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The environmental cost of subsistence: Optimizing diets to minimize footprints

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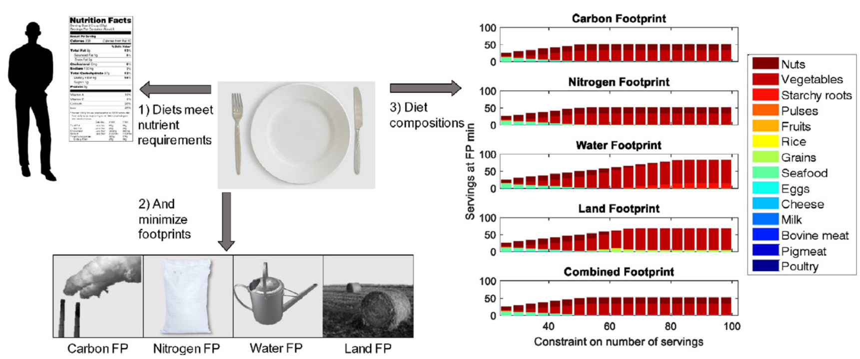
HIGHLIGHTS

- Identifies low footprint (FP) subsistence diets and quantifies FP tradeoffs.
- Synergies among FPs suggested by similar diets at each FP minimum
- Plants and seafood supply macronutrients and micronutrients most efficiently

GRAPHICAL ABSTRACT



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ABSTRACT

The question of how to minimize monetary cost while meeting basic nutrient requirements (a subsistence diet) was posed by George Stigler in 1945. The problem, known as Stigler's diet problem, was famously solved using the simplex algorithm. Today, we are not only concerned with the monetary cost of food, but also the environmental cost. Efforts to quantify environmental impacts led to the development of footprint (FP) indicators. The environmental footprints of food production span multiple dimensions, including greenhouse gas emissions (carbon footprint), nitrogen release (nitrogen footprint), water use (blue and green water footprint) and land use (land footprint), and a diet minimizing one of these impacts could result in higher impacts in another dimension. In this study based on nutritional and population data for the United States, we identify diets that minimize each of these four footprints subject to nutrient constraints. We then calculate tradeoffs by taking the composition of each footprint's minimum diet and calculating the other three footprints. We find that diets for the minimized footprints tend to be similar for the four footprints, suggesting there are generally synergies, rather than tradeoffs, among low footprint diets. Plant-based food and seafood (fish and other aquatic foods) commonly appear in minimized diets and tend to most efficiently supply macronutrients and micronutrients, respectively. Livestock products rarely appear in minimized diets, suggesting these foods tend to be less efficient from an environmental perspective, even when nutrient content is considered. The results' emphasis on seafood is complicated by the environmental impacts of aquaculture versus capture fisheries, increasing in aquaculture, and shifting compositions of aquaculture feeds. While this analysis does not make specific diet recommendations, our approach demonstrates potential environmental synergies of plant- and seafood-based diets. As a result, this study provides a useful tool for decision-makers in linking human nutrition and environmental impacts.

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1. Introduction

In 1945 economist George Stigler published on the minimal cost diet that meets basic nutritional requirements (Stigler, 1945). Since no technique existed to solve for the true minimum, he invented a method to find a diet whose cost could not be substantially reduced. The diet consisted of wheat flour, evaporated milk, cabbage, spinach and dried navy beans, at a cost $39.93 per year (in 1939 prices). In 1947 the newly-developed simplex algorithm for solving linear programming problems was tested on Stigler's "diet problem" and found the true minimum to be only 24 cents less than Stigler's calculation (Dantzig, 1990).

While the question of how to provide low cost nutrition is still relevant, there is an additional question of how to produce food with low environmental costs. As global food production has increased to keep up with population growth and changing diet preferences, greenhouse gas emissions, nutrient pollution, water use, and land use have all increased. Globally, 15% of greenhouse gas emissions from human activities is related to food production (Olivier et al., 2005). Fertilizer application has improved yields, but also releases nutrients into waterways, groundwater, and the atmosphere, leading to water acidification, eutrophication, climate change, and biodiversity loss (Galloway et al., 2003; Erisman et al. 2013). Over 80% of freshwater use is allocated to food production (Carr et al., 2013). Land conversion for agricultural production further increases biodiversity loss, nutrient runoff, and soil erosion (Turner et al., 2007; Lambin and Meyfroidt, 2011).

Concerns over the environmental effects of food production have led to studies measuring the impacts and the development of footprint (FP) indicators, including the carbon, nitrogen, water, and land footprints. However, these footprints focus on single environmental impacts. Indicators that do include multiple impacts, such as the ecological footprint, convert all impacts into a single unit (land units in the case of the ecological footprint). This has prompted attempts to consider multiple indicators simultaneously (Galli et al., 2012; Leach et al., in revision). For example, Galli et al. (2012) present the "Footprint Family" and advocate for simultaneous consideration of carbon, water, and ecological footprints by policymakers.

Focusing on a single footprint ignores potential tradeoffs among the different impacts. Accounting for tradeoffs is important because policies incentivizing decreases in one footprint may inadvertently increase another footprint. However, focusing on multiple impacts simultaneously can lead to confusion and may not take advantage of synergies. For example, since every footprint indicator shows a large environmental impact for beef production (Leach et al., in revision), all four environmental footprints considered can be improved by consuming less beef.

Further, environmental impacts cannot be evaluated in isolation from their nutritional value. A diet consisting exclusively of a single product that has the lowest footprint would not meet basic nutritional needs. As a result, the question of how to minimize a given footprint while meeting a set of nutritional requirements can be answered using the solution to an old problem in a new way. In order to evaluate potential tradeoffs and synergies in footprints within a diet, we modified Stigler's "diet problem" to calculate the diet that minimizes each of the carbon, nitrogen, water, and land footprints in the United States. We use this method to assess which products tend to appear in minimized diets. Tradeoffs are then quantified by taking the composition of each footprint's minimum diet and calculating the other three footprints. In this way, we can quantify the increase in a footprint by moving from the diet at one footprint's minimum to the diet at another. Through our approach, we provide a quantitative tool for integrating nutritional requirements with environmental impacts.

2. Methods

2.1. Data

Food products were selected and grouped based on the USDA Dietary Guidelines (2010) and the more detailed Harvard University Healthy Eating Plate (http://www.hsph.harvard.edu/nutritionsource/healthy-eating-plate/) food groups. In this analysis we consider both animal products (chicken, pigmeat, beef, fish and other aquatic foods (seafood), eggs, milk and cheese) and vegetable products (wheat, rice, fruits, pulses, starchy roots, vegetables and nuts). We used four footprint indicators to analyze the environmental impacts of the production of these foods; the carbon footprint (greenhouse gas emissions), nitrogen footprint (pollution), water footprint (blue and green water use), and land footprint (land use). Each footprint details a different aspect of the environmental impacts of food production and together are able to portray a more complete picture of how different food products impact the environment (Leach et al., in revision).

2.1.1. Carbon footprint

Carbon footprint values for the vegetable and animal products were reported by Heller and Keoleian (2014). Heller and Keoleian (2014) conducted a meta-analysis of life-cycle studies of around 100 food products and calculated the average carbon footprints by food type. Given the diversity in the methodology of the life-cycle analyses, their approach provides carbon footprints meant to be representative and within the range of expected values for the given food types produced in developed countries (Supplementary Table 1).

2.1.2. Nitrogen footprint

A nitrogen footprint reports the amount of reactive nitrogen (all species of nitrogen except N_2) released to the environment associated with the consumption of resources. A food nitrogen footprint typically has two parts: food consumption and food production. The food consumption N footprint is the nitrogen contained in the consumed food product, which ultimately enters the wastewater stream. The food production N footprint accounts for all of the nitrogen lost to the environment throughout the food production process, such as from fertilizer runoff, manure losses, and food waste. The food production N footprint can be estimated using virtual N factors, which report the amount of N lost to the environment per unit of N consumed for major food categories (Leach et al., 2012). These factors are available for the following food categories in the United States: poultry, pigmeat, beef, seafood, milk, grains, pulses, starchy roots, and vegetables.

To estimate the N footprint associated with different diets in this study, we used the virtual N factors from Leach et al., 2012 to calculate the food production N footprint (Supplementary Table 1). The virtual N factors were converted to units of N released per weight of the food product using protein contents from the USDA National Nutrient Database (2013; Supplementary Tables 1 and 5). We focused on the food production N footprint for consistency with the other footprints, which are upstream of food consumption. When a virtual N factor was not available for a particular food category, the most similar virtual N factor was applied (e.g., the milk virtual N factor was used for cheese). This calculation then reports the total amount of reactive N released to the environment as a result of a given diet.

2.1.3. Water footprint

Water footprint values came from Mekonen and Hoekstra (2010a, 2010b) (Supplementary Table 1). We focus on surface water (blue water) and soil water (green) use. United States water footprints were calculated as the production-weighted average for 62 foods belonging to 13 food commodity groups. Since the water footprint database does not include an estimate for the water footprint of seafood, it was estimated using the global production of the top cultivated aquaculture products (excluding aquatic plants), the conversion factor to become an edible product (with minimal processing), the total feeds used for each product group, the composition of feeds for each product group, and the water footprint of the inputs. The water footprint of capture production, bivalves, fishmeal, and fish oil were assumed to be zero within the system boundaries of the water footprints calculated by Mekonnen and Hoekstra (2012) following the arguments of Gephart et al. (2014).

We used global production data from Tacon et al. (2011) to ensure that the species groupings were consistent between the production and feed use data. Since production data on bivalves is not included in Tacon et al. (2011), we used the bivalve production data in FAO FishStat (FAO, 2015a). The conversion factors from live weight to edible product are from the FAO (2000). We selected values that represent a minimally processed edible product (e.g. filet or shelled meat). When a value was not available for the product group, the conversion factor for a similar product (or average across similar products) was used. Fishmeal, fish oil, and terrestrial feed ingredients for the species groups are from Tacon et al. (2011). The mean of the estimate ranges were used and scaled so that the percentages from all inputs summed to 100%. The water footprints for the terrestrial feed inputs are from Mekonnen and Hoekstra (2011).

To calculate the water footprint of aquaculture, the water footprint of the feeds for each species group (L/g feed) was calculated by multiplying the water footprint of each input (Supplementary Table 2). A recent study by Pahlow et al. (2015) applied a similar method to compute a global average water footprint for aquafeeds. If we include similar products, the average blue and green water footprint for aquaculture feeds (1712 m^3/t) agrees reasonably well with the global average estimate of 1808 m^3/t by Pahlow et al. (2015). To calculate the overall footprint of seafood we calculated the average of the water footprint of aquaculture (0.00356 m^3/g product) and capture fisheries (0 m^3/g product), weighted by the proportion of global production of each from the FAO FishStat (2015a) (0.399 from aquaculture and 0.601 from capture fisheries for 2010).

It should be noted that the water footprint of seafood based on feeds does not necessarily include all relevant aspects of water use for seafood production. For example, water used in ponds and during processing can be high for some species. Inclusion of the pond evaporation- and infiltration-related water footprint would result in a higher water footprint for seafood (Verdegem and Bosma, 2009) and would be particularly important for countries which have high reliance on pond aquaculture (e.g. China). While a more comprehensive calculation of water use for seafood production is needed, the approach here provides a reasonable estimate of the water footprint associated with aquafeeds, which is comparable to the system boundaries used to calculate the water footprints of livestock (Mekonnen and Hoekstra, 2012).

2.1.4. Land footprint

Country-specific land use efficiency for plant commodities (i.e. ha per kg of crop) was calculated as the harvested area in 2010 divided by the amount of crop production (FAO, 2015b). The land use efficiency value for vegetable oils, η_{vo}, was calculated as:

$$\eta_{vo} = \eta_{oc}\left(\frac{p_{vo}}{(ap_{oc}) - p_{cake}}\right)$$

where η_{oc} is the land use efficiency for oil crops, p_{vo} is the production of vegetable oil in metric tons, a is the fraction of oil crop production used for processed goods, p_{oc} is the production of oil crops and p_{cake} is the production of oilcakes. Based on feed conversion ratios (FCRs) and feed rations reported by MacLeod et al. (2013) and Opio et al. (2013) (Supplementary Table 3), the feed component of the global land use efficiency of animal product k, η_k, was then calculated as follows:

$$\eta_k = f_k \sum\left(\frac{r_{pc,k}\eta_{pc}}{100}\right)$$

where f_k is the FCR for animal product k, $r_{pc,k}$ is the feed ration of a given plant commodity for animal product k and η_{pc} is the land use efficiency of that plant commodity (Supplementary Table 3). Pasture land was split between beef and milk production (92% and 8%, respectively) following the methodology of Eshel et al. (2014). The land footprint of cheese was calculated as 10 times the land footprint of milk, assuming a 10:1 conversion ratio.

The land footprint for seafood was calculated using the same methods as for the water footprint. The land footprints for the terrestrial feed inputs were derived from primary crop yield values reported in the FAOSTAT database (FAO, 2015b). To calculate the land footprint of crop-derived feeds, some conversions were required. The land footprint for feed meal from crop i was calculated as:

$$\eta_{fmi} = \eta_{rc,i}\left(\frac{p_{roc,i}}{p_{oc,i}}\right)$$

where $\eta_{rc,i}$ is the land footprint of raw crop i, $p_{roc,i}$ is the oilcake production of crop i in the year 2010 in raw equivalents, and $p_{roc,i}$ is the oilcake production of crop i in 2010 (FAO, 2015b). This calculation was used for cottonseed meal, mustard seed cake, peanut meal, rapeseed meal, soybean meal, and sunflower seed meal. The value for rapeseed meal was used for canola protein concentrate. The average value of soybean meal and peanut meal was used for lupin kernel meal, faba bean meal and field pea meal.

The land footprints for soybean oil and rapeseed oil were calculated as:

$$\eta_{vo,i} = \eta_{rc,i}\left(\frac{p_{vo,i}}{ap_{rc,i} - p_{oc,i}}\right)$$

where $\eta_{rc,i}$ is the land use efficiency for raw crop i, $p_{vo,i}$ is the production of oil from crop i, a is the fraction of raw crop production used for processed goods, $p_{rc,i}$ is the production of crop i and $p_{oc,i}$ is the production of oilcake from crop i. Finally, because gluten products are the protein concentrate of a crop, wheat gluten and corn meal gluten were calculated as:

$$\eta_{g,i} = \eta_{rc,i}\left(\frac{pc_{food,i}}{pc_{prot,i}}\right)$$

where $pc_{food,i}$ is the daily per capita food supply of wheat or maize and $pc_{prot,i}$ is the daily per capita protein supply of wheat or maize.

The total land use for aquaculture was estimated at 36.6 Mha (Verdegem and Bosma, 2009). Because a reliable value does not exist, the area actually occupied by aquaculture ponds – reported up to 8.2 Mha (Verdegem and Bosma, 2009) – was not included in our estimate.

2.1.5. Combined footprint

The combined footprint is an index calculated as the sum of the four footprints, each normalized to the largest footprint value among the food items. Each normalized footprint then varies between 0 and 1 and the combined footprint between 0 and 4. Coefficients could be added to each of the summed terms to change the relative weights of the footprints. We expand on this point in the discussion.

2.1.6. Nutrition content and constraints

Average nutrient contents of food groups were obtained by averaging the reported nutrient contents of representative food items from the United States Department of Agriculture (USDA) National Nutrient Database (USDA, 2013). The average nutrient content of each food group is provided in Supplementary Table 4 and the list of representative food items is provided in Supplementary Table 5. Nineteen nutrients were selected to represent a broad range of micro- and macro-nutrients required in the diet. Any nutrient not included is assumed to be satisfied whenever the included nutrients are satisfied, following the assumption in the original Stigler's diet problem (Dantzig, 1963). Nutrient requirements are based on the USDA (2010) guidelines with minimum recommendations representing a population-weighted average of the age and gender recommendations, with demographic information from the United Nations Population Division for 2010 (United Nations, 2013). This gave a minimum calorie requirement of 1900 and we selected a maximum calorie intake of 3200 (the maximum recommendation for an active individual). This range ensures that the diet exceeds the minimum requirement without placing stringent constraints on the optimization problem.

Nutrition is more complex than the simple minimum requirements used in this method. For example, we make the simplifying assumption that there is no interaction among the foods. This implies that the presence of a food does not affect the availability of nutrients in another food. However, this is likely an over-simplified view of nutrition, and even when Stigler published his original paper he acknowledged that the optimum quantity of a nutrient depends on the quantities of the other nutrients (Dantzig, 1963). However, the goal of this paper is not to suggest an exact diet that should be adopted. Rather our goal is to evaluate diet composition patterns and tradeoffs at footprint minimums and thus these assumptions are reasonable.

2.2. Data analysis

We used the original formulation of Stigler's diet problem to analyze the diet composition with optimum footprints and conducted an uncertainty analysis of the footprint estimates. For *i* nutrient constraints and *j* food items, the *i* by *j* matrix A consists of the nutrient contents for each food item and the vector b consists of the minimum nutrient requirements. The vector f consists of the carbon (C), nitrogen (N), water (W), land (L), or combined (T) footprint for each food item, and represents the cost vector in the original problem. We minimized fx subject to Ax > b, where x is the vector of the quantity of each food item. The optimum was solved for in Matlab using the Dual Simplex algorithm with linprog. The tradeoffs were calculated by $t = x^*_b f_a - x^*_a f_a$ where $a \in \{C, N, W, L, T\}$, $b \in \{C, N, W, L, T\}$ and is not equal to a, and x^*- represents the optimized diet composition. This gives the increase in the *a* footprint when moving from the minimized diet for *a* to the minimized diet for *b*.

We evaluated the uncertainty in the optimized diets that is due to variability in the footprint estimates by resampling footprint values from a gamma distribution (with shape parameters based on the mean and standard deviation of the footprint estimate for each food group) and rerunning the optimization. When the standard deviation was unavailable, we used 50% of the mean (indicated in Supplementary Table 1). There is greater uncertainty in the diet composition when no serving constraint is imposed, with the largest uncertainty in the optimal servings of fruits, vegetables, and nuts (Supplementary Figs. 1 and 2). Resampling with deviations from the mean footprint also allows identification of alternative diet compositions which may have footprints only slightly larger than true the minimum.

In order to allow other food products to enter the diet at the footprint minimum, we sequentially removed products occurring in the minimized diet. This removal is only possible with a reduced set of nutritional constraints. For each footprint, we found the combinations of up to five product removals that would satisfy the calorie, protein, carbohydrate, and fiber constraints and used a maximum serving constraint of 35. The footprints and tradeoffs with the other footprints were then calculated for this expanded set of diets.

3. Results

3.1. Diet compositions at footprint minimums

The diet compositions that minimize the footprints individually while meeting all nutrient requirements look similar for the carbon and nitrogen footprints, but differ from the water and land footprints. The diets which minimize the carbon and nitrogen footprints consist of about two-thirds vegetables and one-third nuts, with small amounts of seafood and milk (Fig. 1 A–B). The diet which minimizes the water footprint consists of about four-fifths vegetables and one-fifth starchy roots, with small amounts of seafood (Fig. 1 C), while the diet which minimizes the land footprint consists of about nine-tenths vegetables and one-tenth grains, with small amounts of seafood and rice (Fig. 1 D).

These solutions require consuming a large number of servings of the food groups. For example, the diet minimizing water requires over 60 servings of vegetables per day and another 14 servings of starchy roots. Consuming this volume of food would require nearly constant eating. Since there are physical and time limits to the number of servings a person can ingest, we ran the optimization for a range of maximum servings. The lower end of the serving maximums are realistic numbers based on the USDA recommendations. At the lowest serving levels, the problem is highly constrained and the diets for the four footprints look very similar, consisting primarily of seafood, vegetables, nuts, and starchy roots (Fig. 1 A–D).

The diet that minimizes the combined footprint is a balance of the products that minimize each of the four footprints separately (Fig. 1 E). When a low serving constraint is imposed, the optimal diet consists of 13.5 servings of seafood, 9.3 servings of nuts, 1.6 servings of pulses, 1.3 servings of vegetables, and 0.1 servings of milk. As the serving constraint is removed, the number of servings of seafood decreases and the number of servings of nuts and vegetables increase to 16.9 and 33.3 servings respectively.

3.2. Additional low footprint diet compositions

A typical solution to the “diet problem” is a fairly homogenous diet, consisting of only a couple food groups. Meeting the dietary requirements would require consuming a variety of products from within a group since each group's nutrient content represents an average of the nutrient content of a range of products. Nevertheless, these theoretical diets consisting of few product groups do not reflect realistic consumption behavior or recommendations to diversify diets (USDA, 2010.

In order to find other diets with low footprints that require consuming a reasonable number of servings (max of 35), we removed food groups appearing in the minimum diets and reran the optimization to allow other foods to enter the diet. These “knockout” experiments could only be solved for a reduced set of constraints (only calorie, protein, carbohydrates, and fiber constraints, excluding micronutrients). Diets representing a mixture of two different knockout scenarios will have a footprint intermediate to the footprints at the minimums of the two scenarios. For example, with these reduced nutritional constraints, carbon's minimum diet consists of grains and pulses, with a footprint of 0.31 kg CO_2 eq. But when pulses are excluded, the carbon minimum diet consists of grains and starchy roots, with a footprint of 0.34 kg CO_2 eq. A person could have a diet with a mixture of grains, pulses, and starchy roots that would have a footprint intermediate to 0.31 and 0.34 kg CO_2 eq.

For all footprints, diets from the knockout experiments consist primarily of starchy roots, rice, grains, pulses, vegetables, and nuts (Fig. 2). A notable difference between the composition of this diet and the diet with all nutritional constraints is that seafood is rarely included

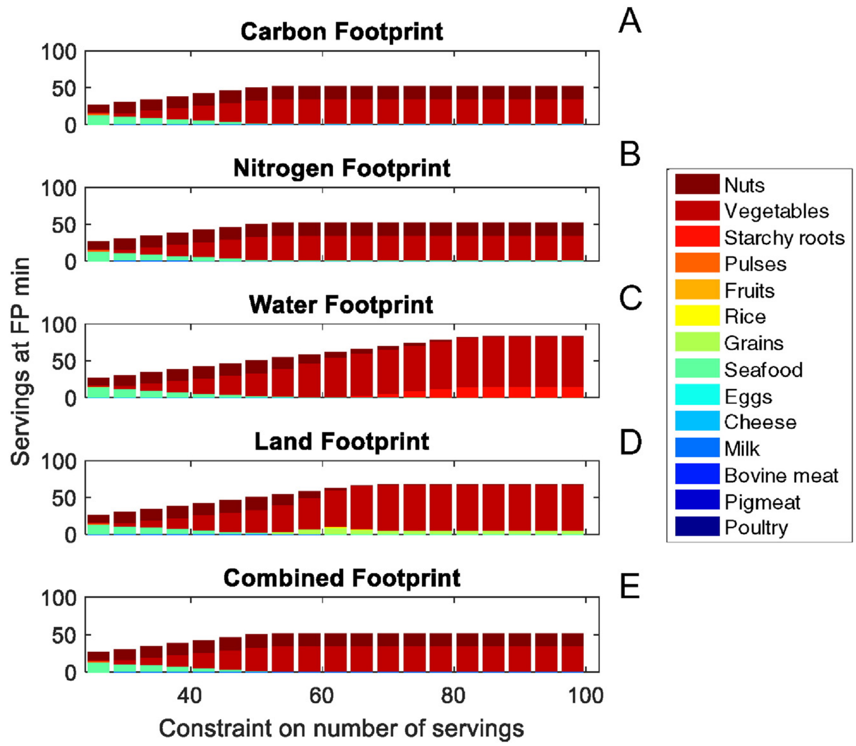

Fig. 1. Diet composition that occurs at the minimum for each footprint versus the number of servings allowed. The stacked bars represent the number of servings from each food group that comprise the diet at each footprint minimum. Beyond a serving constraint of 100, none of the diet composition change, so this diet composition represents the theoretical FP minimum that occurs when no constraint is placed on the number of servings. The combined footprint represents the sum of the footprints standardized by the maximum footprint within the footprint type. Results are presented in terms of kilograms rather than servings in Supplementary Fig. 3.

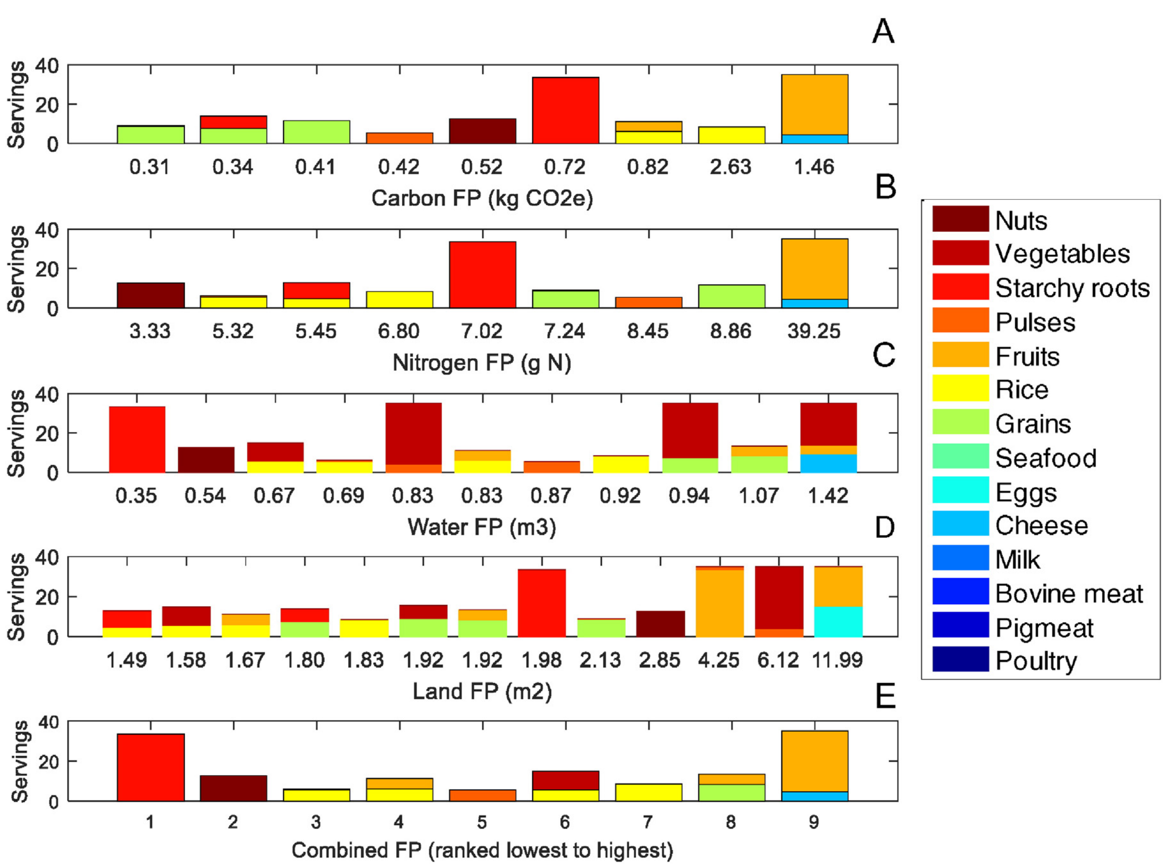

Fig. 2. Unique diet compositions for knockout experiments. The optimization only considered calorie, protein, carbohydrate, and fiber nutrient constraints and a serving maximum of 35. The number of food products removed from the optimization problem ranged from zero to five, with a total of 46 knockout combinations. Repetitive diet compositions were removed for display purposes. Results are presented in terms of kilograms rather than servings in Supplementary Fig. 4.

at the minimum. This implies that seafood is efficient at supplying the micronutrients when the four footprints are minimized, but less efficient than the vegetal products at supplying the macronutrients. In general, other animal products rarely appear in any of the optimized diets. These results extend the findings of prior studies (e.g. Eshel et al., 2014) – that reducing animal product intake is an effective way for individual's to reduce their footprints – by showing that animal products (excluding seafood) are less efficient even when accounting for nutritional content.

3.3. Tradeoffs and synergies among C, N, W, and L footprints in diets

Tradeoffs occur when changing from the diet composition at a given footprint's minimum to the diet composition of a different footprint's minimum. These tradeoffs result in an increase in the footprint of interest. A synergy occurs when there is little to no tradeoff between two footprints. Calculated tradeoffs are visualized in Tables 1 and 2. The tradeoff is quantified by subtracting the footprint at a given footprint's minimum (grey boxes in Tables 1 and 2) from the footprints of the diets at other minimums (white cells in the same column).

Tradeoffs do not occur between carbon and nitrogen, but do occur among the other footprints at their theoretical minimums (when no serving constraint is imposed, Table 1). The largest tradeoff for both carbon and nitrogen is with water. This occurs primarily because of the large number of servings of vegetables in the water footprint's minimum diet (Fig. 1). For the same reason, but to a lesser degree, the carbon and nitrogen footprints also increase when moving from their minimum diets to the minimum land footprint diet. Both water and land have larger tradeoffs with carbon and nitrogen than they do with one another (Table 1). This is because the diets at the minimums for carbon and nitrogen have a high number of servings of nuts, which have water and land footprints six and twelve times as high as the water and land footprints of vegetables, respectively (Supplementary Table 2).

There are small tradeoffs when there is a 26 serving constraint imposed. This can be observed by the similar numbers within the columns of Table 2. The low tradeoffs, or synergies, occur here because the diet compositions are very similar at the minimum of each footprint when there is a serving constraint of 26 (Fig. 1). The tradeoffs for other values of serving constraints are displayed in Supplementary Fig. 5.

The tradeoffs and synergies follow a similar pattern across the diets in the knockout experiments, but the tradeoffs are lower than when all micro- and macro-nutrient constraints are included (Supplementary Fig. 6). Since the diets tend to contain similar food products across the knockout experiments, the average tradeoffs are not significantly different from zero for any combination of footprints. The distribution however does span a wide range of tradeoffs for some combinations of footprints. For example, the median tradeoff of carbon with water is 0.11 kg CO_2 eq. and with land is 0.24 kg CO_2 eq. While there are no significant differences among the tradeoffs between a given footprint and the other footprints, there are differences in the ranges of the tradeoffs. For example, there is a greater range of tradeoffs between land and carbon than between land and water.

4. Discussion

The environmental impacts of food production are a growing concern (e.g. Foley et al., 2011; Godfray et al., 2010). When considering possible diets to reduce impacts, nutritional requirements must also be considered (Vanham et al., 2013). By adapting Stigler's diet optimization approach we identify low environmental footprint diets that meet minimum nutrient requirements. When constraints are placed on the maximum number of servings, the diets minimizing each of the four footprints look very similar, consisting primarily of seafood and vegetal foods (Fig. 1) with few animal products. There are synergies among the four footprints and moving towards the minimized diets would yield benefits for the carbon, nitrogen, water and land impacts of food production.

However, there are many factors involved in an individual changing their diet, and even more in shifting the diet of an entire population. Consumers are generally not likely to compromise taste for health (Verbeke, 2006). However, direct health benefits can increase an individual's willingness to change their diet, especially if facing more than one chronic condition (Boyle et al., 1998). Changing consumption patterns for environmental benefits is less likely to be embraced by the general public (Tobler et al., 2011). While consumers are open to reduced packaging and eating seasonal fruits and vegetables, they are unwilling to eat organic and reduce meat intake and do not understand or value the environmental benefits this would provide (Tobler et al., 2011). Consuming eco-friendly foods, organic products and free-range meat is more common when either health benefits or ethical concerns are considered (Harper and Makatouni, 2002), the product is of a notably higher quality (McCluskey and Loureiro, 2003) or the product is local (Adams and Salois, 2010). Shifting consumer purchasing habits will require careful consideration of many factors, including consumer understanding (Grunert et al., 2014), price concerns, food purchasing habits, product availability, and personal benefit (Röös and Tjärnemo, 2011). Dietary shifts at the population level are more likely to depend on cost and accessibility factors (Popkin et al., 2012) than environmental benefits.

Table 1
Footprints that occur at the minimum when each of the footprints is minimized and no constraint is imposed.

	FP at minimum				
FP being minimized		Carbon (kg CO_2 eq./day)	Nitrogen (g N lost/day)	Water (m^3/day)	Land (m^2/day)
	Carbon	2.59	46.40	1.12	7.75
	Nitrogen	2.59	46.40	1.12	7.75
	Water	3.70	77.84	0.62	4.23
	Land	3.36	72.71	0.92	4.00
	Combined	2.39	39.81	1.30	8.22

Table 2
Footprints that occur at the minimum when each of the footprints is minimized and a constraint of 26 servings is imposed.

	FP at minimum				
FP being minimized		Carbon (kg CO_2 eq./day)	Nitrogen (g N lost/day)	Water (m^3/day)	Land (m^2/day)
	Carbon	4.93	98.90	2.33	17.58
	Nitrogen	4.93	98.90	2.33	17.58
	Water	5.29	103.24	2.26	19.52
	Land	4.93	98.90	2.33	17.58
	Combined	6.57	136.42	2.46	19.18

As an example of shifting diet and some of the complications involved, an advisory board proposed reduced meat intake in order to reduce the environmental impacts of food production for consideration in the updated USDA Dietary Guidelines (2015). This recommendation was criticized by interest groups claiming that the recommendation did not consider the nutrient efficiency of meat products, particularly lean red meat (USDA, 2015). In our analysis, even when products were sequentially removed from inclusion in the minimized diet, animal products rarely appeared in the minimized diet. Further, when they were included the resulting footprint of the diets were five to ten times the minimum footprint (Fig. 2). Even then the included animal products were only milk, cheese or eggs, with pigmeat, chicken, and beef appearing in none.

When micronutrients are included, optimizing diets to minimize selected environmental impacts of production yields a composition emphasizing seafood, nuts and vegetables (Fig. 1). While this diet is in stark contrast to the average global diet – in which cereals and livestock dominate – certain dietary practices resemble these optimized diets. For example, all animal-sourced protein and calories in a pescatarian diet are derived from seafood. Average pescatarian and vegetarian diets also have a relatively high demand for nuts and legumes. That these diets share a number of similarities with the optimized diet patterns identified here suggests that, to a certain extent, our hypothetical diet is achievable. The potential health benefits of the optimized diets are also apparent, being high in omega-3 and omega-6 fatty acids and rich in essential vitamins. Indeed, one recent study by Tilman and Clark (2014) showed that healthy dietary choices (e.g., less red meat) can also mean environmental benefits (e.g., decreased land requirements and GHG emissions), as fewer natural resources would be required to produce an individual's diet. Thus, while it is not practical to expect an individual's dietary choices to exactly reflect the composition presented here, encouraging a shift towards these minimal footprint diets can be made more convincing by highlighting the potential benefits to personal health. Yet despite these multiple benefits, historical dietary trends show a strong relationship to affluence, where increased per capita GDP also means richer diets comprised of more calories and greater percentages of animal products. If changes in diet continue to solely reflect growth in income – without taking into account other factors such as health and environmental impacts – the disparity between actual consumption patterns and what is least environmentally burdensome will continue to grow.

Additionally, the food production systems are evolving, with consequences for the footprints of each food group. This is a critical point for the seafood group because the water, nitrogen, and land footprints for capture fisheries are negligible, but can be quite high for some aquaculture production systems. Aquaculture production is rapidly growing, already comprising half of global seafood production, and additional seafood demands have been projected to come primarily from aquaculture production rather than capture fisheries (FAO, 2014). At the same time, aquaculture is increasing aquafeed use and shifting aquafeed composition. The push for aquafeeds to reduce reliance on capture fisheries by incorporating more terrestrial products is largely motivated by improving the sustainability of the capture fisheries, but would also result in an increase in the water, nitrogen, and land footprints associated with seafood production. As a result, the increases in seafood consumption suggested by the results would likely be met with increases in the footprints for seafood.

The four footprints considered in this study cover a wide range of environmental impacts related to food production, i.e. emissions, pollution, water use and land use. However, there are other aspects of environmental change not covered with these footprints including antibiotic and pesticide use, animal welfare (when applicable), biodiversity, GMO's, industrial pollution, disease risk, etc. Most notably, many of the environmental impacts of capture fisheries and aquaculture are not sufficiently captured by the four footprints considered here, which were developed primarily for agriculture and livestock. For example, the negative impacts of overfishing and bycatch in capture fisheries are not considered here. Additionally, not all aspects of water use in aquaculture are included, nor are the impacts of the conversion of mangroves for aquaculture ponds. Nevertheless, our approach could be applied to other environmental impacts as well given quantitative measures of how the production of food impacts these dimensions of environmental change or harm.

In each case, there will be variability in the environmental impact based on production methods and the location of production. Further, there is high variability within food categories in terms of footprints and nutrient contents. Foods within a group that have low footprints and high nutrient content would be more likely to appear in minimized diets. For example, seafood consists of a broad range of species groups (e.g. finfish, bivalves, crustaceans) and highly diverse production methods. Production methods requiring few feed inputs, such as many bivalve systems, would likely be included more often in minimized diets than seafood as a whole. Conversely, higher resource input systems such as marine shrimps, would be included less frequently in minimized diets. In order to complete an analysis on disaggregated food products, data is needed on the footprints (and variability) of the detailed products for each of the footprint dimensions. Given more detailed footprints, it is likely that more tradeoffs would be identified. In this case minimizing the combined footprint would be needed to make single diet recommendations.

Combining the four footprints into a single factor has value for communicating overall impacts. Two approaches can be taken to combine these footprints: by equal weighting or by conversion to a common unit. For the equal weighting approach, which was used in this study, the four footprints are assigned an equal weight (e.g., 25%) towards a total footprint. The total footprint is then presented on a set scale, (e.g., a unitless range of 0–1) and the sum of the four footprints would then be the total footprint factor. While we summed the four footprints with an equal weighting, with the footprints can be assigned unequal weights based on value judgements. A second approach presents the sum of all four footprints in a common unit, such as the use of land area for the ecological footprint. However converting to a common unit would require assumptions of, for example, the land area required to accommodate a given amount of nitrogen pollution without environmental damage. Such factors vary on small scales and are not readily available. We encourage further research into combining different footprints into a single factor for improved communication.

5. Conclusion

By modifying Stigler's diet problem minimized carbon, nitrogen, water, and land footprints were derived. When micronutrients are included the minimized diets emphasize seafood, nuts and vegetables. When only macronutrients are considered to allow for a broader range of products to enter the diet, minimized diets generally consist of combinations of starchy roots, rice, grains, vegetables, and nuts. Few minimized diets contained livestock products, and when they did the footprints of the diets were much higher than the minimums which contained vegetal products. Since the diet compositions at each footprint's minimum tended to include similar products, the tradeoffs among footprints were low suggesting potential synergies by moving to diets of lower environmental impact. While the aim of this analysis is not to make specific diet recommendations, our approach demonstrates that diets minimizing each of the different footprint indicators yields similar diets. In doing so, this study provides a useful tool for decision-makers in linking human nutrition and environmental impacts.

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Appendix A. Supplementary data

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