The Impact of Diet Preference on Agricultural Productivity and the Environment

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Introduction

Agriculture is a major driver of environmental change and plays a significant role in contributing to global climate change, biodiversity losses, and freshwater withdrawals [1, 2]. Worldwide demand for crops is increasing due to population growth, increased biofuel production, and especially changing dietary preferences [3]. Recent studies find that global crop demands will likely increase by 60–120% by the year 2050 (from baseline year 2005) [3, 4]. Taking these two issues together, contemporary agriculture faces the challenge of roughly doubling crop production, without doubling its environmental footprint. Many recent papers present solutions to this challenge by proposing methods of sustainable intensification, to increase yields on current underperforming croplands by more efficiently using resources such as fertilizers and freshwater [2, 3, 5, 6].

The emphasis placed on more efficiently utilizing current croplands is due to the tremendous ecological costs of recent cropland expansions. In the 1980's and 1990's a majority of cropland expansion has been in the Amazon rainforest in Brazil and tropical rainforests in Indonesia and Malaysia [7]. Deforestation is responsible for ~12 - 20% of global anthropogenic greenhouse gas emissions [8, 9], and also results in the loss of habitats with rich biodiversity and potentially the extinction of endemic species [10]. Halting the expansion of agriculture into forests could reduce CO_2 emissions from land clearing by 98% [11].

Other than sustainable intensification, another place to look for solutions to the challenges facing agriculture is to examine the way we allocate production on current croplands, and whether we can feed more people with current levels of production. In chapter one we redefine agricultural yields, from its current definition of tonnes per hectare (or bushels per acre) to people fed per hectare. We use subnational data on crop yields [12] and national data on crop allocations to spatially describe the productivity of croplands in terms of people fed per hectare. We find huge potential to feed more people with current levels of crop production, if crop production is shifted away from biofuels and animal feed, to food for direct human consumption. However, we note significant social and economic barriers to such a significant shift [13, 14].

In chapter one we also describe another pathway to increasing people fed per hectare, which is to increase the conversion efficiency of crop calories currently directed to animal feed. This alternative pathway would increase food delivery without shifting crops already allocated to feed, but rather shifting the kinds of livestock receiving those crops. Shifting crop calories currently consumed by beef cattle to poultry and pork can increase crop conversion efficiency. Likewise shifting feed calories to produce only eggs and dairy would produce the most animal protein per feed calorie input.

In chapter two we further explore how small changes in diets, like shifting away from beef and pork, can have other ancillary environmental benefits. Using food purchase data from a health insurance company's food subsidy program in South Africa, we quantify how subsidies that decrease consumption of beef and pork can reduce agriculturally driven environmental impacts, such as greenhouse gas emissions, water footprints and land requirements.

Chapter 1

Redefining agricultural yields: from tonnes to people nourished per hectare

Emily S. Cassidy, Paul C. West, James S. Gerber, Jonathan A. Foley

Summary

Worldwide demand for crops is increasing rapidly due to global population growth, increased biofuel production, and changing dietary preferences. Meeting these growing demands will be a substantial challenge that will tax the capability of our food system and prompt calls to dramatically boost global crop production. However, to increase food availability, we may also consider how the world's crops are allocated to different uses and whether it is possible to feed more people with current levels of crop production. Of particular interest are the uses of crops as animal feed and as biofuel feedstocks. Currently, 36% of the calories produced by the world's crops are being used for animal feed, and only 12% of those feed calories ultimately contribute to the human diet (as meat and other animal products). Additionally, human-edible calories used for biofuel production increased four-fold between the year 2000 and 2010, from 1% to 4%, representing a net reduction of available food globally. In this study, we re-examine agricultural productivity from the standard definition of yield (in tonnes per hectare, or similar units) to the *number of people actually fed* per hectare of cropland. We find that, given the current mix of crop uses, growing food exclusively for direct human consumption could, in principle, increase available food calories by as much as 70%, which could feed an additional 4 billion people (more than the projected 2-3 billion people arriving through population growth).   Even small shifts in our allocation of crops to animal feed and biofuels could significantly increase global food availability, and could be an instrumental tool in meeting the challenges of ensuring global food security.

Introduction

Recent studies find that global crop demands will likely increase by 60–120% by the year 2050 (from baseline year 2005) [3, 4], depending on assumptions of population growth, income growth and dietary changes. This projected increase of global crop demand is partly due to a growing global population, but a larger driver is increasing global affluence and associated changes in diet [3]. As global incomes increase, diets typically shift from those comprised of mostly grains, to diets that contain a greater proportion of meat, dairy, and eggs [3, 15-17]. This shift from plant based diets to more intensive demand for animal products is termed the "Livestock Revolution" [17], and it is estimated approximately 40% of the world's population will undergo this revolution to more animal consumption by the year 2050 [3]. In order to meet these demands, global livestock production systems are shifting from using mostly waste products, crop residues, and marginal lands to more industrial systems that require less land and use higher value feed crops [17, 18]. In developing countries with high rates of increasing animal product demands, a greater proportion of cereals are being directed to animals [19].

Increasing demand for meat and dairy is also of importance to the global environment because their production requires more land and other resources than plant-based foods [20-22]. In fact, livestock production is the single largest anthropogenic use of land. According to a 2011 analysis, 75% of all agricultural land (including crop and pasture land) is dedicated to animal production [2]. Livestock production is also responsible for other environmental impacts. Livestock production is estimated to be responsible for 18% of total greenhouse gas emissions [23], and animal products generally have a much higher water footprint than plant-based foods [24].

A central issue facing the global food system is that animal products often require far more calories to produce than they end up contributing to the food system [25, 26]. While efficiencies of feed-to-edible food conversions have increased over time [19, 27], the ratio of animal product calories to feed calories is, on average, still only about 10%

[25, 28]. This suggests using human-edible crops to feed animals is an inefficient way to provide calories to humans.

In addition to growing meat and dairy demands, affluent nations are also directing a growing proportion of high-value feedstock to biofuel production. A great majority of biofuel feedstocks are human-edible, especially from maize in the United States and sugarcane in Brazil. In 2010 global biofuel production represented 2.7 percent of global fuel for road transportation (at 107 billion liters produced), which is more than a 450 percent increase from the year 2000 [29]. To produce these fuels the U.S. and Brazil combined dedicated over 460 million tonnes of maize and sugarcane respectively to biofuel production in 2010, which is 6% of global crop production (by mass) [30].

In this study, we consider how different systems of crop production and crop use are interwoven to actually feed people around the world. Specifically, we map global patterns of *crop production* as well as *crop allocation* (for human consumed food, animal feed, biofuels, and other non-food products) to determine the amount of human-consumable calories produced across the world. By comparing *crop production* (in terms of tonnes of crop per hectare) to *actual food delivery* (in terms of calories of human-consumable product per hectare), we illustrate where tremendous inefficiencies in the global food system exist today – and where opportunities to enhance food security exist by changing dietary preferences and biofuel policies.

Methods

We map the global extent and productivity of 41 major agricultural crops (which account for >90% of total calorie production around the world) by using the EarthStat crop production data of Monfreda *et al.* (2008) [12]. These data use a global compilation of census data and satellite images to depict geographic patterns of crop area and yields across the world on a 5' by 5' latitude-longitude grid (equivalent to roughly 9 km by 9 km on the equator). These Monfreda *et al.* (2008) data are 'circa 2000'. Most values are averaged from 1997 – 2003, except where data are missing [12].

Crop Allocations

National-level crop allocations are determined by:

(1)

$$\text{Crop Allocation}_{c,n} = ([\text{production}_{c,n} - \text{exports}_{c,n}] \times \text{domestic allocations}_{c,n}) + (\text{exports}_{c,n} \times \text{importing nations' allocations}_{c})$$

where Crop Allocation$_{c,n}$ represents the crop uses (subscript c) for a given nation (subscript n), and importing nations' allocations$_{c}$ is a crop specific global average use of importing nations.

Crop Allocation$_{c,n}$ statistics were derived using the Food and Agriculture Organization's (FAO) Food Balance Sheets and trade statistics [31], which report crop production $_{c,n}$, exports $_{c,n}$, and domestic allocations $_{c,n}$ at the national level [31, 32]. We used these data for the years 1997 to 2003 (the same years as Monfreda et al. 2008 [12]). To examine how crops were allocated – whether for human consumed food, animal feed, biofuels, or other non-food uses, relative proportions of crop production going to 'Food', 'Feed', 'Processed' and 'Other' were used for each crop in each nation (See Appendix). These Crop Allocation$_{c,n}$ proportions were then multiplied by the crop production data of Monfreda *et al.* (2008) [12].

Beyond the more straightforward calculations, we had to make a number of key assumptions. We assume that processed oil crop production separates the oils for human consumption or industrial uses, and the protein-dense cake or meal is directed to animal feed [33]. Crops allocated to biofuels were determined for major biofuel producing nations in the year 2000: United States, Brazil, Germany and France. In the year 2000, the United States and Brazil used maize and sugar cane as their respective biofuel feedstocks, whereas France and Germany used rapeseed for biodiesel production. Data on the magnitude of crop production used for biofuel production in 2000 were taken from the World Watch Institute [29]. For maize being directed to ethanol production in the United States, we assume 34% of the calories are redirected into 'Feed' as dried distillers' grains [34]. Likewise we assumed rapeseed meal, as a byproduct of biodiesel production in Europe, was directed to animal feed (See Appendix).

It is important to note that crop production within a given nation is not necessarily consumed domestically. In order to determine how exported crop production was allocated, we used FAO trade statistics to determine how importing nations allocate crops (importing nations' allocations_c) [32]. We then assumed exports were allocated based on these crop specific global average allocations for importing nations. Importing nations crop allocations were weighted by how much each nation was importing, and how they allocated each crop. In this way, we map food delivery per hectare of cropland, regardless of where the food is consumed.

Livestock Feed Conversions and Calorie Delivery

Crop use statistics were used to determine the number of calories delivered to the food system, which include food calories (which were used for direct human consumption), and feed calories after they were converted to meat, egg, and dairy calories. Crops that were used for other non-food uses (biofuels and other industrial uses) were not delivered to the food system. Produced crop calories and protein were determined from the crop caloric and protein contents which were derived by Tilman et al [3].

In our analysis, feed calories are converted to edible meat, egg and dairy calories using conversion efficiencies from the USDA [35], adapted from Smil, 2000a [27] (Table 1). These livestock conversion efficiencies are an estimate of how many edible calories result from the conversion from feed calories, based on national-level livestock production statistics (reported data on 'cattle meat', 'chicken meat', 'pig meat', 'hen eggs', and 'cow's milk' were used) (See Appendix).

Many commonly used feed-to-meat conversions, for example 12 kilograms of feed to 1 kilogram of beef, or 2.5 kilograms of feed to 1 kilogram of chicken, are in terms of kilograms of feed required per kilogram of live weight gain [35]. However, not all of the live weight of an animal is edible to humans. For example, on average only 60% of beef cattle live-weight is edible [36]. To determine the edible feed to edible meat calorie conversions, we utilize USDA feed to live-weight conversions [35], the proportion of animal live weight that is carcass (also known as the "dressed weight"), as well as data on the calorie content of animal carcasses [3, 36]. For example, the beef conversion efficiency used here uses a feed to liveweight conversion of 12.7 [35], and a dressing proportion of 0.6 gives us tonnes of feed per tonne of carcass weight by: $\frac{12.7}{1}$ tonnes feed per tonne liveweight $\times \frac{1}{0.6}$ tonnes of liveweight per tonne of carcass $= \frac{21.17}{1}$ tonnes feed per tonne of carcass weight. This study estimates the inputs and outputs of livestock production on feed grains and does not account for the weight gains beef and dairy cattle obtain during their weaning and grass fed stages (See Appendix).

	Dairy	Eggs	Chicken	Pork	Beef
Calorie conversion efficiency (%)	40	22	12	10	3
Protein conversion efficiency (%)	43	35	40	10	5

Table 1. Livestock conversion efficiencies in calories and protein. Feed to food calorie conversion efficiencies for milk, eggs, chicken, pork, and beef, are shown from left to right. Conversion efficiencies are modified from Smil, 2000a [27](See Appendix).

Our analysis only considers the production of meat and dairy production from animal feed; grazing systems for animal production are not evaluated here. Naturally, animal grazing introduces calories into the food system that did not originate in feed crops;

accordingly, beef cattle grazing was accounted for by including only beef that was produced in landless or mixed crop-livestock systems [23]. Additionally, other ruminants (goats, sheep, etc) were not considered in this study, as they typically do not consume feed grains.

Results

Global Crop Allocations

We investigated crop allocations both in terms of calorie content and protein content. We find that on a global basis, crops grown for direct human consumption represent 67% of global crop production (by mass), 55% of global calorie production, and 40% of global plant protein production (Table 2). Feed crops represent 24% of global crop production by mass. However since feed crops like maize, soybeans, and oil seed meal are dense in both calories and protein content, feed crops represent 36% of global calorie production and 53% of global plant protein production. Together crops used for industrial uses, including biofuels, make up 9% of crops by mass, 9% by calorie content, and 7% of total plant protein production (Table 2).

	Crop use by calories/protein/weight (%)									People fed per hectare	
Country	Food			Feed			Other use			Produced calories	Delivered calories
India	89	77	92	6	18	4	5	5	4	6.5	5.9
China	58	50	67	33	42	26	9	8	7	13.5	8.4
United States	27	14	37	67	80	57	6	6	6	16.1	5.4
Brazil	45	16	39	41	79	14	14	5	27	10.6	5.2
World	55	40	67	36	53	24	9	7	9	10.1	6

Table 2. Global Crop Allocations. Crop allocations in terms of calories, protein and weights of 41 major crops combined are shown, as well as people fed per hectare on produced and delivered calories.

Biofuel production alone represents ~3% of crop production by weight and only 1% of calories produced (sugarcane is a heavy, water-dense crop) for the year 2000. However, biofuel production is estimated to have increased more than 450 percent (in terms of liters produced) between the year 2000 and 2010 [29], representing a significant shift of additional crops to non-food uses. Unfortunately, FAO statistics do not yet differentiate biofuels from other industrial crop uses, making it difficult to have systematic tracking of biofuel consumption of crops. However, looking at other sources for 2010 biofuel statistics, ethanol production from maize in the United States and sugarcane in Brazil alone now represents 6% of global crop production by mass and 4% of calorie production [30].

The allocation of crop production to different uses differs greatly by nation. To illustrate this we will discuss how crop allocations differ in four key countries: India, China, Brazil and the United States. Combined these countries represent 43% of the total cropland area, as well as 48% of global calorie production. India produces mostly wheat and rice, which are primarily used as food for direct consumption. During the study period India directed 89% of produced crop calories to food, and only 6% of crop calories (and 18% of produced plant protein) for animal feed, and the remaining 5% of produced calories (and plant protein) for other uses (Table 2).

China was the world's top producers of rice in the year 2000, and used 82% of rice calories for direct human consumption. However, China was also the world's second largest producer of maize, a major feed crop. China allocated 77% of produced maize calories to animal feed. Overall, a third of produced calories in China went to animal feed, which is 42% of produced plant protein (Table 2). Half of the plant protein produced in China was used for food, which represents 58% of produced calories.

Brazil has similar crop allocation patterns to China in terms of calories. Forty-five percent of crop calories are directed to food for direct consumption (Table 2). Feed calories in Brazil represent 41% of produced calories, and the remaining 14% of calories were directed to biofuels and other uses. Brazil has drastically different crop use proportions than China with respect to the allocation of crop protein. This is due to the fact that more than half of Brazil's soybean production is directed to animal feed. Only 16% of the plant protein produced in Brazil is directed to food, and 79% of produced protein is directed to animal feed.

Like Brazil, the United States directs a majority of produced plant protein to animal feed, but in the United States animal feed also represents more than half of produced calories. During the study period the United States used 27% of crop calorie production for food, and only 14% of produced plant protein is used for food directly. More than half of crop production by mass in the United States is directed to animal feed, which represents 67% of produced calories and 80% of produced plant protein (Table 2). In 2000, biofuels and other industrial uses accounted for 6% of calories, 6% by mass, and 6% by protein content. The United States is the leading producer of maize, which is the world's primary feed crop. However, maize usage is changing rapidly over time: from 2000 to 2010, a greater proportion of maize has been directed to maize ethanol production. In the U.S. for example, maize ethanol production jumped from 6% of U.S. maize production to 38% in the year 2010 [29, 30].

Calorie Delivery and People Fed per Hectare

From the 41 crops analyzed in this study, 9.46×10^{15} calories available in plant form are produced by crops globally, of which 55% directly feed humans. However, 36% of these produced calories go to animal feed, of which 88% is lost, such that only 4% of crop-produced calories are available to humans in the form of animal products. Another 9% of crop-produced calories are used for industrial uses and biofuels and so completely lost from the food system. Including both human-edible crop calories and feed-produced animal calories, only 5.57×10^{15} (59% of the total produced) calories are delivered to the world's food system (Figure 1). Therefore, 41% of the calories available from global crop production are lost to the food system.

Put another way, shifting the crops used for feed and other uses towards direct human food consumption could increase calories in the food system by 3.89×10^{15} calories, from 5.57×10^{15} to 9.46×10^{15} calories, or a ~70% increase. A Quadrillion (1×10^{15}) food calories is enough to feed just over 1 billion people a 2,700 calories per day diet for a year (which is 985,500 calories per year) [4]. Therefore, shifting the crop calories used for feed and other uses to direct human consumption could potentially feed an additional ~4 billion people.

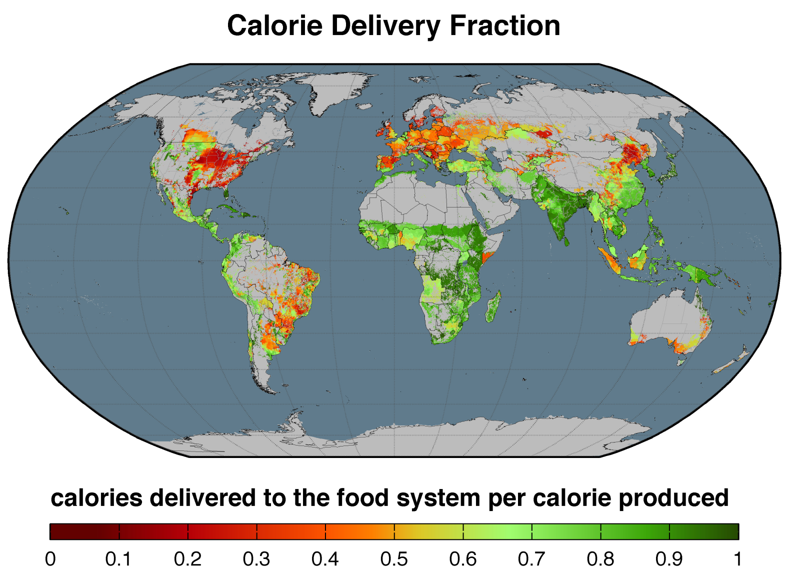


Figure 1. Calorie delivery fraction per hectare. The proportions of produced calories that are delivered as food are shown.

These changes in calorie availability are mirrored by changes in the availability of protein in the food system through changes in global crop allocation. Of the total plant protein produced, only 49% is delivered as plant and animal protein to the food system. Therefore, shifting all crop production to direct human consumption could double protein availability. In the United States, only 14% of produced protein is used as food and 80% of protein is used as animal feed. Because of the high proportion of plant protein being used as animal feed, only 27% of plant protein produced in the U.S. is available for consumption (as either plant or animal product).

Our results show that many of the most productive crops, such as maize and soybeans, are responsible for a high proportion of losses to the food system via livestock and biofuel production (Figure 2). On a global basis, 74% of maize production goes to animal feed. Therefore most of the produced maize calories are lost to the feed to animal production conversion, and increasingly to ethanol production. Only 24% of the global maize calories produced are delivered to the food system as either plant or animal products (Figure 2).

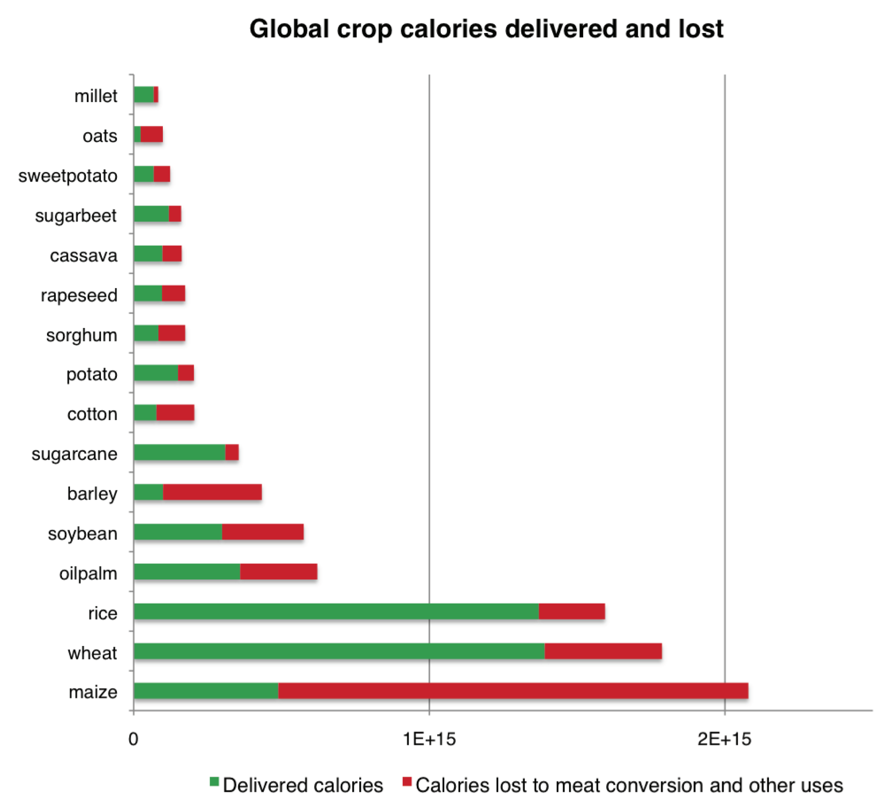
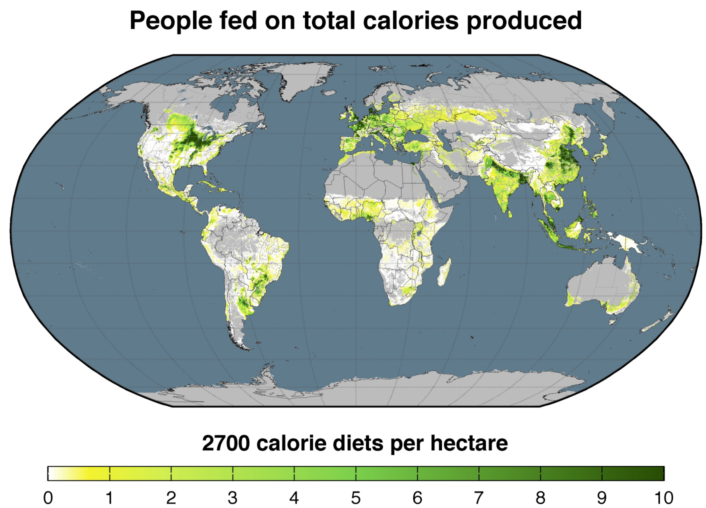


Figure 2. Calorie delivery and losses from major crops. Calories delivered are shown in green (this includes plant and animal calories) and calories that are lost to meat and dairy conversion as well as biofuels and other uses are shown in red.

From the calories delivered to the food system from cropland hectares, we calculate the number of people fed a nutritionally adequate 2,700 calorie diet per day. We consider 41 crops on 947 million hectares of cropland and show that production of raw plant calories is adequate to feed 10.1 people per hectare (Figure 3a), but that calories delivered to the food system, after accounting for animal feed, biofuels and other non-food products, only feed 6 people per ha (Figure 3b).



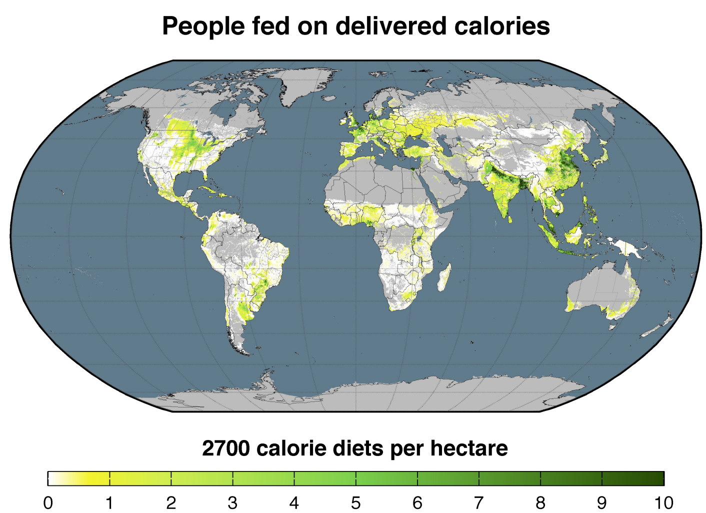


Figure 3 (a & b). Calories produced per hectare (9.46 x10^{15} calories total), divided by 2700 calorie per day diets (985,500 calories per year) are shown in Figure 3a. People fed per hectare from calories that are delivered to the food system (after feed to meat conversions, and biofuels and other uses are taken out) are shown in Figure 3b.

Calorie delivery and people fed per hectare differ greatly between major crop producing nations (Table 2). Because India dedicates land to mostly food crops and 89% of crop calories are used for direct human consumption, the calories produced on croplands and the calories delivered are similar: 90% of the calories produced in India are delivered to the food system. The number of people fed per cropland hectare on calories delivered on Indian croplands averages 5.9 people per hectare, a result of a 90% rate of calorie delivery to the food system. If all produced calories were delivered as food, this figure would rise slightly to 6.5 people per hectare. On delivered calories India is able to feed 5.9 people per hectare, which is about the global average of 6 people fed per hectare. This is a result of a high delivery fraction yet a low number of calories *produced* per hectare in India as compared to the global average.

China produces one fifth of the world's meat, egg and dairy calories, and almost half of the world's pig meat. China uses 58% of its crop calorie production for food and 33% for feed. Of the total calories produced in China, 62% are delivered to the food system. China feeds more people than India per cropland hectare with 8.4 people fed with delivered calories, albeit with a lower calorie delivery fraction of 62%. If all produced calories were food, that number would rise substantially to 13.5 people per hectare.

Brazil directs 46% of calorie production to human food and 41% to animal feed. Of the calories produced in Brazil, 50% are delivered to the food system. Therefore, Brazil could feed twice as many people per hectare. Croplands in Brazil could feed 10.6 people per hectare, but only feed 5.2 people. A high proportion of Brazil's calorie production goes to animal feed. Soybean production in Brazil accounted for 28% all calories produced, and over one-third of soybean production was exported to other nations. Calorie delivery reflects the number of calories delivered to the global food system per calorie produced on croplands, regardless of where they are consumed. In the case of soybeans produced in Brazil, if they are exported to another country and used as feed, those calorie losses are reflected on Brazilian croplands, not in the importing nations that use them.

The U.S. uses 67% of total calorie production for animal feed. Because so much of the United States calorie production goes to animal feed, only 34% of the calories produced in the U.S. are delivered to the food system. The U.S. is the world's top producer of beef cattle, producing 22% of global beef supply. The number of domestically produced calories allocated to feed in the United States is 1.8 times the number allocated to feed in China. Yet when we look at the total of all meat, egg, and dairy calories produced, China produces 44% more than the United States [37]. However, because these numbers reflect allocation of only domestically produced feed crops, we aren't fully capturing grain-fed livestock production in China. China's livestock production is more import dependent than the United States. This is especially the case for soybeans imported to China from Brazil [38]. For example, in 2000 45% of soybean supply in China was imported, and that proportion has increased over time to roughly 70% in 2009 [31].

The United States could feed almost three times as many people per cropland hectare on calories produced from major crops. U.S. croplands feed 5.4 people per hectare but could feed 16.1 people per hectare if the current 34% efficiency rose to 100%. The U.S. agricultural system alone could feed 1 billion additional people by shifting crop calories to direct human consumption.

Alternate Diet Scenarios

Shifting all crops currently allocated to animal feed back to human food implies that either the global population would stop consuming animal products, or else the only sources of animal products would be grass fed or wild caught. However, we also investigated different scenarios of diet shifts that could increase global calorie availability. Shifting grain-fed beef production equally to pork and chicken production could increase feed conversion efficiencies from 12% to 23%, which would increase global calorie delivery by 6% (or 3.52×10^{14} calories), representing 357 million additional people fed on a 2700 calorie per day diet. Alternatively, shifting all feed directed to meat production to the production of milk and eggs (or a lacto-ovo vegetarian diet) could increase feed conversion efficiencies to 35%, which would increase calorie delivery by 14% (or 8.04×10^{14} calories), representing 815 million additional people fed. In both cases the feed allocated to livestock production stays the same as it was during this study period, but more meat, egg, and dairy calories could be produced from this feed as a result of efficiency gains. Of course, reducing the consumption of meat and dairy can also have large impacts on calorie delivery. For example reducing the consumption of grain-fed animal products by 50% would increase calorie availability enough to feed an additional 2 billion people.

Discussion and Conclusions

The pressures on the world's food system in the coming decades – from population growth, increased meat consumption, and increased demand for biofuels – will place a tremendous burden on the world's croplands. While many efforts to address food security have focused primarily on improving crop yields [39, 40], it is also possible to dramatically increase the availability of food in the world by shifting the allocation of our crops from animal feed and biofuels towards more direct means of feeding the human population.

This study's estimates of food availability are pre-waste, and waste significantly reduces food availability. A recent study estimates food waste accounts for up to a third of crop production [41]. It's important to note food calories that are not produced from croplands were not included in this study, and in many parts of the world can be significant sources of protein (notably grass fed goats and sheep, as well as marine derived food products). In addition, the feed calculations in this study were limited by the crops we had the nutritional contents for, which are human-edible crops. Grassy forage crops and crop residues were not accounted for in this study and would change the livestock conversion efficiencies. A conclusion that could be made from our findings is that without large amounts of supplementation from grasses and crop residues, we are able to produce 41% (4.11×10^{14} calories) of total livestock production (1.01×10^{15} calories). We caution that this is unrealistic. This study separates human-edible crops from other forages due to data limitations, but this split is hypothetical. Livestock production requires a mix of grassy forages, crop residues and human-edible feed crops.

A limitation of this study is that it treats plant and animal proteins equally, even though their proteins differ in bio-availability and amino acid content. Animal proteins contain all the amino acids not produced by the human body (which are essential amino acids). However, cereal crops as well as legumes can be combined to provide all of the essential amino acids for complete proteins [42]. In order to produce the appropriate amino acids in places currently directing much of their production to animal feed, the crops produced would likely need to change (i.e., more legumes). Future studies are needed to investigate how changing diets may impact agricultural landscapes.

In this study, we demonstrate that global calorie availability could be increased by as much as 70% (or 3.88×10^{15} calories) by shifting crops away from animal feed and biofuels to human consumption. To put this number of calories in perspective, we investigated the additional calories produced from yield increases alone for maize, wheat, and rice in recent decades, keeping cropland extent constant at 1965 levels [37]. We find the increased number of calories available from shifting crop allocations is approximately equal to the number of calories gained from yield increases for these three crops over the period from 1965 to 2009. Addressing future challenges to food security can thus be met by increasing both the supply of crop production *and* the way we manage global demands for crops, especially by making human consumption a top priority over animal feed and biofuels.

However, we face a world where the opposite may be happening. For example, the demand for meat and dairy is expected to increase by 68% for meat and 57% for dairy by 2030 [43]. In addition, biofuel production from food crops has increased sharply in recent years, which has directed more calories away from feed and human food. One recent study estimates feeding nine billion people a Western diet with Western technologies would require almost twice the amount of cropland currently under cultivation [15]. Of particular concern is the environmental impact of developing new agricultural land [3]. In 1980s and 1990s, tropical forests were the source of over 80% new agricultural land [7]. Given that global population is increasing and diets are changing, the number of people fed per cropland hectare must increase in order to meet the challenges of food security and prevent further cropland expansion into tropical forests [2].

While shifting the use of crops as animal feed and biofuels would have tremendous benefits to global food security and the environment, there are numerous political and cultural obstacles to such a shift [13, 14]. However, in some places, a shift towards less meat-intensive diets is underway, primarily as a result of health concerns [44]. Many people in affluent nations consume more animal products than is nutritionally recommended [45]. Further, overconsumption of red meats is associated with many health problems like obesity [46], cardiovascular disease [47], and some cancers [48, 49]. Reducing meat consumption, or shifting meat consumption away from beef to poultry and pork has the potential to increase cropland food productivity and feed more people per hectare of cropland.

Chapter 2

Healthy Food Subsidy Programs Can Drive Substantial Reductions in Environmental Impact

Emily S. Cassidy, Darren Segal, Derek Yach, Jonathan A. Foley

Summary

Agricultural activity, especially livestock production, is a major driver of environmental degradation worldwide. Of particular concern are animal products, which are generally more land-, water-, and energy-intensive than plant-based foods. Therefore reducing the consumption of animal products could reduce the environmental impacts of agricultural activity. This study investigates a major health insurer's cash-back program to promote healthy eating, including reductions in meat consumption, for 21 thousand people in South Africa. While this program's end goal was to improve human health and reduce the risk of certain non-communicable diseases, we investigate how observed diet changes might affect per capita environmental impacts as well. Using data on crop yields, synthetic fertilizer applications, water consumption and greenhouse gas emissions, we quantify the environmental impacts associated with the production of seven major food categories. Comparing monthly purchases of customers before and after participating in the cash-back program we find significant reductions in proportionate beef, pork and dairy purchase weights. We quantify the reductions in environmental metrics associated with these reductions in animal product purchases. Overall, we find 9.4 percent decrease in overall land requirements associated with their diet, a 8.1 percent decrease in their dietary water footprint, and a 10.7 percent reduction in dietary greenhouse gas emissions associated with these changed purchasing decisions. Small reductions in beef consumption are responsible for a majority of the reductions in environmental metrics. These results show programs incentivizing healthy eating may also reduce the consumption of red meats, and therefore reduce agriculture-related environmental impacts. Such interventions may produce "triple bottom line" wins of

improved health, reduced health care costs, and reduced environmental impacts within the food system.

Introduction

Agriculture and the food system have profound impacts on the environment and our health.

First, agriculture is the single largest human use of land and water and is a major driver of global environmental change [1, 2]. Across the sector, livestock production contributes a disproportionate fraction of the footprint of agriculture. Animal products require substantially more land and water than plant-based foods [50]. In fact, according to a recent study, livestock production occupies 75 percent of all global agricultural land [2]. Livestock production also emits about half of all agriculture-related GHGs, while they contribute only about 12.9 percent of global calorie supply (27.9 percent of protein supply) [43].

Second, our food system – especially through our dietary choices – has a profound impact on our health. Of concern: Non communicable diseases (NCDs) such as coronary heart disease, diabetes, and cancer are the cause of 60 percent of deaths worldwide [51]. One possible strategy to reduce NCDs is with dietary interventions [51]. Recent studies find that food subsidy programs increased the intake of targeted foods and suggest this could reduce the risk of NCDs [52, 53]. For example, consuming more fruits and vegetables can play a significant role in preventing diabetes [54, 55]. Also the consumption of certain red meats is associated with NCDs such as coronary heart disease and certain cancers [47, 48], so reducing the consumption of red meats has the potential to reduce the risk of NCDs [56, 57].

Discovery, a major international health insurer (www.discovery.co.za) initiated a program with South African food retailers to subsidize healthy food purchases. Their 'HealthyFood' program subsidized the purchases of foods they determine with the retailer to be considered healthy by 25%. Healthy foods that were subsidized included vegetables, fruits without added sugars, whole grain cereals, nonfat dairy products, and certain lean meats, among others. A complete list of eligible healthy food items (more than 6000) can be found on Discovery's web- site (www.discovery.co.za). Discovery's HealthyFood benefit program set out to improve the nutrition of policyholders in order to reduce the risk of non-communicable diseases. A recent study confirmed that the HealthyFood program shifted purchasing habits towards healthier foods and reduced the purchase of unsubsidized foods [58]. Sturm et al. [58] tracked dietary changes in terms of proportion of total expenditures. Sturm et al found at a 25 percent rebate level, there was a 9.3 percent increase in the ratio of expenditures on healthy food purchases and a 7.2 percent decrease in the ratio of expenditures on less desirable foods [58]. They also found an 8.5 percent increase in proportionate expenditures on fruits and vegetables [58].

The goal of this analysis is to quantify the environmental impacts of these dietary changes. In this study we show how purchasing habits of HealthyFood program participants change, and quantify this change in terms of environmental metrics such as land requirements, water footprint and greenhouse gas emissions.

Methods

Vitality Scanner Data Analysis

To examine whether participation in the HealthyFood program changed consumption, we used scanner data from "Pick-n-Pay" supermarkets collected by Discovery in South Africa from November 2009 to February 2012. Of the 245,335 Discovery policyholders we had data for, we only analyzed data for those policyholders that joined the HealthyFood program *during* the study period. In this way we tracked consumption changes for the same group of people as a result of HealthyFood program participation. Out of the total 245,335 policyholders tracked, we analyzed data for the 9 percent or 21,972 policyholders that joined some time during the study period.

We examined purchase data (in kilograms) for seven major food categories: fruits, vegetables, cereals, dairy, chicken, pork and beef. Absolute purchase weight per policyholder was found to increase over time, and this was unsurprising given that the subsidy program was expected to give Pick-n-Pay retailers a competitive advantage [58]. Therefore, instead of comparing changes in absolute purchase weights, we compared purchases in terms of proportions of total purchase weights, similar to the methods of Sturm et al. [58]. We compared monthly purchase weight proportions of policyholders before and after program participation using a 2-tailed t-test. We calculated average monthly purchase weight for policyholders that joined during the study period to be 14.35 kilograms. Using this average monthly purchase weight, we estimated how change in purchase weight proportions impacts average environmental impacts per policyholder.

Environmental Metrics

Differences in consumption were used to determine change in diet-related environmental metrics. We estimated the land requirements, water footprint and greenhouse gas emissions associated with crops produced within South Africa. We used several different sources to quantify these environmental metrics.

Water. Water consumption data for the seven food categories were derived from Mekonnen & Hoekstra [59], who documented the water footprints of crops produced at the national-level. Although Discovery food purchase data were pre-sorted into categories, we weighted the water footprint of each food category by the domestic supply quantity (used as a proxy for food available for consumption), according to the FAO's 'Food Balance Sheets' [60], of each crop within that category. For example for cereals, maize represents 57 percent of the domestic supply of cereals in South Africa [60]. Therefore the water footprint calculation for cereals was weighted by water requirements for maize production. Similarly, we determined water footprints for animal products based on crops being directed to feed in South Africa. We used feed compositions and requirements from Bouwman et al. [61](Table 3). Water footprints per kilogram of product are shown in Figure 4.

		Beef	Chicken	Pig	Dairy
Feed requirements	kg feed per kg carcass weight	56	4.1	6.6	3.1
Feed composition	Food + Fodder	0.2	1	1	0.3
	Grass	0.8	0	0	0.7

Table 3. **Feed requirements per animal product**, simplified from Bouwman et al. [61] East Africa estimates. We assumed the Food and Fodder fraction comes from feed stocks documented in the FAO Food Balance Sheets [60] and the grass proportion came from South African mixed grass production from Monfreda et al. [12].

Land. For land requirements, we used crop area and yield data from Monfreda et al. [12]. Monfreda et al. [12] data are 'circa 2000'. Most values are averaged from 1997 to 2003, except where data are missing. From yield data for South African crops, we calculated the land requirements using the following equation:

$$Land\ area = \frac{yield\left(\frac{tonnes}{hectare}\right)}{weight(tonnes)}$$

We then converted land requirements in hectares to land requirements in square meters per kilogram produced (Figure 5). We used the same weighting methods as were used in the water footprints calculations, and weighted the land footprints for each food category by the domestic supply of relevant crops. Land requirements for animal products were determined using the same method as water requirements—weighting land required by crops being directed to animal feed according to FAO FBS [60], with feed compositions and conversions shown in Table 3.

Greenhouse Gases. Agriculture related greenhouse gas (GHG) emissions come from many sources: major sources include enteric methane emissions from ruminants, nitrous oxide emissions from crop fertilization, carbon dioxide emissions from land use change, and nitrous oxide emissions from manure management [62]. While carbon dioxide emissions from land use change are a significant source of agriculture related GHG emissions, we did not include these in our emissions accounting. Land use change is typically a one-time occurrence of a large amount of carbon dioxide emissions and therefore prohibits our ability to associate these emissions with specific commodities grown in a specific year.

In this study we accounted for nitrous oxide (N_2O) emissions from crop fertilization, enteric methane (CH_4) emissions from ruminants, emissions from manure management, and methane emissions from rice cultivation. According to the United Nation's Food and Agriculture Organization, these emission categories account for 94 percent of global agricultural GHG emissions (not including land use change), and in South Africa these emissions account for 97 percent of agricultural emissions [63]. Most of the greenhouse gas emissions associated with livestock production occur during the farm stage, with emissions from processing and transportation representing a minor proportion of emissions [64].

Enteric CH_4 emissions and emissions from manure management were taken from a recent FAO report on livestock emissions [62]. This FAO report uses IPCC 2007 [8] methods to determine kilograms of CO_2 equivalent emissions per kilogram of carcass weight for each animal product. Global average emissions per kilogram of carcass weight were used [62].

To determine N_2O emissions associated with the production of a kilogram in each food category, we used recently published data on crop specific fertilizer applications [5]. Using IPCC "Tier 1" estimation methods, we assume a fixed percentage of applied nitrogen fertilizer becomes N_2O emissions [8]. To get category specific emissions from crop specific numbers, we used the same method as land and water metrics and weighted them based on the domestic supply of each crop.

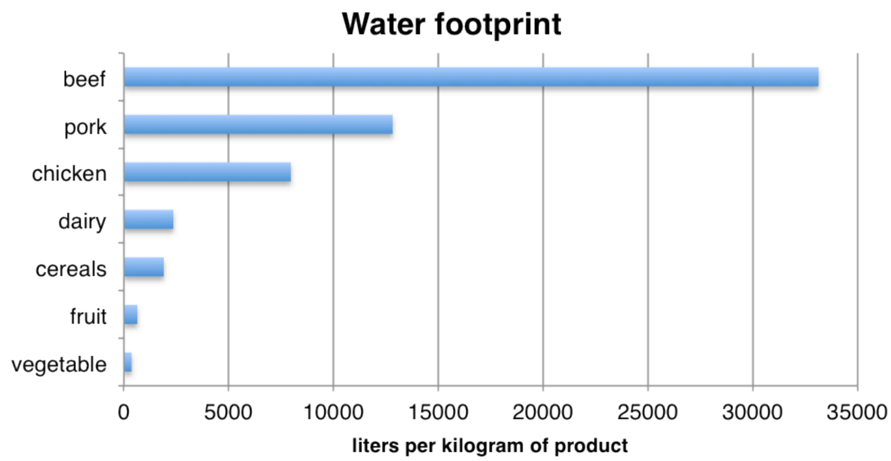


Figure 4. *Water footprint associated with a kilogram of production for seven food categories.*

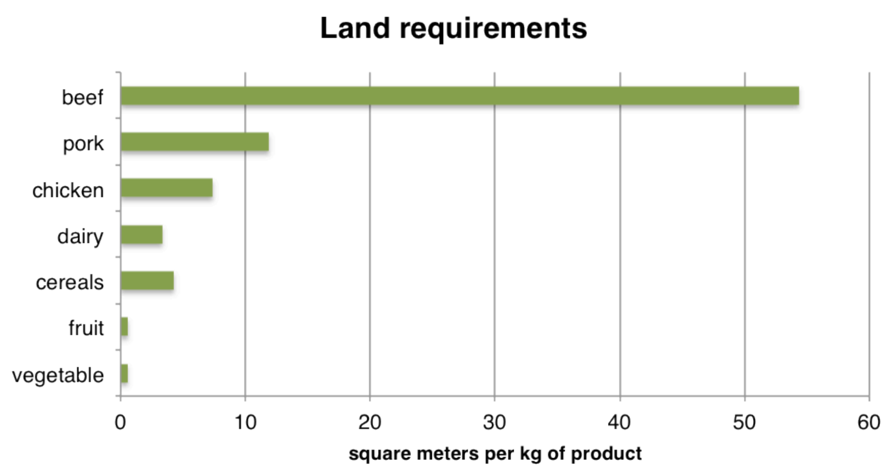


Figure 5. *Land requirements associated with a kilogram of production for seven food categories.*

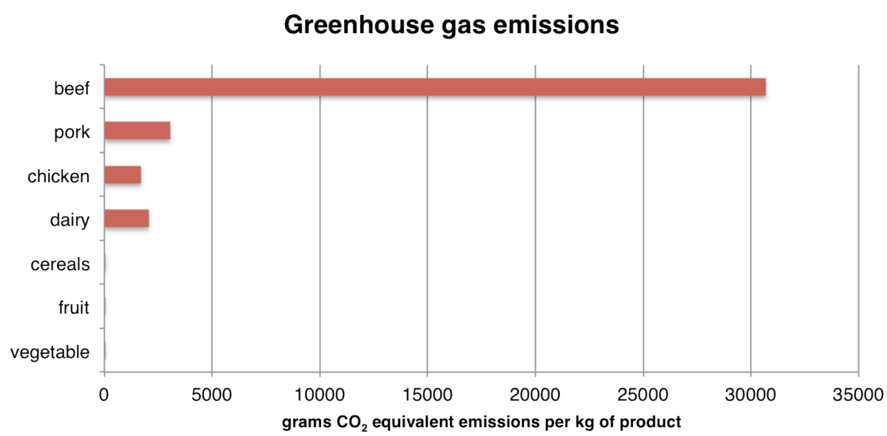


Figure 6. *Greenhouse gas emissions associated with a kilogram of production of seven food categories.*

Results

<u>Change in Purchase weights</u>

Similar to results shown in Sturm et al. [58], we find average monthly consumption of healthy food categories such as fruits and vegetables increased during the study period (Figure 7). Monthly purchase weight of fruits and vegetables for program participants increased as a proportion of total purchases by 8.3 percent (95% CI= 7.2, 9.5) and 4.3 percent (95% CI= 3.6, 4.9), respectively. Monthly average purchase weight proportion of cereals decreased by 14.0 percent (95% CI=10.0, 18.1). Dairy purchase weight proportion decreased by 2.8 percent (95% CI=1.8, 3.7). Chicken consumption increased very slightly by 2.2 percent (95% CI= 0.5, 4.0). Both beef and pork consumption decreased, by 16.8 percent (95% CI=9.9, 23.6) and 11.3 percent (95% CI=8.5, 14.1), respectively.

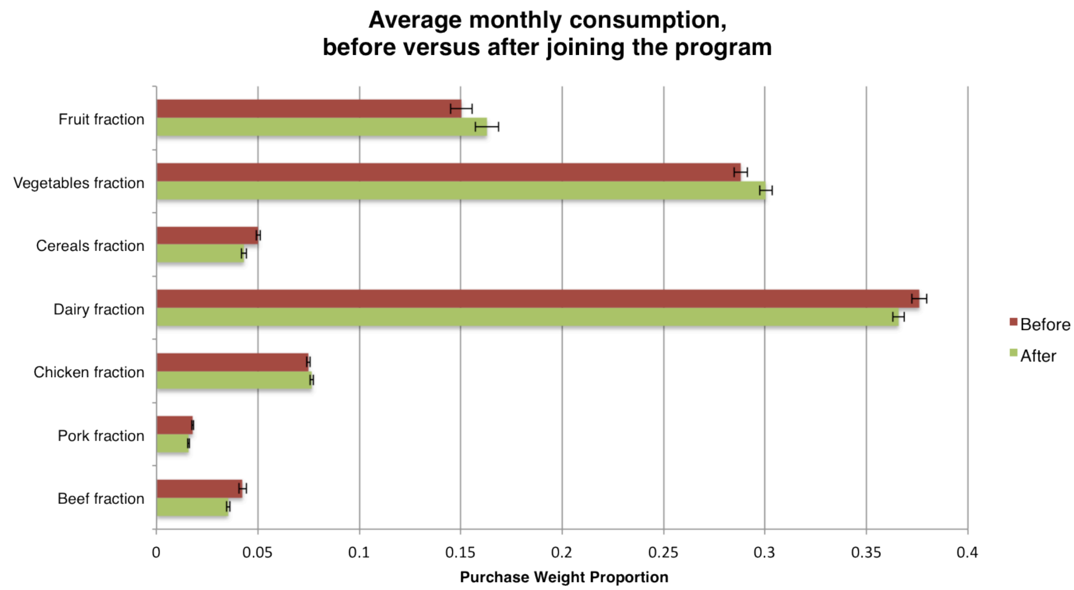


Figure 7. Average proportions of the seven food categories are shown. Error bars show standard errors in both directions (Table 4).

Purchase weight proportion by participation status

	Beef **	Pork**	Chicken	Dairy*	Cereals**	Vegetables**	Fruit
Before	0.0425 (0.0019)	0.0179 (0.0005)	0.0750 (0.0008)	0.3761 (0.0036)	0.0501 (0.0010)	0.2881 (0.0033)	0.1503 (0.0053)
After	0.0353 (0.0008)	0.0159 (0.0004)	0.0767 (0.0008)	0.3658 (0.0028)	0.0431 (0.0013)	0.3004 (0.0032)	0.1629 (0.0058)

*p-value < 0.05 **p-value < 0.01

Table 4. Average proportions of the seven food categories are shown by participation status. Standard errors are in parentheses.

<u>Environmental Impacts</u>

Based on the consumption changes described above, we calculated the change in relative environmental footprint as a result of program participation. Using an average purchase weight of 14.35 kilograms, we show changes in relative environmental footprint.

We find a 10.7 percent reduction in greenhouse gas emissions, a 9.4 percent reduction in land area requirements, and an 8.0 percent reduction in water requirements associated with these diet changes. Environmental metrics associated with 14.35 kilograms of consumption per month changed in the following ways: Water footprints changed from 49,020 liters to 45,094 liters per month; land requirements were reduced by 6.4 square meters per month, from 68.7 to 62.3 square meters; greenhouse gas emissions went from 32.7 kilograms to 29.2 kilograms of CO_2 equivalent emissions per month.

Beef represents a small proportion of total purchase weights (on average, 4.3 percent before program participation), but it represents a large proportion of total diet related environmental metrics. Before program participation, beef represents 37 percent of total water footprint, 44 percent of land requirements, and 53 percent of total greenhouse gas emissions (Figure 8). The small change in beef consumption seen here (from 4.3 percent to 3.5 percent of purchase weights) drives much of the change in environmental metrics. These observed reductions in beef purchases are responsible for 86 percent of the reduction in water and land footprint, and 90 percent of reductions in GHG emissions.

Reductions in pork purchase weight are responsible for 9 percent of water footprint reductions, 2.5 percent of reductions in greenhouse gas emissions, and 5 percent of the reductions in land requirements.

Average GHG emissions were reduced by 3.49 kilograms of CO_2 equivalent emissions per month per policyholder, or 41.85 kilograms CO_2-equivalent emissions per year. (For comparison, assuming average fuel efficiency of a passenger vehicle in South Africa is 175 grams CO_2 / kilometer [65], these yearly CO_2 savings translate to reducing travel by 239.12 kilometers per person.) The product of these per capita emissions savings and the 21,972 policyholders is 919,437 kilograms of CO_2 equivalent emissions per year.

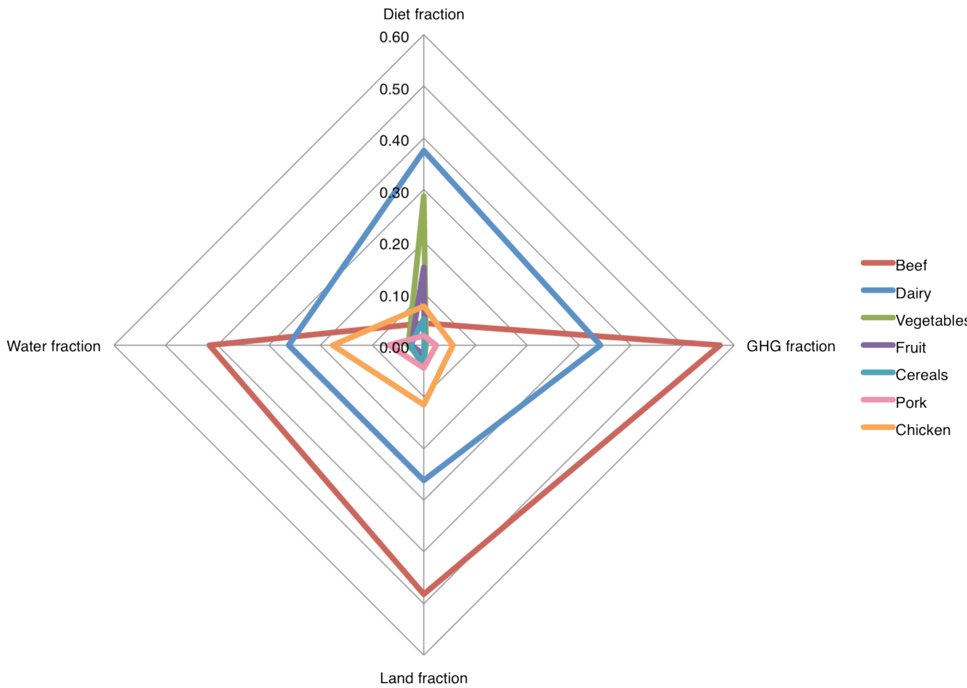


Figure 8. Proportionate make-up of food categories in terms of total diet (weight proportions) (top), total water footprint (left), land requirements (bottom), and total GHG emissions (right).

Program participation reduced water footprint by 8.0 percent or 3,926 liters per policyholder per month. According to Hoekstra & Chapagain [66] domestic per capita water use in South Africa is 4,750 liters per month. Therefore in a month Healthy Food program participation saves 24.9 days of domestic water consumption per capita. And annually program participation saves about 10 months of average domestic water consumption.

To put these results in context, if every South African in the year 2009 reduced beef consumption from 4.2 percent of their dietary purchase weight (or 1.28 kg per month according to the FAO [60]) to 3.5 percent (or 1.07 kg per month) we could expect even greater reductions in environmental metrics. This small shift in beef consumption could reduce per capita water footprints by 81,405 liters per person per year, which for all of South Africa would be 4,050 billion liters saved annually. Per capita GHG emissions would be reduced by 75.4 kilograms of CO_2 equivalent emissions per year. Given there are 49.7 million people living in South Africa in the year 2009, that would be a total GHG emissions reduction of 3.75 Megatonnes CO_2 equivalent. This is the equivalent of cutting South African transportation sector emissions by 8 percent, or a 1 percent reduction in all South African anthropogenic greenhouse gas emissions.

Discussion and Conclusions

Non-communicable diseases are a major threat to public health as well as economic growth. Health care costs in South Africa represent 8.3 percent of Gross Domestic Product [67], and much of these costs are spent on treating diseases that could have been prevented. One study estimates that healthcare costs attributable to high levels of meat consumption in 1992 were anywhere between \$28 – \$61 billion [56]. Lifestyle interventions such as the HealthyFood program have the potential to improve the health of participants by reducing NCDs, which are responsible for 60 percent of deaths worldwide [51], as well reduce health care costs. More research is needed to quantify the long-term health outcomes of HealthyFood program participants.

Limitations to this study include the fact that we may not be capturing all of policyholder purchasing habits. Even though Pick-n-Pay retailers have a majority of the market share in South Africa [58], policyholders may also be shopping elsewhere for groceries. In addition, this study is limited to foods that could be categorized into seven food categories, so we are not including foods that could not be put into these categories.

This analysis did not account for environmental impact associated with fertilizer production, transportation, food processing, food storage, or food preparation. These activities can be a significant contributor to the life cycle GHG emissions of diets [68, 69].

Although the end goal of the Discovery's HealthyFood program examined here was to improve the health of policyholders, we find such a subsidy programs can have significant environmental benefits. These results show how small changes in dietary habits, away from beef and pork, and towards fruits and vegetables, can have significant environmental benefits. Even slight changes in meat consumption (especially beef) had a large disproportionate impact on environmental impacts.

Diet interventions like this could, if designed well, have profound impacts on the triple bottom line of improved human health, lowered economic costs to health care system, and improved environmental impacts. Tools like this may be one of the effective solutions the world's food system needs.

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Appendix

Supplementary Information

1. ***Crop Allocation Methods***
2. ***Livestock Conversion Methods***
3. ***Calorie availability increases from yield improvements***

a. Crop Allocation Methods

Data from Food and Agriculture Organisation's Food Balance Sheets (FBS) were used to determine the crop allocations of 41 major crops: apples, bananas, barley, beans, cassava, cereals other, citrus other, coconuts, cottonseed, dates, fruits other, grapefruit, grapes, maize, millet, oats, oil crops other, olives, onions, oranges and mandarins, palm oil, peas, pineapples, plantains, potatoes, pulses other, rape and mustard seed, rice (paddy), roots other, rye, sesame seed, sorghum, soybeans, sugar beet, sugar cane, sunflower seed, sweet potatoes, tomatoes, vegetables other, wheat, yams [1].

The FBS split crop allocations into categories of Food, Feed, Processed, Other Utilization, Waste and Seed. These categories reflect how the domestic supply of a given crop is allocated. The domestic supply of a crop is give by FAOSTAT as: domestic supply = production – exports + imports +/- stock variations [1]. However, in this study we focused on how crop production (averaged over 1997 – 2003) in a given country was allocated, either domestically or externally. In other words we determined how crops produced within a country are used, regardless of where they are used. In order to approximate how crop production in a given country was allocated, we determined country specific crop allocations from FBS data, which were applied to an approximated domestic supply, which is: approximated domestic supply = production – exports. Exported crops accounted for 10% of produced calories circa 2000. These exported crops were allocated based on global average crop specific allocations. We calculated a global average allocation for each crop based on importing nations' allocations [2]. These importing nations' allocations were weighted by how much each nation was importing, and how they allocate their domestic crop supply. This results in country specific allocations for each crop, equation 1 in the main text:

$$\text{Crop Allocation}_{c,n} = ([\text{production}_{c,n} - \text{exports}_{c,n}] \times \text{domestic allocations}_{c,n}) + (\text{exports}_{c,n} \times \text{importing nations' allocation}_{c})$$

where Crop Allocation$_{c,n}$ represents the crop uses (subscript c) for a given nation (subscript n), and importing nations' allocation$_c$ is a crop specific global average use of importing nations.

In order to describe crop allocations in terms of Food, Feed, and Other non-food uses, we had to estimate how the 'Processed', 'Seed' and 'Waste' categories of the FBS would be allocated. We determined how Processed crops were used based on the crop type. Oil seed crops (rape and mustard seed, soybeans, sunflower seed, cotton seed, sesame seed and oil crops other) were assumed to be processed into oils for human consumption and meal for animal feed. The fraction of the crop that is oil (Table SI) was taken from Oilseed Crops[3], and are similar to FAO Technical Documentation [4].

For all other (non-oil seed) crops, 'Processed' crops were allocated into food and feed based on how the rest of the domestic supply was being allocated into food and feed. For example: Food, 3 tonnes; Feed 3 tonnes; Processed, 4 tonnes; we would allocate Processed weight back into food and feed (Food, 5 tonnes; Feed, 5 tonnes).

Other utilizations include biofuel and other industrial uses [1]. We derived crops being allocated into the 'Other utilizations' category both by the FBS 'Other Utilization' allocation as well as our calculations of crops being allocated to biofuel production. We assume the "Other utilization" category as defined by FAOSTAT did not already include crops routed to biofuels, because the crop weight routed to this category was much smaller than the weight reported being routed to biofuels from World Watch Institute [5]. For example, in the year 2000 maize production routed to 'Other Utilization' was 7 million tonnes, whereas maize production routed to biofuels in the year 2000 is over 14 million tonnes [5, 6].

Crops allocated to biofuels were determined for major biofuel producing nations in the year 2000: United States, Brazil, Germany and France. In the year 2000, the United States and Brazil used maize and sugar cane as their respective biofuel feedstocks, whereas France and Germany used rapeseed for biodiesel production. Data on the magnitude of crop production used for biofuel production in 2000 were taken from the World Watch Institute [5]. For maize and rapeseed production being used for biofuels, we assumed after processing the oil is used for biofuels and is in the 'Other' crop allocation category. Oil extracted from maize was estimated to represent 66% of calories of maize used for ethanol production. The remaining 34% maize calories were allocated to 'Feed'(Table S2). We assumed all of the protein content of processed oil crops was left in the meal, or dried distiller's grains in the case of maize, and allocated to 'Feed'. We used the same methods to calculate crop allocations to biofuels in 2010 (Table S3), using FAPRI biofuels data [7]. In the main text when referring to the mass of calories of a crop being directed to biofuels, we are referring to the total amount being allocated. However, when referring to the calories ending up in 'Feed' and 'Other' we are accounting for the 34% of corn being redirected into dried distiller's grains (DDGS) [8], and 41% of rapeseed being redirected to 'Feed' as meal (Table S2).

b. Livestock Conversions

A major component of this study is determining how many food (meat, dairy and egg) calories were derived from crop feed calories (which comprise 36% of global calorie production). While there are many ways to derive feed to animal product conversions, this study is interested only in the fate of human-edible feed crops.

There are many different ways of calculating feed conversion ratios in the literature [9, 10]. These feed conversion ratios differ based on the assumptions made about the composition of livestock diets. Monogastrics (in this study chickens and pigs) typically have diets dense in grains because unlike ruminants, they are unable to properly digest grasses. Ruminants (in this study beef cattle and dairy cattle) have periods during their life cycle where they consume only grasses, and later in their life cycle consume feed more dense in calories, containing grains such as maize, wheat, soy meal, etc. The feed conversions used in this study approximates the feed grain to ruminant meat and dairy calorie conversion during the stage of the life cycle that cattle are on feed (as opposed to weaning and grass fed stages). In this way we are only accounting for the inputs and outputs of production systems while livestock are being fed grains. We are limited, however, by lack of global data on the inputs and outputs of grain-based livestock production systems. For livestock conversions used here we estimate the proportion livestock types consuming feed grains, and how efficiently they are converted into animal products.

In general we assume the kinds of livestock consuming feed grains is proportionate to their production. Livestock products tracked in this study were chicken meat, pig meat, chicken eggs, cattle meat, and cow milk. We also wanted to account for beef cattle that are grazed throughout their life cycles and don't consume feed grains. The proportion of beef cattle that is produced from grazing production systems differs globally. Livestock's Long Shadow estimates 16% and 32% of beef cattle is produced from grazing systems in developed and developing nations respectively [11]. In this study we defined 'developed' nations to be in the World Bank's 'high income' economic group [12]. Therefore livestock conversions derived in this study include beef cattle produced only in mixed and landless production systems. However, even when cattle are on calorie-dense feeds, there can be a substantial component of the feed from grassy fodder crops. Therefore in this study we assumed beef cattle feeds have a 15%

grassy fodder component (as reported by the USDA) [13] and dairy cow feeds have a 60% grassy fodder component [14].

Livestock conversions differ a great deal dependent on feed composition. Typically feeds with higher grass content have higher feed conversion ratios (requiring more feed per kilogram of animal product), and feeds dense in grains have lower feed conversion ratios. For this study we used the United States Department of Agriculture (USDA) reported conversions for livestock on feed [15]. These conversions are given in terms of kilograms of feed required per kilogram of live weight gain. In order to derive feed calorie to animal product calorie conversions, we had to translate these USDA feed conversion ratios into feed to carcass weight conversions using dressing proportions for beef cattle, chickens and pigs. Table S4 shows 'dressing percentages' of the livestock considered in this study, as well as the range of reported dressing percentages from the FAO [4]. The dressing percentage of beef cattle used in this study (0.6) was higher than the FAO reported ranges (0.4 – 0.57), but has been reported as high as 0.6 elsewhere [16, 17].

Livestock conversion sensitivity

Assumptions of feed conversion efficiencies (tonnes of feed required for a tonne of animal live weight gain) impact the calorie delivery of global feed calories. Smil's 'Feed the World: A Challenge for the Twenty-First Century' details the USDA reported range of feeding efficiencies of major livestock types from ~1910 to 2000 [18]. We can use this range of feeding efficiencies, as well a the FAO range of dressing proportions (Table S4) to define an upper and lower bound of livestock conversion efficiencies for livestock on feed. Table S5 shows the range of feeding efficiencies for the livestock products tracked in this study.

From the range of feed conversion efficiencies and dressing proportions, we defined our upper and lower bound feed conversion efficiency scenarios. For the High Input scenario, we used the highest reported feed requirements per tonne live-weight gain, and also the lowest dressing proportion. This scenario is similar to the one used in our calorie delivery model in the main text, but it differs on the dressing proportions used for the livestock products. Combining efficiencies of tonnes of feed per tonne of liveweight (Table S5), and assumptions of dressing proportions (Table S4), we determined the tonnes of feed required per tonne of carcass weight (Table S6). For example, the beef conversion efficiency used here uses a feed to liveweight conversion of 12.7, and a dressing proportion of 0.6 gives us tonnes of feed per tonne of carcass weight by: $\frac{12.7}{1}$ tonnes feed per tonne liveweight $\times \frac{1}{0.6}$ tonnes of liveweight per tonne of carcass $= \frac{21.17}{1}$ tonnes feed per tonne of carcass weight. Table S6 shows theses feed to carcass weight conversions, as well as their respective calorie conversions.

Results for global average conversion efficiency of feed calories into livestock product calories for the high input scenario show an efficiency of 10%, which is similar to the average conversion of 12% in the main text (Table S6). The High Input scenario delivers 13% less feed calories to the food system. The Low Input scenario has high dressing proportions (Table S4) and low feed requirements (Table S5). The global average conversion efficiency for the Low Input Scenario was ~20%. This scenario contributes 67% more feed calories to the food system (Table S7). The conversion efficiencies in the main text are more similar to the High Input scenario than the Low Input scenario, but it is reasonable to assume that the United States has more efficient livestock conversions than other countries. Feed conversion efficiencies in Bouwman et al. (2005) demonstrate this [9]. In addition, USDA feed to live-weight conversions for the year 2000 are very similar to the High Input Feeding efficiencies in Table S5 [15].

Calorie availability increases from yield improvements

In order to put some of our results in perspective, we analyzed how changing yields have impacted food availability. In this paper we find shifting crop allocations away from animal feed, biofuels, and other uses to direct human consumption could increase global crop availability by 70% (which is 3.88×10^{15} calories). We used FAO production statistics to analyze how changing yields for maize, wheat and rice [6], as opposed to increasing cropland area, has impacted calorie availability. If we look at the average yields for maize, for example: maize yields have increased from 2.16 to 5.13 tonnes per hectare on average globally. Wheat increased from 1.27 to 3.03 tonnes per hectare, and rice increased from 2.09 to 4.32 tonnes per hectare [6]. Keeping harvested areas for these three crops at their 1965 levels, we multiplied yield increases by 1965 crop extent for each crop to determine the number of calories we produced from yield increases alone. We determined the number of calories gained from yield increases from these 3 crops, from 1965 to 2009, amounted to 3.18×10^{15} calories, which is 82% of the 3.88×10^{15} calories we could get from shifting crop allocations.

Table S1
Oil content proportions by crop type

Crop type	Oil content[1]	
	Weight	*Calories*
Cotton seed	0.18	0.39
Oil palm	0.4	0.65
Oil crops other	0.33	0.77
Rape and mustard seed	0.33	0.59
Sesame seed	0.43	0.66
Soybeans	0.19	0.47
Sunflower seed	0.42	0.66

Oil proportions of the relevant crop are shown in terms of weight and calories.
1. Calculated from [3] and similar to [4].

Table S2
Biofuel Crop Allocation Year 2000

Country	Crop	Tonnes	Calories	Feed %	Feed calories	Fuel Calories
USA	Maize	14759615	5.28E+13	0.34[1]	1.80E+13	3.49E+13
FRA	Rapeseed	1089325	5.38869E+12	0.41[2]	2.21E+12	3.18E+12
DEU	Rapeseed	1089325	5.38869E+12	0.41[2]	2.21E+12	3.18E+12
BRA	Sugarcane	116279070	3.38842E+13	0	0.00E+00	3.39E+13
Total		**1.33E+08**	**9.75E+13**		**2.24E+13**	
Proportion of 2000 crop production		**0.03**	**0.01**			

1. Calculated from [8]
2. Calculated from [3]

Table S3
Biofuel Crop Allocation Year 2010

Country	Crop	Tonnes	Calories	Feed %	Feed calories
USA	Maize	119512195	4.27867E+14	0.34	1.45475E+14
BRA	Sugarcane	348461000	1.01543E+14	N/A	N/A
Total		467973195	5.2941E+14		
Proportion 2010 crop production		0.06	0.04		

Table S4

Livestock Dressing proportions

Livestock type	Dressing Proportion Range[1]	In Publication	High Input	Low Input
Cattle	0.4 - 0.57	0.6	0.4	0.6
Pigs	0.65 - 0.85	0.7	0.65	0.85
Chickens	0.73 - 0.83	0.75	0.73	0.83

1. Range from FAO Technical Conversion Factors [4]

Table S5
Feeding Efficiencies of livestock in terms of tonnes feed / tonne Live Weight

	In Publication	Range[1]	High Input	Low Input
Beef	12.7	8 - 12.7	12.7	8
Pork	6.5	5 - 6.5	6.5	5
Chickens	2.5	2 - 2.5	2.5	2
Eggs	2.5	2 - 2.5	2.5	2
Dairy	1.1	0.6 - 1.1	1.1	0.6

1. Range from Smil 2000a [18]

Table S6
Livestock feed conversion efficiencies

	Beef		Pork		Chicken		Eggs		Dairy	
	tonnes feed / tonne carcass weight	calorie conversion	tonnes feed / tonne carcass weight	calorie conversion	tonnes feed / tonne carcass weight	calorie conversion	tonnes feed / tonne carcass weight	calorie conversion	tonnes feed / tonne carcass weight	calorie conversion
In publication	21.17	0.0308	9.29	0.1043	3.33	0.1178	2.50	0.2207	1.10	0.4025
Low Input	13.33	0.0489	7.14	0.1356	2.67	0.1472	2.00	0.2399	0.60	0.7380
High Input	31.75	0.0205	10.00	0.1043	3.42	0.1146	2.50	0.2207	1.10	0.4025

Table S7
Livestock Sensitivity impacts on calorie delivery

	Feed calories	Conv efficiency	Converted calories
In Publication	3.45E+15	0.120	4.12E+14
High Input	3.45E+15	0.104	3.60E+14
Low Input	3.45E+15	0.200	6.91E+14

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Crop Calorie Data

EarthStat name	FAO name	Calories per tonne	Tonnes protein per tonne
apple	Apples	479479.33	0.0027
banana	Bananas	614244.63	0.0090
barley	Barley	3360215.93	0.1052
bean	Beans dry	3388881.91	0.2173
cassava	Cassava	1058035.85	0.0080
cerealnes	Cereals nes	3399999.94	0.0800
citrusnes	Citrus fruit nes	258070.35	0.0050
coconut	Coconuts	1430000.04	0.0151
cotton	Cottonseed	4100000.00	0.2300
date	Dates	1885819.82	0.0156
fruitnes	Fruit Fresh Nes	452010.61	0.0051
grapefruitetc	Grapefruit (inc. pomelos)	209379.65	0.0038
grape	Grapes	591589.58	0.0057
maize	Maize	3580802.60	0.0943
millet	Millet	3463917.52	0.0986
oats	Oats	3850000.19	0.1300
oilseednes	Oilseeds Nes	3770116.94	0.1451
olive	Olives	1534649.52	0.0123
onion	Onions dry	394971.60	0.0126
orange	Oranges	295398.96	0.0054
oilpalm	Oil palm fruit	5400000.00	0.0190
pea	Peas dry	3407849.16	0.2268
pineapple	Pineapples	291709.66	0.0028
plantain	Plantains	846666.67	0.0072
potato	Potatoes	702122.60	0.0161
pulsenes	Pulses nes	3281390.25	0.2047
rapeseed	Rapeseed	4940000.00	0.1960
rice	Rice paddy	2800000.00	0.0600
rootnes	Roots and Tubers nes	861611.93	0.0140
rye	Rye	3190000.00	0.1100
sesame	Sesame seed	5747185.43	0.1780
sorghum	Sorghum	3430000.40	0.1010
soybean	Soybeans	3596499.11	0.3631
sugarbeet	Sugar beet	700000.00	0.0130
sugarcane	Sugar cane	291428.56	0.0019
sunflower	Sunflower seed	2982902.68	0.1140
sweetpotato	Sweet potatoes	939797.99	0.0107
tomato	Tomatoes	192585.69	0.0093
vegetablenes	Vegetables fresh nes	220000.00	0.0140
wheat	Wheat	3284000.00	0.1120
yam	Yams	1090000.00	0.0170