's *Agricultural Chemical Usage, 1999 Fruit and Nut Summary*(59) for the production of almonds, apples, grapes, oranges and peaches, and from the US Department of Agriculture's *Agricultural Chemical Usage, 1998 Vegetable Summary*(60) for beans and watermelon. Data for the production of alfalfa and maize used for animal feed were obtained from CRS. N, P and K were combined to give a value for total fertilizer input. Table 2 shows fertilizer use data for each food item.

Pesticide use

The *Summary of Pesticide Use Report Data 1997* from the California Environmental Protection Agency provided pesticide use data for almonds, apples, dried beans, grapes, oranges, peaches, watermelon, and alfalfa and

Table 2 Primary inputs and use efficiencies for each food

		Water		Energy		Fertilizer		Pesticides*	
Food item	Yield (kg/ha)	Irrigation rate (litres/ha)†	Use efficiency (litres/kg)	Supply (MJ/ha)	Use efficiency (kJ/kg)	Application rate (kg/ha)	Use efficiency (g/kg)	Application rate (kg/ha)	Use efficiency (g/kg)
Eggs			1388·10‡		2802·94‖		32·95††		1·59‖‖,¶¶
Chicken			1388·14‡		2802·94¶		32·95‡‡		1·59‖‖,¶¶
Beef			8291·40§		7880·94**		147·92§§		7·07‖‖,***
Peaches	33 998·70	10 968 121·45	322·74	11 701·95	344·19	119·06	3·50	85·69	2·52‖‖
Apples	67 250·91	9 140 101·62	135·97	21 029·77	312·71	60·65	0·90	116·12	1·73‖‖
Watermelon	56 042·43	9 140 101·62	163·16	39 804·98	710·27	206·67	3·69	16·65	0·30‖‖
Oranges	22 990·84	8 226 090·47	357·95	11 409·27	496·25	121·31	5·28	219·40	9·54‖‖
Almonds	2241·70	10 968 121·45	4894·86	10 417·07	4646·33	201·05	89·68	48·91	21·81‖‖
Grapes	4483·39	10 663 449·42	2379·44	8947·51	1995·88	93·23	20·79	15·22	3·40‖‖
Dried beans	2652·71	6 702 740·2	2527·82	7592·24	2861·76	103·33	38·95	5·75	2·17‖‖

*Pesticides listed by the State of California Environmental Protection Agency, Department of Pesticide Regulation as of special concern.

†Calculated by taking the annual acre-footage (acft) applied times 1 233 482 litres/acft.

‡Water use calculated by adding the product of maize water use (136·08 litres/kg) times net feed ratio of 1·37 kg/kg broiler or egg produced and direct consumption for broiler and egg production (9·69 and 9·65 litres/kg, respectively).

§Water use calculated by adding the product of maize water use (136·08 litres/kg) times net feed ratio of 5·62 kg maize/kg beef produced and the product of alfalfa water use (131·35 litres/kg) times net feed ratio of 2·66 kg alfalfa/kg beef produced and direct consumption for beef (53·361 litres/kg).

‖Energy supplied in joules per litre of gasoline is 34 828 427 and per litre of diesel is 38 657 950.

¶Energy use calculated by adding the product of maize energy use (875 691 J/kg) times net feed ratio of 1·37 kg/kg broiler or egg produced and direct consumption for broiler and egg production (1 603 246 J/kg).

**Energy use calculated by adding the product of maize energy use (875 691 J/kg) times net feed ratio of 5·62 kg maize/kg beef produced and the product of alfalfa water use (624 031 J/kg) times net feed ratio of 2·66 kg alfalfa/kg beef produced and direct expenditure for beef (1 299 636 J/kg).

††Fertilizer rate standardized by the percentage acreage applied because not all acres received fertilizer.

‡‡Fertilizer use calculated by adding the product of maize fertilizer use (N 0·024, P 0, K 0 kg/ha) times net feed ratio of 1·37 kg/kg broiler or egg produced.

§§Fertilizer use calculated by adding the product of maize fertilizer use (N 0·024, P 0, K 0 kg/ha) multiplied net feed ratio of 5·62 kg maize/kg beef produced and the product of alfalfa fertilizer use (N 0, P 0, K 0·0048 kg/ha) multiplied by net feed ratio of 2·66 kg alfalfa/kg beef produced.

‖‖Average of the data points.

¶¶Pesticide use calculated by averaging the product of maize pesticide yield ratio (F 0·0018, K 0·0014, SJ 0·00030) times net feed ratio of 1·37 kg/kg broiler or egg produced.

***Pesticide use calculated by the product of the average maize pesticide yield ratio (F 0·0018, K 0·0014, SJ 0·00030) times net feed ratio of 5·62 kg maize/kg beef produced and the product of the average alfalfa pesticide yield ratio (F 0·00037, K 0·000061, SJ 0·00018) times net feed ratio of 2·66 kg alfalfa/kg beef produced.

maize (used for animal feed)(61). The use of listed pesticides (special concern due to environmental contamination and risk to human health) in California was available and therefore utilized. Pesticides applied to chickens for egg and meat production (Don Bell, personal communication) and beef(62) were considered inconsequential due to the limited quantities of listed pesticides applied per unit produced. Table 2 shows the total quantity of listed pesticides applied for each food item (the reported weight represents the weight of an active ingredient applied).

Results

Efficiency rates, described as input requirements per unit of crop yield(63), were derived for water, energy, fertilizer and pesticides by dividing the amount applied per hectare by the yield per hectare (see Table 2). The results show a range of water-use efficiencies with beef having the least efficient use rate across all food items. From the plant food items, almonds had the least efficient water use rate; however, they were still about 1·5 times more efficient than beef. Beef also had the least efficient energy and fertilizer use. Almonds had the least efficient pesticide use, followed by beef which was about three times more efficient.

Comparing the diets

Table 3 shows the input requirements to produce each food item for each dietary pattern. Cumulatively, the HAP diet required 13 545 litres of water, 14 226 kJ of energy, 232 g of fertilizer and 32 g of pesticides and the LAP diet required 3293 litres of water, 4317 kJ of energy, 46 g of fertilizer and 26 g of pesticides per week. In relation to the absolute difference between the dietary patterns, the LAP diet required the application of approximately 4·1 times less water, 3·3 times less energy, 5·1 times less fertilizer and 1·2 times less pesticides compared with the HAP diet. The greatest contribution to the difference came from the higher consumption of animal products (beef, chicken and eggs) in the HAP diet.

Discussion

The present findings demonstrate that the production of a diet relatively higher in animal products requires significantly greater amounts of water, energy, fertilizer and pesticides than a diet containing lower amounts of animal products. The analysis focused on the absolute difference between two dietary patterns based on eleven food groups, using geographically and temporally specific food

Table 3 Requirement of primary inputs to produce each dietary type and food item

Food item	Dietary group*	Water (litres/week)	Energy (kJ/week)	Fertilizer (g/week)	Pesticides (g/week)
Eggs	LAP	140·49	283·67	3·33	0·16
	HAP	320·70	647·53	7·61	0·37
Chicken	LAP	11·64	23·51	0·28	0·01
	HAP	288·29	582·09	6·84	0·33
Beef	LAP	330·50	314·14	5·90	0·28
	HAP	10 590·55	10 066·27	188·94	9·03
Peaches	LAP	137·05	146·16	1·49	1·07
	HAP	76·48	81·56	0·83	0·60
Apples	LAP	109·93	252·83	0·73	1·40
	HAP	77·89	179·13	0·52	0·99
Watermelon	LAP	181·91	791·89	4·11	0·33
	HAP	115·55	503·02	2·61	0·21
Oranges†	LAP	729·17	1010·90	10·76	19·43
	HAP	662·84	918·94	9·78	17·67
Almonds	LAP	320·96	304·66	5·88	1·43
	HAP	135·69	128·80	2·49	0·60
Raisins	LAP	1084·02	909·28	9·47	1·55
	HAP	1114·52	934·87	9·74	1·59
Dried beans	LAP	246·99	279·62	3·81	0·21
	HAP	162·14	183·56	2·50	0·14
Total primary inputs required	LAP	3292·67	4316·66	45·75	25·88
	HAP	13 544·65	14 225·78	231·85	31·53
Difference between the LAP and HAP		10 251·98	9909·11	186·10	5·65

*LAP, lower animal products, HAP, higher animal products.
†Oranges and orange juice are presented together.

production and consumption data. Despite this specificity, the findings are consistent with more recent and geographically diverse analyses that have estimated the resource requirements and/or environmental footprint of food types and/or dietary patterns, in that animal products generally had higher resource requirements compared with plant foods and therefore resulted in greater environmental impacts(2,3,21,23,64–74). Hence, from an environmental sustainability perspective, what a person chooses to eat matters.

When considered over an extended time period the differences in the inputs required to produce the LAP and HAP diets become more pronounced. Over the period of one year, the LAP diet would require 515 273 kJ less energy, 9677 g less fertilizer, 294 g less pesticides and 533 102 litres less water compared with the HAP diet. These results are consistent with those reported elsewhere, for example Horrigan *et al.*(10) and Leitzmann(75). Considered within a wider context of water use, the average daily indoor and outdoor water consumption per person in the USA is 333 litres(76). Therefore, per day, the LAP diet conserves the equivalent water usage for just over four people in comparison to the HAP diet.

The potential savings could be much more substantial when considered in the national context. In comparison to the average consumption of animal products in North America (using consumption data for 1985), the LAP and HAP diets contained about 98 % and 50 % less beef, 99 % and 80 % less chicken, and 75 % and 45 % less eggs, respectively(34). There is potential to attain further savings by reducing the animal product content towards 100 % plant-based or vegan diets, which have been estimated to incur less greenhouse gas emissions than diets including animal products(2,68).

Implications on environmental factors

Rockstrom *et al.*(77) identify industrialized agriculture as a key contributor to exceeding three of the eight measured planetary sub-systems (climate change, biodiversity and the N cycle). The production of animal products has been identified as a key component to exacerbating nutrient losses, pollution levels and land degradation, while further threatening the quality of water, air and soils, and affecting climate and biodiversity(6,17,22,66,78,79). In addition, livestock production accounts for 70 % of agricultural land use and occupies 30 % of the global land surface(80). Hence, given their large contribution to the agricultural sector, reducing the consumption of animal products has substantial implications when considered within a broad environmental sustainability context and also in terms of resource security and scarcity, including water, land, energy and food.

Implications on public health

Reducing the consumption of animal products offers substantial health benefits. Meat-based diets are intrinsically linked to poor health outcomes(81–86), while plant-based diets have positive impacts on human health and life expectancy(31,74,87–91). The negative health impacts associated with intensive animal farming, such as zoonotic diseases, could also be reduced. In addition, the reduced exposure to environmental contaminants would provide health benefits.

Future research

The scope of the research could be extended beyond food production to include inputs for the entire life cycle, including land, and outputs, such as greenhouse gas emissions. The geographical study area could be extended to allow the inclusion of more food items, such as complex products, and soyabeans used in the diets and for animal feed. A detailed analysis of varying dietary types, to include those which contain no animal products for comparison, would help to elucidate patterns in terms of resource requirements. The AHS1 sample had favourable health outcomes in comparison to the general population; therefore the use of a sample with different health characteristics could require more attention on the nutritional aspects of the diet(s). Due to the time of data collection, the AHS1 data may not represent current consumption patterns and hence use of current consumption data may show differences. To maximize the value of future research, a comprehensive approach including all relevant impacts and being inclusive of the full range of environmental, ethical, health, social and economic aspects would be most valuable.

Conclusions

The present unique analysis synthesized 'real-world' empirical data, which served to ground-truth previous analyses based on simulated data. Using dietary patterns that are considered to be nutritionally adequate, the results showed a clear relationship between dietary consumption and the expenditure of resources relating to production: the low animal product (LAP) diet required significantly less inputs to produce than the high animal product (HAP) diet. The amount of animal products in the diet, particularly beef, was the most significant contributor to the requirement for higher inputs. The results demonstrate that as a method for reducing resource requirements for food production or feeding ourselves more efficiently, dietary changes offer substantial scope. More specifically, and in line with other analyses(17,21,24,68,74,78,92), the findings suggest that eating more plant foods and less animal products would increase the environmental sustainability of food production.

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References

1. Garnett T (2013) Food sustainability: problems, perspectives and solutions. *Proc Nutr Soc* **72**, 29–39.
2. Berners-Lee M, Hoolohan C, Cammack H *et al.* (2012) The relative greenhouse gas impacts of realistic dietary choices. *Energy Policy* **43**, 184–190.
3. Heller MC & Keoleian GA (2014) Greenhouse gas emission estimates of US dietary choices and food loss. *J Ind Ecol* (In the Press).
4. Food and Agriculture Organization of the United Nations (2010) Water withdrawal by sector. AQUASTAT database. http://www.fao.org/nr/aquastat (accessed November 2013).
5. Tanji KK & Enos CA (1994) Global water resources and agricultural use. In *Management of Water Use in Agriculture*, pp. 3–24 [KK Tanji and B Yaron, editors]. Berlin: Springer-Verlag.
6. Sutton MA, Bleeker A, Howard CM *et al.* (2013) *Our Nutrient World: The Challenge to Produce More Food and Energy with Less Pollution. Global Overview of Nutrient Management*. Edinburgh: Centre for Ecology and Hydrology, on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative.
7. International Energy Agency (2012) *Key World Energy Statistics 2012*. Paris: IEA.
8. Canning P, Charles A, Huang S *et al.* (2010) *Energy Use in the US Food System. Economic Research Report* no. ERR-94. Washington, DC: USDA/Economic Research Service.
9. US Environmental Protection Agency (2013) 2006–2007 Pesticide Market Estimates: Usage. http://www.epa.gov/opp00001/pestsales/07pestsales/usage2007.htm (accessed October 2014).
10. Horrigan L, Lawrence RS & Walker P (2002) How sustainable agriculture can address the environmental and human health harms of industrial agriculture. *Environ Health Perspect* **110**, 445–456.
11. Crépet A, Tressou J, Graillot V *et al.* (2013) Identification of the main pesticide residue mixtures to which the French population is exposed. *Environ Res* **126**, 125–133.
12. Barcelona MJ & Robbins GA (2003) Soil and groundwater pollution. In *Encyclopedia of Physical Science and Technology*, 3rd ed., pp. 49–62 [RA Meyers, editor]. New York: Academic Press.
13. Mahugija JAM, Henkelmann B & Schramm K-W (2014) Levels, compositions and distributions of organochlorine pesticide residues in soil 5–14 years after clean-up of former storage sites in Tanzania. *Chemosphere* **117**, 330–337.
14. Király Z (1996) Sustainable agriculture and the use of pesticides. *J Environ Sci Health, Part B* **31**, 283–291.
15. Levitan L, Merwin I & Kovach J (1995) Assessing the relative environmental impacts of agricultural pesticides: the quest for a holistic method. *Agric Ecosyst Environ* **55**, 153–168.
16. Food and Agriculture Organization of the United Nations (2011) *Current World Fertilizer Trends and Outlook to 2015*. Rome: FAO; available at ftp://ftp.fao.org/ag/agp/docs/cwfto15.pdf
17. Eshel G & Martin PA (2009) Geophysics and nutritional science: toward a novel, unified paradigm. *Am J Clin Nutr* **89**, issue 5, 1710S–1716S.
18. Erisman JW, Galloway JN, Seitzinger S *et al.* (2013) Consequences of human modification of the global nitrogen cycle. *Philos Trans R Soc B Biol Sci* **368**, 20130116.

19. Foley JA, Ramankutty N, Brauman KA *et al.* (2011) Solutions for a cultivated planet. *Nature* **478**, 337–342.
20. van der Werf HMG, Garnett T, Corson MS *et al.* (2014) Towards eco-efficient agriculture and food systems: theory, praxis and future challenges. *J Cleaner Prod* **73**, 1–9.
21. van Dooren C, Marinussen M, Blonk H *et al.* (2014) Exploring dietary guidelines based on ecological and nutritional values: a comparison of six dietary patterns. *Food Policy* **44**, 36–46.
22. Eshel G, Shepon A, Makov T *et al.* (2014) Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. *Proc Natl Acad Sci U S A* **111**, 11996–12001.
23. Masset G, Vieux F, Verger EO *et al.* (2014) Reducing energy intake and energy density for a sustainable diet: a study based on self-selected diets in French adults. *Am J Clin Nutr* **99**, 1460–1469.
24. Garnett T (2011) Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Policy* **36**, Suppl. 1, S23–S32.
25. McMichael AJ, Powles JW, Butler CD *et al.* (2007) Food, livestock production, energy, climate change, and health. *Lancet* **370**, 1253–1263.
26. Popp A, Lotze-Campen H & Bodirsky B (2010) Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production. *Global Environ Change* **20**, 451–462.
27. Sabate J & Soret S (2014) Sustainability of plant-based diets: back to the future. *Am J Clin Nutr* **100**, Suppl. 1, 476S–482S.
28. Bajzelj B, Richards KS, Allwood JM *et al.* (2014) Importance of food-demand management for climate mitigation. *Nat Clim Chang* **4**, 924–929.
29. Carlsson-Kanyama A & Gonzalez AD (2009) Potential contributions of food consumption patterns to climate change. *Am J Clin Nutr* **89**, issue 5, 1704S–1709S.
30. Beeson WL, Mills PK, Phillips RL *et al.* (1989) Chronic disease among Seventh-day Adventists, a low-risk group. Rationale, methodology, and description of the population. *Cancer* **64**, 570–581.
31. Fraser GE (2009) Vegetarian diets: what do we know of their effects on common chronic diseases? *Am J Clin Nutr* **89**, issue 5, 1607S–1612S.
32. Fraser GE, Lindsted KD, Knutsen SF *et al.* (1998) Validity of dietary recall over 20 years among California Seventh-day Adventists. *Am J Epidemiol* **148**, 810–818.
33. Marlow H (2006) The environmental impact of dietary choice and agriculture in California. PhD Thesis, Loma Linda University.
34. Putnam J & Allshouse J (1999) *Food Consumption, Prices, and Expenditures, 1970–97. Statistical Bulletin* no. SB-965. Washington, DC: USDA/Economic Research Service.
35. US National Agricultural Statistics Service (1999) *1997 Census of Agriculture*. Washington, DC: USDA/National Agricultural Statistics Service.
36. California Agricultural Statistics Service (1998) *1997 Agricultural Commissioners' Data*. Sacramento, CA: USDA/National Agricultural Statistics Service and State of California, Department of Food and Agriculture, Agricultural Statistics Branch.
37. Caprile J, Grant J, Holtz B *et al.* (2001) *Sample Costs to Establish an Apple Orchard and Produce Apples*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
38. Day K, Andris H, Beede R *et al.* (2000) *Sample Costs to Establish a Peach/Nectarine Orchard and Produce Peaches/Nectarines*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
39. Frate C, Klonsky K & DeMoura R (2001) *Sample Costs to Produce Blackeye Beans, Double Cropped*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
40. Frate C, Klonsky K & DeMoura R (2001) *Sample Costs to Produce Blackeye Beans, Single Cropped*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
41. Hendricks L, Duncan R, Vcrdegaal P *et al.* (1998) *Sample to Establish an Almond Orchard and Produce Almonds Northern San Joaquin Valley, Flood Irrigation*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
42. Klonsky K, Christensen P, Costello M *et al.* (1997) *Sample Costs to Establish a Vineyard and Produce Raisins*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
43. Klonsky K, Freeman M, Sibbett G *et al.* (1997) *Sample to Establish an Almond Orchard and Produce Almonds*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
44. Long R, Munier D, Cahn M *et al.* (1999) *Sample Costs to Produce Beans*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
45. Mayberry K (2000) *Sample Costs to Establish and Produce Watermelon*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
46. O'Connell K, Klonsky K, Freeman M *et al.* (1999) *Sample Costs to Establish an Orange Orchard and Produce Oranges*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
47. Vasquez S, Leavitt G, Peacock W *et al.* (2003) *Sample Costs to Establish a Vineyard and Produce Dried-on-Vine Raisins*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
48. Frost W, Klonsky K & DeMoura R (2000) *Sample Costs to Produce Fresh Market Peaches*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
49. Hasey J, Duncan R, Sanders H *et al.* (1998) *Sample Costs to Establish a Cling Peach Orchard and Produce Cling Peaches*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
50. National Research Council (2000) *Nutrient Requirements of Beef Cattle*, 7th revised ed. Washington, DC: National Academy Press.
51. Mathews M, Canevari M, Frate C *et al.* (1998) *Sample Costs to Establish an Alfalfa Stand and Produce Alfalfa*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
52. Vargas R, Mueller S, Frate C *et al.* (2003) *Sample Costs to Establish an Alfalfa Stand and Produce Alfalfa*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
53. Vargas R, Frate C, Mathews M *et al.* (1999) *Sample Costs to Produce Field Corn*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.
54. Brittan K, Muiner D, Klonsky K *et al.* (2004) *Sample Costs to Produce Field Corn*. California: University of California Cooperative Extension and UC Davis Department of Agricultural and Resource Economics.

55. Bell D & Weaver W (2002) *Commercial Chicken Meat and Egg Production*. Norwell, MA: Kluwer Academic Publishers.
56. Ensminger M, Oldfield J & Heinemann W (1990) *Feeds and Nutrition*. Clovis, CA: The Ensminger Publishing Co.
57. National Research Council (1994) *Nutrient Requirements of Poultry*, 9th revised ed. Washington, DC: National Academy Press.
58. US Department of Transportation (2006) *National Transportation Statistics 2006*. Washington, DC: US DOT/Bureau of Transportation Statistics.
59. US Department of Agriculture (2000) *Agricultural Chemical Usage, 1999 Fruit and Nut Summary*. Washington, DC: USDA/National Agricultural Statistics Service.
60. US Department of Agriculture (1999) *Agricultural Chemical Usage, 1998 Vegetable Summary*. Washington, DC: USDA/National Agricultural Statistics Service.
61. California Environmental Protection Agency (1999) *Summary of Pesticide Use Report Data 1997, Indexed by Commodity*. Sacramento, CA: CEPA, Department of Pesticide Regulation.
62. US Department of Agriculture (2000) *Agricultural Chemical Usage, 1999 Cattle and Cattle Facilities*. Washington, DC: USDA/National Agricultural Statistics Service.
63. Howell T (2001) Enhancing water use efficiency in irrigated agriculture. *Argon J* **93**, 281–289.
64. Mekonnen M & Hoekstra A (2012) A global assessment of the water footprint of farm animal products. *Ecosystems* **15**, 401–415.
65. Macdiarmid JI, Kyle J, Horgan GW *et al.* (2012) Sustainable diets for the future: can we contribute to reducing greenhouse gas emissions by eating a healthy diet? *Am J Clin Nutr* **96**, 632–639.
66. Stehfest EBL, van Vuuren DP, den Elzen MGJ *et al.* (2009) Climate benefits of changing diet. *Climatic Change* **95**, 83–102.
67. Schmidinger K & Stehfest E (2012) Including CO_2 implications of land occupation in LCAs – method and example for livestock products. *Int J Life Cycle Assess* **17**, 962–972.
68. Scarborough P, Appleby P, Mizdrak A *et al.* (2014) Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. *Climatic Change* **125**, 179–192.
69. Friel S, Barosh LJ & Lawrence M (2014) Towards healthy and sustainable food consumption: an Australian case study. *Public Health Nutr* **17**, 1156–1166.
70. Wilson N, Nghiem N, Ni Mhurchu C *et al.* (2013) Foods and dietary patterns that are healthy, low-cost, and environmentally sustainable: a case study of optimization modeling for New Zealand. *PLoS ONE* **8**, e59648.
71. Meier T & Christen O (2012) Environmental impacts of dietary recommendations and dietary styles: Germany as an example. *Environ Sci Technol* **47**, 877–888.
72. Biesbroek S, Bueno-de-Mesquita HB, Peeters PH *et al.* (2014) Reducing our environmental footprint and improving our health: greenhouse gas emission and land use of usual diet and mortality in EPIC-NL: a prospective cohort study. *Environ Health* **13**, 27.
73. Marlow HJ, Hayes WK, Soret S *et al.* (2009) Diet and the environment: does what you eat matter? *Am J Clin Nutr* **89**, issue 5, 1699S–1703S.
74. Soret S, Mejia A, Batech M *et al.* (2014) Climate change mitigation and health effects of varied dietary patterns in real-life settings throughout North America. *Am J Clin Nutr* **100**, Suppl. 1, 490S–495S.
75. Leitzmann C (2003) Nutrition ecology: the contribution of vegetarian diets. *Am J Clin Nutr* **78**, 3 Suppl., 657S–659S.
76. Maupin MA, Kenny JF, Hutson SS *et al.* (2014) Estimated use of water in the United States in 2010. US Geological Survey Circular 1405. http://pubs.usgs.gov/circ/1405/pdf/circ1405.pdf (accessed December 2014).
77. Rockstrom J, Steffen W, Noone K *et al.* (2009) A safe operating space for humanity. *Nature* **461**, 472–475.
78. Goodland R & Anhang J (2009) *Livestock and Climate Change: What if the Key Actors in Climate Change Are Cows, Pigs, and Chickens?* Washington, DC: World Watch Institute.
79. Sonja J, Vermeulen BMC, John S *et al.* (2012) Climate change and food systems. *Annu Rev Environ Res* **37**, 195–222.
80. Steinfeld HGP (2006) *Livestock's Long Shadow: Environmental Issues and Options*. Rome: FAO.
81. Pan A, Sun Q, Bernstein AM *et al.* (2012) Red meat consumption and mortality: results from 2 prospective cohort studies. *Arch Intern Med* **172**, 555–563.
82. Salehi M, Moradi-Lakeh M, Salehi MH *et al.* (2013) Meat, fish, and esophageal cancer risk: a systematic review and dose–response meta-analysis. *Nutr Rev* **71**, 257–267.
83. Huang W, Han Y, Xu J *et al.* (2013) Red and processed meat intake and risk of esophageal adenocarcinoma: a meta-analysis of observational studies. *Cancer Causes Control* **24**, 193–201.
84. Xu X, Yu E, Gao X *et al.* (2013) Red and processed meat intake and risk of colorectal adenomas: a meta-analysis of observational studies. *Int J Cancer* **132**, 437–448.
85. Micha R, Wallace SK & Mozaffarian D (2010) Red and processed meat consumption and risk of incident coronary heart disease, stroke, and diabetes mellitus: a systematic review and meta-analysis. *Circulation* **121**, 2271–2283.
86. Rohrmann S, Overvad K, Bueno-de-Mesquita HB *et al.* (2013) Meat consumption and mortality – results from the European Prospective Investigation into Cancer and Nutrition. *BMC Med* **11**, 63.
87. Pettersen BJ, Anousheh R, Fan J *et al.* (2012) Vegetarian diets and blood pressure among white subjects: results from the Adventist Health Study-2 (AHS-2). *Public Health Nutr* **15**, 1909–1916.
88. Rizzo NS, Sabate J, Jaceldo-Siegl K *et al.* (2011) Vegetarian dietary patterns are associated with a lower risk of metabolic syndrome: the Adventist Health Study 2. *Diabetes Care* **34**, 1225–1227.
89. Tonstad S, Stewart K, Oda K *et al.* (2013) Vegetarian diets and incidence of diabetes in the Adventist Health Study-2. *Nutr Metab Cardiovasc Dis* **23**, 292–299.
90. Jacobs DR Jr, Haddad EH, Lanou AJ *et al.* (2009) Food, plant food, and vegetarian diets in the US dietary guidelines: conclusions of an expert panel. *Am J Clin Nutr* **89**, issue 5, 1549S–1552S.
91. Sabate J (2003) The contribution of vegetarian diets to health and disease: a paradigm shift? *Am J Clin Nutr* **78**, 3 Suppl., 502S–507S.
92. Vanham D, Hoekstra AY & Bidoglio G (2013) Potential water saving through changes in European diets. *Environ Int* **61**, 45–56.
93. Verheijen L, Wiersema D, Hulshoff Pol L *et al.* (1996) Livestock and the Environment – Finding a Balance. Management of Waste from Animal Product Processing. Coordinated by the FAO, USAID and World Bank. http://www.fao.org/ag/againfo/programmes/en/lead/toolbox/Refer/IACwaste.PDF (accessed September 2011).
94. US Department of Agriculture, Agricultural Research Service. (2011) USDA National Nutrient Database for Standard Reference, Release 24. Nutrient Data Laboratory Home Page. http://www.ars.usda.gov/ba/bhnrc/ndl (accessed September 2011).