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Phosphorus Impacts from Meat-, Dairy-, and Plant-Based Diets

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Abstract

Phosphorus (P) is a finite resource located within certain geologic reserves around the world. Morocco and the Western Sahara together account for roughly 75% of reserves, raising questions of how to more sustainably use this precious resource. Phosphorus is mined from rock and eventually converted into usable fertilizer, which is applied to croplands. This study aims to contribute to the literature on phosphorus sustainability by analyzing the yearly diet choices of an average American consumer using Life Cycle Assessment (LCA) software. When ascertaining dietary phosphorus use, meat- and plant-based diets have traditionally been juxtaposed. Using data from the United Nations and a study by a consulting firm in Boston, the LCA queries through the food materials that meat-based, dairy-based, and plant-based diets contain, and yields a rough estimate of total P consumption in kilograms. Findings show that as anticipated, a meat-based diet is higher in P consumption than a dairy-based or plant-based diet and gives credence to the notion that consumers in their everyday lives can affect the sustainable use of scarce resources such as phosphorus. Concluding this report is a brief discussion summarizing literature findings on how to use P more sustainably in other sectors, such as wastewater treatment.

Author's Note

My personal interest in this stemmed from a discussion with my capstone advisor in graduate school. She had mentioned that phosphorus is a hot topic in present research, and I wanted to continue working with LCA. I am particularly interested in anything in the sustainability realm that deals with food or waste and being able to explore diet choices allowed me to better understand what is required to grow different foods.

Keywords: Phosphorus, life cycle assessment, diet, meat, plant.

1.0 Introduction

1.1 Phosphorus

The Food and Agricultural Organization (FAO) of the United Nations estimates that the number of individuals following meat- and dairy-based diets will double by 2050, especially in developing countries (Cordell and White, 2013). This presents a problem in sustainability because meat- and dairy-based diets require up to three times the amount of phosphorus (P) as a vegetarian or plant-based diet (Cordell and White, 2013), which reduces or eliminates the consumption of animal products and by-products. In the coming decades, P usage will increase due to surging interest in meat-based products in rapidly industrializing countries including India, China, and Brazil. This is cause for concern, especially when the impact of climate change on precipitation patterns could mean that much of the phosphorus applied to agricultural lands runs off into waterways. Thus, it is important to analyze the P intensity (raw kilogram P/raw kilogram of food item) of various products to see how consumers can use their diets to shift demand, ultimately affecting overall P consumption.

1.2 Impact of Diet

Diet plays a large part in phosphorus consumption. The more P-intense a food item is, the more P is required to produce it for human consumption. Meat production has contributed tremendously to the increase in mining for phosphorus: according to one study, meat production causes 72% of the global average P footprint (Metson et al., 2012). One of the main reasons meat is so P-intensive is because of the multi-step process required to bring meat to market. Cattle, chickens, pigs, and other animals from which we source meat require feed to grow, and this feed is often grain – which requires P. Meat adds an extra step to the process: instead of the direct human consumption of P-nourished grain, it becomes feed and is eaten by livestock. Additional losses occur in the feed production process (Metson et al., 2012), and animals, depending on size, will need a substantial amount of P to grow and sustain themselves. This is where the P-intensity of meats, especially beef, is amplified.

2.0 Methodology

2.1 Development of Representative Diets

A Morningstar Life Cycle Assessment (LCA) report conducted by Quantis and information from UN Food and Agricultural Organization statistics (FAO-STAT) were the data sources used to model two typical diets within the United States. The two specific libraries used within SimaPro to model food items included the EcoInvent version 3.3 database and the Agri-footprint version 2.0 economic allocation database. Both databases were used in a concerted effort to fully capture phosphorus fertilizer use regardless of the food item pulled through. The Agri-footprint catalogue contains meat items including pork, chicken, and beef, and given that the comparison of meat-based with plant-based diets is inherent to this study, it was an obvious choice.

Table 1: Quantis Modeling Methodology

Category	NHANES Commodities Included	Category Total per Diet	Modeled in SimaPro
Other Veggies	Other Vegetables Tomatoes and Tomato Mixtures	Meat: 60.22 kg Meatless 60.61 kg	Sugar Beet, RoW, market for, 23% Rest of vegetables, GLO, market for: Potato and Tomato, fresh grade, 22% each Maize Grain and Spinach, 5% each Cauliflower and Lettuce, 4% each Broccoil and Onion, 3% each Green bell pepper, Protein Pea, and Carrot, 2% each Celery, Cucumber, and Zucchini, 1% each
Dairy Milk	Milks and milk drinks	Meat 42.22 kg Meatless 109.23 kg	Cow milk, GLO, market for
Fruit Mixture	Citrus fruits, juices Other fruits Fruit juices and nectars excluding citrus	Meat 59.25 kg Meatless 83.07 kg	Citrus Pulp Dried, from drying, at plant/US Economic, 49% Rest of fruits, GLO, market for Apple, 17% Melon and Banana, 8% Grape, 7% Pineapple, 5% Strawberry and Peach, 3%
Grain Mixture	Yeast breads/rolls Grain mixtures, frozen plate meals, soup Pasta, cooked cereals, rice	Meat 100.1 kg Meatless 253.09 kg	Wheat flour, from dry milling, at plant/NL Economic, 74% Maize flour, from dry milling, at plant/US Economic, 11% Rice, GLO, market for, 11% Oat Grain, GLO, market for, 4%
Eggs	Egg mixtures	Meat 17.02 kg Meatless 16.23 kg	Consumption eggs, laying hens > 17 weeks, at farm/NL Economic
Potato	White potatoes, starch vegetables	Meat 38.38 kg	Potato, GLO, market for
Chicken	Poultry	Meat 29.93 kg	Chicken meat, fresh, at slaughterhouse/NL Economic
Beef	Beef	Meat 17.78 kg	Beef meat, fresh, from beef cattle, at slaughterhouse/IE Economic
Fish	Fish and shellfish	Meat 18.77 kg	Can't model (not in SimaPro)
Meat Mixture	Organ, sausages, lunchmeats, spreads	Meat 22.49 kg	Represented as 25.1% beef, 46.6% poultry, 21.5% pork, and 6.8% fish based on Quantis' source data: Beef, poultry (chicken) same as above Pork: Pig meat, fresh, at slaughterhouse/NL Economic
Meat/Veggie Mixture	Meat, poultry, fish w/ nonmeat items	Meat 89.44 kg	Represented as 50/50 split between meat and veggies: Meat and vegetable breakdown same as above
Meat/Veggie/Grain Mixture	Frozen, shelf-stable plate meals, w/ meat	Meat 26.24 kg	Represented as 33/33/33 split between meat, veggies, and grains: Meat, vegetable, and grain breakdown same as above

Source: Dettling et al., 2016

The Quantis LCA report contained self-reported amounts of food eaten within a 24-hour period. Participants surveyed within the 2011-2012 year were asked what they had eaten for breakfast, lunch, and dinner (in kilograms) (Dettling et al., 2016). Averages were found across responses for each meal type, and broken down further into certain food groups, or commodities, as shown in Table 1. Given that the reported amounts only spanned a 24-hour period, this study scaled those totals to an annual aggregate amount in SimaPro.

If the entire self-reported totals for food consumption across a year were to be modeled in the Quantis study, the amounts would have been 624 and 628 kilograms, for meat-based and meatless diets, respectively (meatless equates to plant-based for this study, which is defined as a diet with approximately 80% vegetables, fruits, and grains). However, as demonstrated in Table 2, only 521.84 kilograms of meat-based and 522.23 kilograms of plant-based diets were originally modeled. This is because a screening tool was applied whereby the 10 and 17 largest food commodities (in kilograms) were selected for the plant-based and meat-based diets, respectively. This means that roughly 83% of the Quantis food data was modeled. However, since SimaPro does not contain fish, this study did not model them. This reduced the meat-based diet modeled total from 521.84 kilograms to 503.07 kilograms. Given the discrete food groups reported by consumers and my screening methodology, the plant-based diet total remained at 522.23 kilograms. This is a methodological choice on a functional unit basis, which I concede could slightly skew phosphorus totals higher than the true values for plant-based diets, but not by much.

Table 2: Quantis Diets Modeled

	Weight per diet (in kg)	
Categories	**Meat**	**Meatless**
Other veggies	60.22	60.61
Dairy milk	42.22	109.23
Fruit mixture	59.25	83.07
Grain mixture	100.1	253.09
Eggs	17.02	16.23
Potato	38.38	
Chicken	29.93	
Beef	17.78	
Fish	18.77	
Meat mixture	22.49	
Meat/veggie mixture	89.44	
Meat/veggie/grain mixture	26.24	
	521.84	**522.23**

Source: Dettling et al., 2016

One key component that is absent from the Quantis report is the loss of food items in the supply chain, from food leaving the factory gate up until delivery to the consumer. According to a report by the Natural Resources Defense Council (NRDC), there are five main stages during which food can be wasted. These stages include production, postharvest, handling and storage, processing and packaging, distribution and retail, and consumption, which includes out-of-home consumption (Gunders, 2012). Thus, the self-reported totals from the National Health and Nutrition Examination Survey (NHANES) are lower than what is necessary (accounting for losses in the supply chain) to provide adequate volumes of food to consumers. The Quantis report does, however, account for post-consumer waste, assuming certain percentages across food groups as explained in Buzby et al. (2014).

To fully capture the phosphorus impacts of growing food for a diet, I used the United Nations' FAO-STAT data to examine the number of crops and commodities grown in year 2014 (most recent data available), as this would provide a closer approximation of real phosphorus impacts from growing the necessary amount of food. The FAO-STAT data is where Pimentel and Pimentel (2003) retrieved data for an average American's diet, whether meat-based or lacto-ovo-based. Lacto-ovo in this study is meant to also encapsulate the meatless foundation of a diet that still includes dairy items. Against Pimentel and Pimentel's totals, I compared my own query for the production totals of 2014, making certain assumptions which are delineated in the next section. Table 3 shows this comparison between the Pimentel and Pimentel study and my own with food group totals for each diet.

Table 3: FAO-STAT Diets Modeled

	Meat (in kg)		Lacto/ovo (in kg)	
Item	**Pimentel**	**FAOSTAT**	**Pimentel**	**FAOSTAT**
Food grain	114	277.76	152	313.63
Pulses/legumes	4.3	8.67	7.5	9.79
Veggies	239	106.76	286	120.54
Oil crops	6	0	8	0
Fruit	109	124.76	112	140.85
Meat	124	132.19	0	0
Fish	20.3	-	0	0
Dairy	256	357.73	307.1	403.86
Eggs	14.5	18.73	19.2	21.15
Veggie oils	24	30.44	25	34.37
Animal fat	6.7	0	6.7	0
Sugar/sweetener	74	87.54	74	98.83
Nuts	3.1	12.23	4	13.81
Total	994.9		1001.5	
Total w/o fish	974.6	1156.81		1156.81

Sources: Pimentel and Pimental, 2003; FAO-STAT

2.2 Modeling Assumptions

Appendix 1 shows the output from the FAO-STAT query. One key discovery is that for certain widely consumed crops, average kilogram consumption of P per capita is high, especially with maize, soybeans, wheat, sugar beet, sugar cane, and sorghum. Thus, certain assumptions are made about these crops in order to to scale down the per capita consumption to a manageable size. The pared-down totals are then consolidated into the category totals seen in Table 3.

Fresh whole cow's milk, a food item output from the FAO-STAT query, was also high in per capita consumption, at 293.07 kilograms. However, I did not screen this or pare it down in any way, as I did not rationalize how it could be used for biofuels or go toward any other purpose, so the entirety of the food line item was modeled in SimaPro. This did have a discernible impact on phosphorus use, especially since milk is a dairy product (animal-based), but it did not have a large enough impact to offset the P counts associated with meat products (chicken, beef, pork, turkey).

Another assumption of the FAO-STAT data was that turkey was to be modeled as chicken in SimaPro. Turkey has a sufficient associated kilogram count to be included in the model. However, SimaPro does not contain turkey and it was categorized as chicken or, more broadly, poultry. An additional postulation was that the procedure modeled meat items within the context of either Netherlands or Ireland.

One significant problem in SimaPro is the integration of micro-spatial, or GIS, data with food production. Older versions of SimaPro do not contain this level of granularity, through which one is able to discern the different application rates of fertilizers (phosphorus included) on various hectares of land. Because of this lack of granularity, a conscious choice was made to model global food items to the greatest extent possible where those items existed in SimaPro. The only place where this did not hold was in modeling meats and eggs. For meats, the goal was to show the general P impact of bringing meats to the factory gate, regardless of where those meats originated. Broadly speaking, the numbers for P associated with meats should not be too different if modeled in another country, which Quantis attempted to do with meat impacts in its LCA for Morningstar. That level of detail is beyond the scope of this study.

Certain crop or commodity yields were too large to warrant their full inclusion in either FAO-STAT diet, so further breakdown analysis was performed on soybeans, corn, sorghum, wheat, sugar cane, and sugar beets. Soybean production, on a per capita basis, yielded 335.15 kilograms. 85% percent of soybeans are crushed, and of that, 80% become meal as opposed to oil or fiber (Solecki; "Soy Facts"). To get the leguminous bean, two percent of the meal portion was calculated to arrive at 4.56 kilograms per capita, a reasonable estimate.

For corn, a National Corn Growers Association report delineated how much product is used in various applications, including high-fructose corn syrup (HFCS), sweeteners, starches, cereals, beverages/alcohol, and seeds ("World of Corn"). Using a bushel-to-ton converter, I then converted production of corn to bushels, and found percentages of corn used in the various product groups above based on overall production. 62.14 kilograms HFCS and sweetener, 19.97 kilograms of starch/grains, and 26.63 kilograms of cereal/beverage grains were calculated. While in SimaPro, these product groups had no bearing on how corn was modeled, breaking up these product groups allowed for allocation of certain portions of corn to different parts of the diet. Seeds were excluded for modeling purposes.

Sorghum, used in food industry applications, was assumed at two percent of production totals in FAO-STAT ("All About"). 65% of the wheat crop was assumed for food applications, and the entirety of this percentage was modeled as wheat grain ("Feeding the World"). For sugar cane and beets, an Economic Research Service (ERS) report by the USDA showed that 8.1 million tons of sugar (beet and cane) is refined every year, with 55% coming from beet and 45% from cane ("U.S. Sugar"). Applying these calculations against the overall production totals seen in Appendix 1 yielded roughly 11.43 kilograms of sugarcane and 13.97 kilograms of sugar beets, which were both were modeled in SimaPro.

One final assumption was scaling the lacto-ovo diet with the FAO-STAT data to an equivalent functional unit to facilitate comparison with the meat-based diet. Table 4 shows this scale-up. Pimentel and Pimentel (2003) followed this same scaling factor on a functional unit basis, but with calories. One detriment to scaling this diet and excluding meat is that many product categories were pushed above the production threshold. Obviously, no one would eat what was not produced, but, for representative purposes, the scaling still shows the impact P use has in a meat-based vs. lacto-ovo diet.

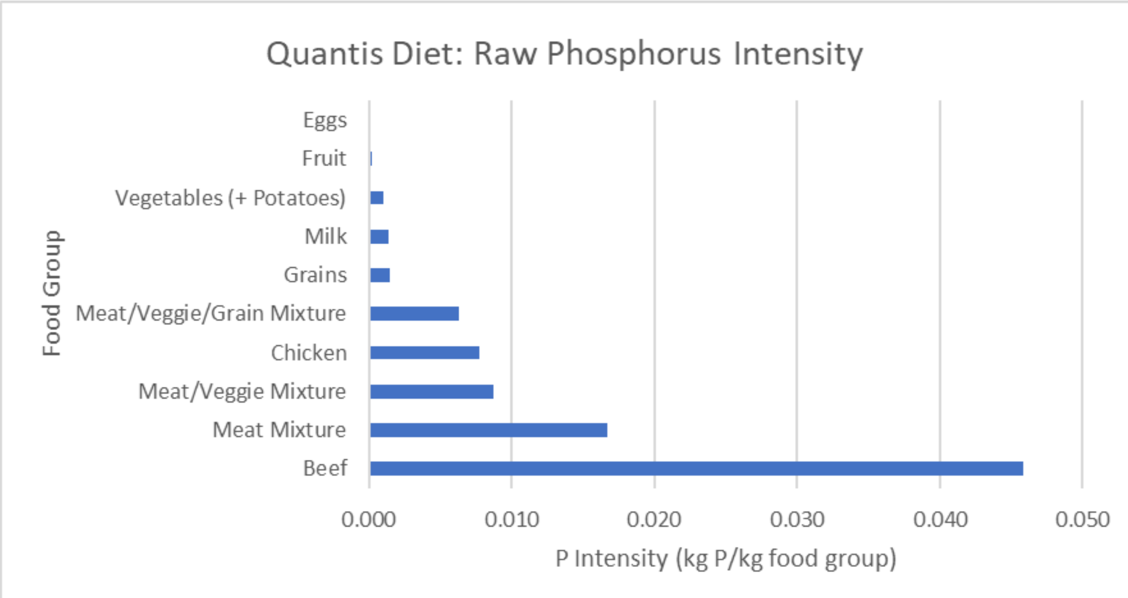
3.0 Results-Raw P Intensity

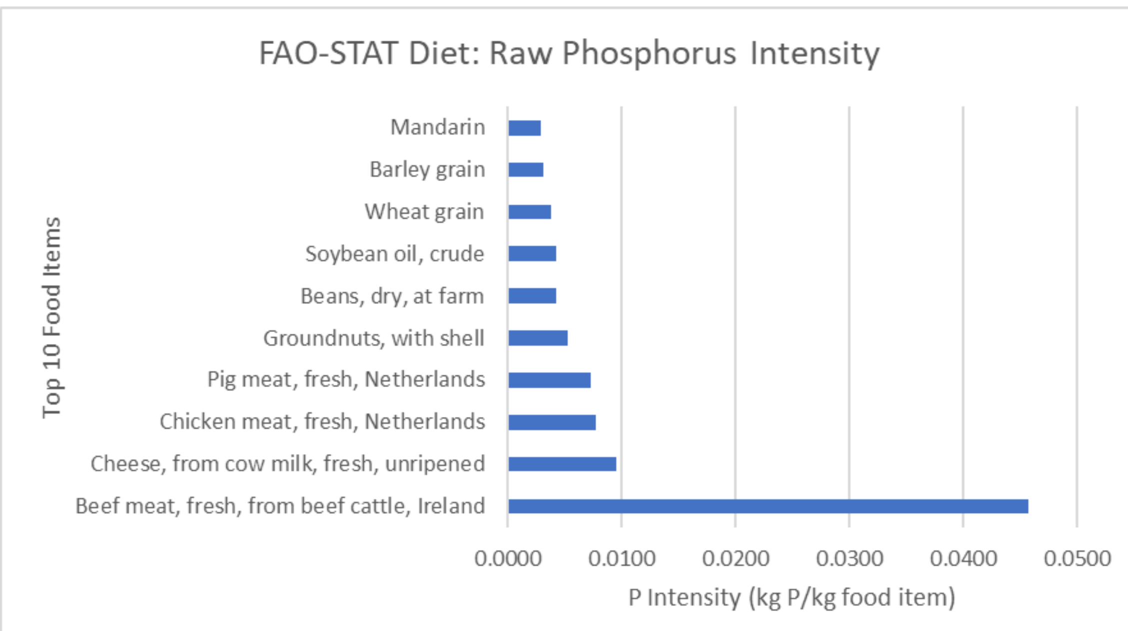
One of the most surprising results of this analysis was the phosphorus intensity (raw kilograms P/kilograms of food item) associated with both data sets. Figure 1 shows the P intensities for both Quantis and FAO-STAT data sources.

Table 4: Scaling Diets

Scaling Table for Lacto/Ovo FAO-STAT Diet			
	Meat diet (minus meat) in kg	Percentage of Item in Meat Diet (w/o meat)	Lacto/ovo diet in kg
Cow milk	293.07	0.286	330.86
Eggs	18.73	0.018	21.15
Cheese	16.37	0.016	18.48
Skim milk	48.29	0.047	54.52
Barley	83.30	0.081	94.04
Soybean oil	30.44	0.030	34.37
Maize	108.75	0.106	122.77
Soybean	4.56	0.004	5.15
Wheat	112.40	0.110	126.89
Sugar beet	13.97	0.014	15.77
Sugar cane	11.43	0.011	12.90
Potato	67.10	0.065	75.75
Tomato	45.52	0.044	51.39
Sorghum	0.69	0.001	0.78
Rice	31.61	0.031	35.69
Grape	22.43	0.022	25.32
Orange	19.25	0.019	21.73
Apple	16.26	0.016	18.36
Lettuce	11.89	0.012	13.42
Onion	9.93	0.010	11.21
Groundnuts	7.38	0.007	8.33
Almond	4.85	0.005	5.48
Melon	7.20	0.007	8.13
Carrot	4.53	0.004	5.11
Strawberry	4.30	0.004	4.85
Beans, dry	4.11	0.004	4.64
Oat	3.20	0.003	3.61
Cauliflower	1.915	0.002	2.162
Broccoli	1.915	0.002	2.162
Peach	3.01	0.003	3.40
Cabbage White	1.505	0.001	1.699
Cabbage Red	1.505	0.001	1.699
Green pepper	2.87	0.003	3.24
Cucumber	2.51	0.002	2.83
Pear	2.37	0.002	2.68
Lemon	2.34	0.002	2.64
Mandarin	2.08	0.002	2.35
Spinach	1.10	0.001	1.24
	1024.68		1156.81

Figure 1: Raw Phosphorus Usage in Growing Food





For the FAO-STAT diet, the top 10 food items from Table 4 were selected for the sake of brevity. It is not surprising that beef has the highest P intensity in either diet study. For Quantis, most of the impact from P use comes from having some component of meat (pork, beef, or chicken) as part of the diet, followed by grains and milk. Cheese and other meat products in the FAO-STAT study also have high P intensity, followed by various grains.

Table 5: FAO-STAT Raw P Intensities

Food Items	Lacto/Ovo Diet		Meat Diet		P Intensity (kg P/kg food item)
	Food Item Modeled in SimaPro (kg)	Raw Phosphorus Used (kg)	Food Item Modeled in SimaPro (kg)	Raw Phosphorus Used (kg)	
Pig meat, fresh, at slaughterhouse/NL Economic	-	-	32.51	0.238	0.0073
Beef meat, fresh, from beef cattle, at slaughterhouse/IE Economic	-	-	35.91	1.645	0.0458
Chicken meat, fresh, at slaughterhouse/NL Economic	-	-	63.76	0.495	0.0078
Cow milk {GLO}| market for | Alloc Rec, U	330.86	0.453	293.07	0.401	0.0014
Cheese, from cow milk, fresh, unripened {GLO}| market for | Alloc Rec, U	18.48	0.177	16.37	0.157	0.0096
Skimmed milk, from cow milk {GLO}| market for | Alloc Rec, U	54.52	0.045	48.29	0.040	0.00082
Barley grain {GLO}| market for | Alloc Rec, U	94.04	0.297	83.30	0.263	0.0032
Soybean oil, crude {GLO}| market for | Alloc Rec, U	34.37	0.147	30.44	0.130	0.0043
Maize grain {GLO}| market for | Alloc Rec, U	122.77	0.221	108.75	0.196	0.0018
Soybean {GLO}| market for | Alloc Rec, U	5.15	0.012	4.56	0.010	0.0023
Wheat grain {GLO}| market for | Alloc Rec, U	126.89	0.495	112.40	0.439	0.0039
Sugar, from sugar beet {GLO}| market for | Alloc Rec, U	15.77	0.006	13.97	0.006	0.00040
Sugar, from sugarcane {GLO}| market for | Alloc Rec, U	12.90	0.023	11.43	0.020	0.0018
Potato {GLO}| market for | Alloc Rec, U	75.75	0.112	67.10	0.099	0.0015
Tomato, fresh grade {GLO}| market for tomato, fresh grade | Alloc Rec, U	51.39	0.029	45.52	0.025	0.00056
Sorghum, at farm/US Economic	0.78	0.002	0.69	0.002	0.0026
Rice {GLO}| market for | Alloc Rec, U	35.69	0.054	31.61	0.048	0.0015
Grape {GLO}| market for | Alloc Rec, U	25.32	0.011	22.43	0.010	0.00045
Orange, fresh grade {GLO}| market for orange, fresh grade | Alloc Rec, U	21.73	0.015	19.25	0.013	0.00068
Apple {GLO}| market for | Alloc Rec, U	18.36	0.008	16.26	0.0069	0.00042
Lettuce {GLO}| market for | Alloc Rec, U	13.42	0.003	11.89	0.0024	0.00020
Onion {GLO}| market for | Alloc Rec, U	11.21	0.013	9.93	0.0113	0.0011
Groundnuts, with shell, at farm/US Economic	8.33	0.044	7.38	0.0393	0.0053
Almond {GLO}| market for almond | Alloc Rec, U	5.48	0.0022	4.85	0.0019	0.00040
Melon {GLO}| market for | Alloc Rec, U	8.13	0.0036	7.20	0.0032	0.00044
Carrot {GLO}| market for | Alloc Rec, U	5.11	0.0019	4.53	0.0017	0.00037
Strawberry {GLO}| market for | Alloc Rec, U	4.85	0.0030	4.30	0.0026	0.00062
Beans, dry, at farm/US Economic	4.64	0.0203	4.11	0.0179	0.0044
Oat grain {GLO}| market for | Alloc Rec, U	3.61	0.0087	3.20	0.0077	0.0024
Cauliflower {GLO}| market for | Alloc Rec, U	2.16	0.0008	1.915	0.0007	0.00036
Broccoli {GLO}| market for | Alloc Rec, U	2.16	0.0008	1.915	0.0007	0.00036
Peach {GLO}| market for peach | Alloc Rec, U	3.40	0.0030	3.01	0.0027	0.00088
Cabbage white {GLO}| market for | Alloc Rec, U	1.70	0.0006	1.505	0.0005	0.00036
Cabbage red {GLO}| market for | Alloc Rec, U	1.70	0.0006	1.505	0.0006	0.00037
Green bell pepper {GLO}| market for | Alloc Rec, U	3.24	0.0008	2.87	0.0007	0.00026
Cucumber {GLO}| market for | Alloc Rec, U	2.83	0.0003	2.51	0.0002	0.00010
Pear {GLO}| market for | Alloc Rec, U	2.68	0.0025	2.37	0.0022	0.00095
Lemon {GLO}| market for lemon | Alloc Rec, U	2.64	0.0013	2.34	0.0011	0.00048
Mandarin {GLO}| market for mandarin | Alloc Rec, U	2.35	0.0070	2.08	0.0062	0.0030
Spinach {GLO}| market for | Alloc Rec, U	1.24	0.0003	1.10	0.0003	0.00026
Consumption eggs, laying hens >17 weeks, at farm/NL Economic	21.15	0.0005	18.73	0.0004	0.000023
Total	1156.81	2.227	1156.86	4.350	

What is most surprising from this analysis is that in both studies, eggs registered the lowest overall P intensity, which is contrary to other findings in the literature. One study concluded that one kilogram of P can produce the most kilograms of starchy roots, followed by pulses, fruits, vegetables, cereals, milk, and then eggs, poultry, pork, and beef ("What to Eat Next"). Thus, this study anticipated a much higher egg P intensity. While eggs were assumed to have originated in the Netherlands (as mentioned above), the result should not change drastically when different countries are modeled.

Many data sources, including Metson et al. (2012), state that the United States' annual per capita consumption of phosphorus is between six and seven kilograms for a meat-based diet, and less than one kilogram for a plant-based diet. Looking at the Quantis totals, those phosphorus amounts are 2.69 and 0.59 kilograms for a meat-based and plant-based diet, respectively. The plant-based amount is in a similar range to that found by many other studies, but the meat-based P total is lower by roughly a factor of three. One of the key reasons this may have been lower is because of the sheer amount of total P in a diet (in kilograms) modeled in SimaPro. However, when studies such as those conducted by Metson et al. (2012) state specific per capita P consumption rates by country, I approach those with skepticism. It is hard enough to model an average diet with relatively complete information from FAO-STAT and Quantis.

Nonetheless, to deal with losses throughout the food supply chain and account for the total amount of food produced in the United States, I turned to the FAO-STAT totals, as the diets modeled from this data source were more than double the Quantis amounts in total kilograms. The result was that the FAO-STAT phosphorus per capita consumption numbers deviated even further from those in other studies. As seen in Table 5, total raw phosphorus usage was 2.23 kilograms for the lacto-ovo diet and 4.35 kilograms for the meat-based diet. Considering these data encompassed end-to-end food production for consumption purposes (with any losses accounted for), it is no surprise that both numbers for total P use were higher than those associated with the Quantis study. Furthermore, in FAO-STAT, the raw P use in the meat-based study was double that used in the lacto-ovo diet. In the Quantis analysis, P use was five times higher in the meat-based study, demonstrating an interesting divergence in the total P usage for growing food for human consumption, whether self-reported or taken from aggregate production totals.

Raw P intensities associated with the entire Quantis meat-based and meatless diet were 0.0053 and 0.0011 kilograms respectively as shown in Table 6. For the FAO-STAT diets, these intensities dropped from 0.0053 to 0.0038 kilograms P for a meat-based diet and increased from 0.0011 to 0.0019 kilograms P for a meatless diet. One possible explanation is the sheer amount of grains consumed in the FAO-STAT diets. Grains are somewhat more intense in their use of P than items like vegetables and fruits (see Figure 1). For the meat-based diet, this P intensity may have dropped when analysis was switched from Quantis to FAO-STAT, because the meat totals modeled from both data sources were roughly equivalent. Because meat accounts for the largest amount of phosphorus use, if that category of food stays roughly the same in a diet ratio and other, less P-intensive crops are added to the diet, the overall P intensity for that diet will drop, as evidenced below.

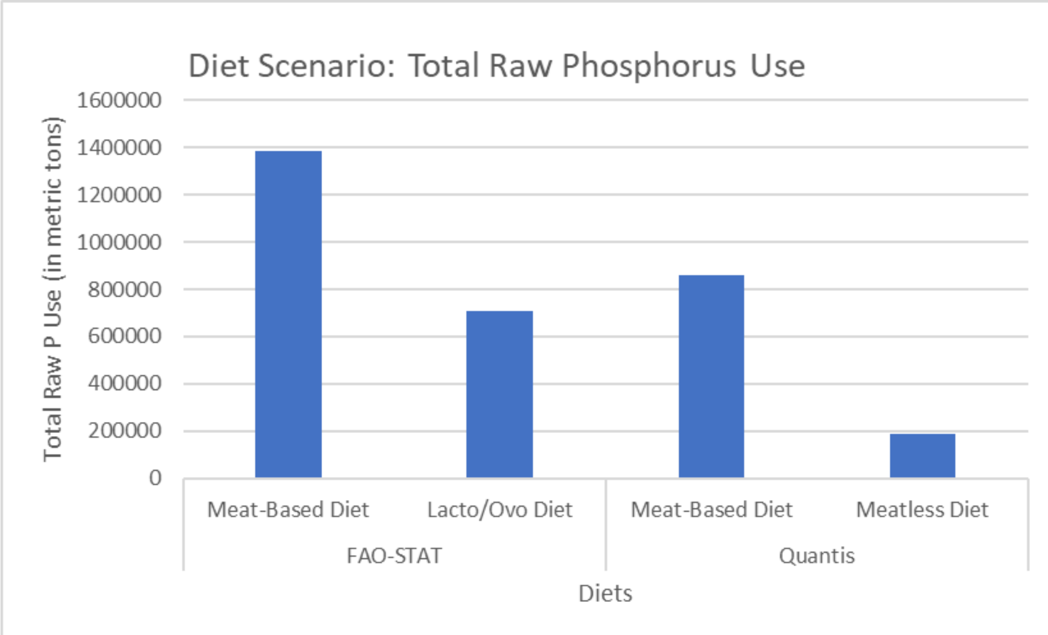
Table 6: Quantis Raw P Intensities

Meat-Based Diet			
Item	Raw Phosphorus (kg)	Modeled in SimaPro (kg)	P Intensity (kg P/kg food item)
Milk	0.058	42.22	0.0014
Vegetables (+ Potatoes)	0.10	98.6	0.0010
Fruit	0.013	59.25	0.00021
Grains	0.15	100.1	0.0015
Eggs	0.00039	17.02	0.000023
Meat/Veggie Mixture	0.78	89.44	0.0087
Meat/Veggie/Grain Mixture	0.17	26.24	0.0063
Meat Mixture	0.38	22.49	0.017
Beef	0.81	17.78	0.046
Chicken	0.23	29.93	0.0078
Total	2.69	503.07	0.0053
Meatless Diet			
Item	Raw Phosphorus (kg)	Modeled in SimaPro (kg)	P Intensity (kg P/kg food item)
Milk	0.15	109.23	same as meat-based
Vegetables	0.045	60.61	0.00074
Fruit	0.018	83.07	same as meat-based
Grains	0.37	253.09	same as meat-based
Eggs	0.00037	16.23	same as meat-based
Total	0.59	522.23	0.0011

3.1 Scenario Analysis

The main purpose of this study is to analyze the effects of diet choice on phosphorus consumption, and Figure 2 below is a concise summary. It shows the overall effect that choice in diet at a national level (all citizens accounted for) would have on the aggregate raw P usage in 2014. A population estimate for the United States was taken from the World Bank. The U.S. population for 2014, when data was queried, was 318.6 million.

Figure 2: U.S. Consumption of Raw P



As Figure 2 shows, both meat-based diets from Quantis and FAO-STAT were higher in P use than the plant-based and lacto-ovo diets. According to the USGS, the U.S. consumed roughly 29.1 million metric tons of phosphate rock in 2014. The meat-based diet, assuming all citizens followed it, would comprise three and five percent of that total for the Quantis and FAO-STAT sources, respectively.

3.2 Alternative Routes to Responsible P Management

There are many routes to responsible P management that go beyond shifting diet patterns. These are predominantly focused on the supply side of the P equation, with measures including more efficient recovery of P from mine waste, responsible sourcing of fertilizers from renewable pathways including food waste, human excrement, and manure, and increasing plant uptake efficiency of P through better crop and soil management (Cordell and White, 2013).

Additionally, wastewater phosphorus must be contended with, as this growing problem will require innovative recovery technologies including chemically precipitated struvite, which aggregates phosphate, ammonia, and magnesium into crystals within the piping systems of a wastewater treatment plant (Cordell and White, 2013). If managed correctly, struvite can be harvested to act as a slow-release fertilizer in croplands. Of the three million tons of P in wastewater treatment plants, only ten percent is recovered and sent back to agricultural operations; the remaining

90% is wasted in waterways, causing major eutrophication (Cordell and White, 2013). That means that a lot more can and should be done in this realm to affect sustainable P use in the coming decades.

Policy mechanisms should be leveraged to affect sustainable P use. These mechanisms include mandates from governments stipulating goals for certain percentage recoveries of phosphorus from various waste streams, such as municipal wastewaters and factory farms' and feedlots' cow manure. Unfortunately, policy mandates cannot stipulate what people eat, but they can tax certain food products (i.e., soda taxes) if appropriate justification is given to demonstrate how much P is used in creating a product.

Finally, another place to affect change is in regions where farmers make meager earnings and thus have little purchasing power for fertilizers to sustain crops. These include Sub-Saharan Africa, South East Asia, and Latin America (Cordell and White, 2013). P is low in these agricultural lands; where soils are lacking, people are going hungry, and enough food cannot be grown to sustain farmer livelihoods. International agreements should strive for the proper trade of P using economic instruments to lower fertilizer prices, subsidize costs for poorer nations, or deploy recovery technologies in parts of the world where P-recovery efforts would greatly benefit farmers who need help growing and sustaining crop yields. There are myriad ways to affect sustainable phosphorus use in a growing world. Shifting diet choices coupled with appropriate policy and economic measures may begin to result in less reliance on phosphate rock mining and more reliance on P flows already in the system.

3.3 Implications of Phosphorus Use

As this study has found, one of the primary reasons to switch to a plant-based diet is to alleviate the strain on our planet's finite resources, such as phosphorus. Phosphorus is non-substitutable, meaning it is essential and non-replaceable in its uses. Moreover, Western Sahara sits on 73.5% of the world's reserves of phosphate rock, according to the 2017 U.S. Geological Survey (Jasinski, 2016). That presents tremendous geo-political risk if the world is ever in short supply of this precious commodity. This could certainly become reality in a burgeoning market, where the demand for agricultural crops would vastly exceed the fertilizers available. In such a situation, demand would outstrip supply, prices would skyrocket, and nations would have to dole out additional dollars. Sustainable management of phosphorus (including curtailing its agricultural use), however, can prevent these potential consequences. Thus, diet choice has extraordinary potential to ameliorate not only the way we use P, but other resources too, such as nitrogen, potassium, and fresh water.

Phosphorus overuse also has implications for the environment, primarily eutrophication. Typically, over-saturated soils (those inundated with P) will have excess phosphorus, which is then washed off into waterways during precipitation events. This often is the case along the Mississippi River, where large swathes of farmlands lose surplus nutrients. Problems arise when P enters surface water and causes algal blooms. The algae will eventually die, and bacteria decompose the sinking algae, which sucks up available dissolved oxygen. Fish in the proximate area are deprived of necessary oxygen, and the entire area becomes hypoxic (oxygen-depleted). Thus, life cannot be sustained. While "dead zones" are not necessarily permanently relegated to being deprived of oxygen (it is a cycle), it stands to reason that we need to be doing a better job with how we apply phosphorus and other nutrients to croplands. Why should fish have to sacrifice their lives for irresponsible application of nutrients upstream?

It is also important to mention the disparity in phosphorus use across the globe, and how dynamic behaviors in developing countries can be leverage points in the global fight for a sustainable future. In the U.S., a developed country, both diets modeled are well studied, and the total P use in either diet for both sources is a reasonably good approximation of how much raw P is actually used. However, in booming countries like Brazil, Russia, India, and China, diet choices may be much more varied, or the data for production may be less comprehensive. Thus, the diet choices modeled for the U.S. would not necessarily hold for a country at present or in the near future; different nations consume different quantities of food groups for a variety of reasons (i.e., religious purposes, agricultural restraints).

The purpose of this paper was to investigate what a diet looks like in the U.S., however, which is a majority meat-eating country. Accordingly, these totals would over-estimate how much P other countries are consuming per capita, unless those countries consume even more meat (one would need to consult UN data). This is because meat tends to be the most P-intensive. The key point, then, is that this study shows the course certain countries may be on in terms of annual per capita P consumption, especially if meat-eating trends continue to grow as the middle-class booms in countries such as China and India, increasing national demand for animal products. This study aims to help people in such countries think about diet choices in advance of a crisis to mine and produce the necessary agricultural P.

4.0 Conclusion

Diet choice is one of the most sustainable lever points we have at our individual disposal. This study examined the sustainability of such a choice through the lens of a finite resource, phosphorus. Overall, meat-based diets consume more phosphorus because the uptake efficiency of turning P into consumable food is much lower for meat-based products such as beef, pork, and chicken. A cow will only supply a certain amount of meat, and growing that meat requires a tremendous amount of grain. This efficiency is much lower than the P needed to grow a much smaller amount of grain to directly feed a consumer. We have the personal ability to affect how resources are used on a daily basis, and this study takes a systematic approach to examine how individuals can use data to inform their decisions. With this in hand, readers should consult other resources around what additional benefits plant-based diets confer over meat-based diets, and if plant-based diets are right for them in other ways.

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Appendix 1: FAO-STAT Query Output for United States

Domain	Item	Production in kg	per capita consumption (kg)	Modeling category	Amount modeled
Crops*	Maize	3.61091E+11	1132.30	grain/sweetener	108.75
	Soybeans	1.06878E+11	335.15	legume	4.56
	Wheat	55147120000	172.93	grain	112.40
	Sugar beet	28381270000	89.00	sugar/sweetener	13.97
	Sugar cane	27600190000	86.55	sugar/sweetener	11.43
	Potatoes	20056500000	62.89	veggie	62.89
	Tomatoes	14516060000	45.52	fruit	45.52
	Sorghum	10987910000	34.46	grain	0.69
	Rice, paddy	10079500000	31.61	grain	31.61
	Seed cotton	9791640000	30.70	Cotton production - animal feed	-
	Grapes	7152063000	22.43	fruit	22.43
	Oranges	6139826000	19.25	fruit	19.25
	Apples	5185078000	16.26	fruit	16.26
	Cottonseed	4649320000	14.58	Cotton production - animal feed	-
	Barley	3952610000	12.39	grain	12.39
	Lettuce and chicory	3791140000	11.89	veggie	11.89
	Cotton lint	3593000000	11.27	not modeled	-
	Maize, green	3447520000	10.81	assume for animal feed	-
	Onions, dry	3166740000	9.93	veggie	9.93
	Groundnuts, with shell	2353540000	7.38	nuts	7.38
	Almonds, with shell	1545500000	4.85	nuts	4.85
	Watermelons	1508780000	4.73	fruit (model as melons)	4.73
	Carrots and turnips	1443120000	4.53	veggie	4.53
	Strawberries	1371573000	4.30	fruit	4.30
	Sweet potatoes	1341910000	4.21	veggie (model as potato)	4.21
	Beans, dry	1311340000	4.11	legume	4.11
	Cauliflowers and broccoli	1222930000	3.83	veggie (split 50/50)	3.83
	Rapeseed	1140140000	3.58	not modeled	-
	Oats	1019410000	3.20	grain	3.20
	Sunflower seed	1004630000	3.15	not modeled	-
	Peaches and nectarines	959983000	3.01	fruit	3.01
	Cabbages and other brassicas	958930000	3.01	veggie (split 50/50-r&w)	3.01
	Grapefruit (inc. pomelos)	949822000	2.98	can't model-not in SimaPro	-
	Chillies and peppers, green	914490000	2.87	veggie	2.87
	Pumpkins, squash and gourds	863460000	2.71	can't model-not in SimaPro	-
	Vegetables, fresh nes	834292000	2.62	not modeled	-
	Cucumbers and gherkins	799820000	2.51	veggie	2.51
	Melons, other (inc.cantaloupes)	787030000	2.47	fruit	2.47
	String beans	786750000	2.47	can't model-not in SimaPro	-
	Peas, dry	778140000	2.44	can't model-not in SimaPro	-
	Pears	754415000	2.37	fruit	2.37
	Lemons and limes	747520000	2.34	fruit (lime is chemical)	2.34
	Tangerines, mandarins, clementines, satsumas	664059000	2.08	fruit	2.08
	Walnuts, with shell	518002000	1.62	can't model-not in SimaPro	-
	Mushrooms and truffles	432100000	1.35	not modeled	-
	Tobacco, unmanufactured	397535000	1.25	not modeled	-
	Cranberries	381018000	1.19	can't model-not in SimaPro	-
	Spinach	350410000	1.10	veggie	1.10
	Cherries	329852000	1.03	can't model-not in SimaPro	-
	Peas, green	329180000	1.03	can't model-not in SimaPro	-
Crops Processed	Beer of barley	22600000000	70.87	grain	70.87
	Oil, soybean	9706000000	30.44	soybean oil	30.44
Livestock Processed	Milk, skimmed cow	15400000000	48.29	skim milk	48.29
	Cheese, whole cow milk	5221857000	16.37	cheese	16.37
Livestock Primary	Milk, whole fresh cow	93460920000	293.07	whole milk	293.07
	Meat, chicken	17722312000	55.57	chicken	55.57
	Meat, cattle	11453253000	35.91	beef	35.91
	Meat, pig	10368214000	32.51	pork	32.51
	Eggs, hen, in shell	5973968000	18.73	eggs	18.73
	Meat, turkey	2610710000	8.19	chicken	8.19
*Cutoff applied at 1 kg of food item per capita					