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The imprint of crop choice on global nutrient needs

Esteban G Jobbágy[1] **and Osvaldo E Sala**[2]

[1] Grupo de Estudios Ambientales – IMASL, Universidad Nacional de San Luis – CONICET, San Luis 5700, Argentina
[2] School of Life Sciences and School of Sustainability, Arizona State University, Tempe, Arizona 85287-4501, USA

E-mail: jobbagy@unsl.edu.ar

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Abstract

Solutions to meet growing food requirements in a world of limited suitable land and degrading environment focus mainly on increasing crop yields, particularly in poorly performing regions, and reducing animal product consumption. Increasing yields could alleviate land requirements, but imposing higher soil nutrient withdrawals and in most cases larger fertilizer inputs. Lowering animal product consumption favors a more efficient use of land as well as soil and fertilizer nutrients; yet actual saving may largely depend on which crops and how much fertilizer are used to feed livestock versus people. We show, with a global analysis, how the choice of cultivated plant species used to feed people and livestock influences global food production as well as soil nutrient withdrawals and fertilizer additions. The 3 to 15-fold differences in soil nutrient withdrawals per unit of energy or protein produced that we report across major crops explain how composition shifts over the last 20 years have reduced N, maintained P and increased K harvest withdrawals from soils while contributing to increasing dietary energy, protein and, particularly, vegetable fat outputs. Being highly variable across crops, global fertilization rates do not relate to actual soil nutrient withdrawals, but to monetary values of harvested products. Future changes in crop composition could contribute to achieve more sustainable food systems, optimizing land and fertilizer use.

S Online supplementary data available from stacks.iop.org/ERL/9/084014/mmedia

Keywords: agriculture, fertilization, soil nutrients

1. Introduction

During the last century, exponential growth in global food consumption has been paralleled by agricultural output supported by increasing cultivated area and even more by raising yields and resource inputs (Foley *et al* 2011). These transformations have created unprecedented imprints on the global cycles of nitrogen, phosphorus, carbon and water (Vitousek *et al* 1997, Bennett *et al* 2001, Rockstrom *et al* 2007, Dalin *et al* 2012). During the current century, expanding human demands and rapidly degrading environment call for novel food-supply systems that are both sustainable and more productive (Foley *et al* 2005). Limited land availability together with growing desires to protect natural ecosystems and their services have turned attention to yield improvements (Lobell *et al* 2009, Foley *et al* 2011, Tilman *et al* 2011) and reduction of animal product consumption (Steinfeld *et al* 2006, De Vries and De Boer 2010, MacDonald *et al* 2011, Bonhommeau *et al* 2013, Cassidy *et al* 2013), as the most sustainable avenues to improve the global-food system. While raising yields alleviates land demand, it increases soil nutrient withdrawals per unit of area and, as a very likely consequence, fertilization needs (Mueller *et al* 2012, Sánchez 2010); simultaneously stressing limited fossil energy and mineral reserves and magnifying some of the most critical global

pollution problems of this era (Vitousek *et al* 2009, Tilman *et al* 2001, Cordell *et al* 2009). Lowering our reliance on animal food may offer a path to limit land, soil nutrient and fertilizer needs, yet actual savings will depend on which crops are grown and how they are fertilized when feeding livestock versus people. In addition, nutrient savings may be more modest than those achieved for land since partial recycling from livestock producing systems back to agricultural plots is taking place (Steinfeld *et al* 2006, De Vries and De Boer 2010, MacDonald *et al* 2011, Metson *et al* 2012).

Besides increasing yields and plant/animal ratios in our diet, our choice of crops may have a strong, and to our knowledge largely overlooked, influence on the sustainability of the global-food system (Kastner *et al* 2012). Particularly, crop choices affect global demand for nutrients. In order to explore to what extent crop choice offers the potential to increase food outputs at a faster rate than soil nutrient withdrawals and fertilizer use on the same available land, we explored three aspects of major global crops. The first one was stoichiometric and involved the variation in mineral nutrient (e.g. N, P, K) per unit of edible dietary energy and proteins in harvested products. Flexibility in this dimension will offer a chance to supply more food with the same amount of nutrient withdrawals by selecting the most efficient crops. The second aspect was agronomic and was concerned with the match between soil nutrient withdrawals and fertilizer addition across major crops. A tight match would suggest that withdrawal savings will result in fertilizer savings and that increased production would be tied to increased fertilizer use. On the contrary, a loose match would help identify 'luxurious' or overfertilized crops versus 'austere' or tightly fertilized crops that would have contrasting impacts on global fertilizer demand and pollution. We anticipate these types of contrasts to emerge in response to the socioeconomic context of crops (e.g. market values) rather than from their biological attributes. The third aspect involved crop choice flexibility and how its current trends in combination with crop stoichiometry are impacting global soil nutrient withdrawals and dietary supply. Are recent crop choice shifts (css) amplifying or ameliorating the raise of soil nutrient withdrawals driven by the overall increase of global agricultural production? To what extent are they contributing to satisfy the growing demand of plant energy, protein and fat driven by population growth and per-capita consumption of food and non-food crop products?

We explored the flexibility of nutrient needs by global crops from a top-down perspective focusing on the stoichiometric, agronomic, and human choice aspects introduced above. Across the major global crops we (i) characterized the nutritional composition of their harvested products (i.e. N, P, K and edible energy and protein), (ii) estimated their average global nutrient balances by calculating their mean annual rates of nutrient withdrawals and fertilization per unit of area, and (iii) described their 20-year temporal shifts (1990–2010) in yield, total production and global coverage, calculating their effects on global N, P and K withdrawals and edible energy, protein and fat output. We show unexpectedly large differences in the nutrient composition of crops with clear impacts on nutrient withdrawals but weak influence on fertilization rates, and highlight how recent shifts in the composition of cultivated plants have already influenced the intensity global nutrient withdrawals with different signs depending on the element being considered. To perform these analyses, we compiled data on elemental and dietary composition of plant and animal products, and on their current global production, fertilization rates, market values, and uses grouping them into ten crop categories and five animal product categories representing >95% of the overall global agricultural outputs (see supplementary information tables 1 and 2).

2. Methods

Our study was focused on agricultural crops and the land, soil nutrient withdrawals and fertilizer use that were involved in their production, ignoring cultivated pastures and rangelands. We organized agricultural products as reported by FAO (2012) into ten crop groups. For comparisons, we included five dominant animal groups (see supporting information table 1). In both cases, these groups represented >95% (dry mass basis) of all global plant and animal product outputs. Groups were defined based on common types of harvested organs, chemical composition, and uses. Some groups included a single species with several sub-components (e.g. soybean) while others pooled a large list of species (e.g. fruits & vegetables). In the case of composite groups, we used between one and five dominant species to obtain an average elemental and dietary composition that was applied to the rest of the species in the group.

From a stoichiometric perspective, we wanted to evaluate how the nutrient withdrawals and dietary supply embedded in the harvested materials changed across different crop and animal product groups. We estimated mineral nutrient withdrawals, defined as the mass of N, P, and K embedded in a unit of mass of harvested materials including those that may represent wastes (e.g. rice husk, poultry feathers) and dietary nutrient supply, defined as the content of edible calories and mass of fat, protein, and carbohydrates per unit of mass of harvested materials. Data were obtained from the USDA Nutrient Database for Standard Reference (USDA 2011) and complemented with additional sources from the nutritional, industrial, and agronomic literature (see supporting information table 1 and 2). These additional sources of information were particularly important to account for the fraction of elemental nutrients that are withdrawn from the soil but embedded in non-edible fractions and hence unreported by the USDA database. In the case of N withdrawals by leguminous crop groups (soybean and pulses), c only 5% of the embedded N was derived from soils and the rest was obtained from biological fixation as explained in more detail below. The stoichiometric analysis was complemented with estimates of mineral nutrient withdrawals and dietary supply rates per unit of area across crop groups and estimates of the monetary value of dietary energy and protein across crop and animal product groups based on FAO reports on crop production,

Table 1. Major agricultural products, dietary characteristics, land and nutrient demands, and farm-gate values. The edible fraction includes all materials that can be consumed by humans as food and the rest of the values refer to that edible fraction. Land and nutrient requirements to produce a unit of edible energy and protein are based on average yields and consider the effective withdrawal of nutrients embedded in harvested products. N harvesting for soybean and pulses excludes their biological fixation. Protein costs are not applicable (NA) for sugar crops.

Item	Production		Dietary composition					Requirements								Farm value	
	Area	Yield	Edible fraction	Edible energy	Protein	Fat	Carbo hydrates	For edible energy				For edible protein				Energy	Protein
								Land	N	P	K	Land	N	P	K		
	(M ha)	(Mg dry matter ha^{-1} yr^{-1})	(Dry mass basis)	(Kcal $100\ g^{-1}$)	(% Mass)			(m^2 G cal^{-1})	(mg $Kcal^{-1}$)			(m^2 Kg $prot^{-1}$)	(mg g^{-1})			(USD G cal^{-1})	(USD Kg $prot^{-1}$)
Wheat & other fine grains	302.1	2.6	1	378	13.7	2.0	82.6	1007	6.2	1.12	1.18	28	172	31	33	44	1.22
Maize	160.6	4.7	1	407	10.5	5.3	82.9	528	4.1	0.58	0.79	20	160	22	30	37	1.42
Rice	156.6	5.7	0.63	413	8.6	3.1	86.9	666	4.3	1.09	1.73	32	206	53	83	79	3.79
Sugar crops	28.4	23.2	0.29	389	0.0	0.0	95.0	380	2.3	0.53	5.85	NA	NA	NA	NA	77	NA
Fruits & vegetables	110.0	1.5	1	354	8.2	1.6	86.3	1886	2.8	0.57	4.96	81	118	24	213	816	35.05
Soybean	99.4	2.2	1	488	39.9	21.8	33.0	939	0.7	1.58	4.03	11	19	19	49	49	0.60
Roots & tubers	62.7	4.4	1	387	6.1	0.6	90.3	583	1.9	0.40	3.22	37	119	26	205	123	7.82
Oil palm	14.9	8.5	0.41	836	5.7	91.6	0.7	342	2.7	0.40	3.39	50	393	59	496	45	6.63
Other oils	74.3	1.4	1	640	21.7	56.8	10.4	1152	6.1	1.06	1.51	34	179	31	45	70	2.06
Pulses	96.3	1.0	1	486	24.2	31.6	33.2	2162	0.4	0.80	1.97	43	19	16	40	82	1.65
Poultry & other birds			0.77	572	61	34	3		20.6	4.28	1.31		194	40	12	816	7.67
Eggs			0.88	600	53	40	3		14.1	1.42	0.97		161	16	11	620	7.06
Pork			0.82	737	30	68	0		8.0	2.29	0.86		198	57	21	513	12.72
Beef, mutton & goats			0.58	680	39	57	0		14.4	4.15	0.95		251	72	17	1194	20.82
Milk			1	514	27	28	40		8.3	1.38	2.16		160	27	42	479	9.28

cultivated area, yields and farm gate prices for the triennium 2008–2010 (FAO 2012) (see supporting information table 2).

All calculations and values reported in this work discounted moisture content (i.e. we present all data on a dry matter basis). Our nutrient withdrawal estimates are conservative since they assumed that all non-harvested nutrients held by crops were recycled to the land without representing a net withdrawal. This criterion ignored nutrient losses such as those that could result from stubbles being burned, consumed by herbivores and not recycled in-situ, or captured by humans for uses that are not reported in production statistics (e.g. fuel) or wasted off-farm.

From an agronomic perspective, we explored to what extent the variability in nutrient withdrawals across crops was related to their fertilizer input rates. This analysis was based on global figures of nutrient withdrawals introduced above and fertilizer use discriminated by crop obtained for 2007 (last available period) from an existing report (Heffer 2009). The analysis of fertilization versus soil withdrawals was performed on an area basis for year 2007 using its corresponding global production values as reported from FAO data and was restricted to those crop groups for which fertilization data was available. In the case of N, we estimated the total harvested amount, which includes biological fixation. In order to obtain a net N withdrawal figure for leguminous crops (soybean and pulses), we assumed that 95% of the N embedded in their harvested grains was obtained through biological fixation and the rest from the soil based on total harvested and fertilized N for these crops. The resulting 5% of net soil N withdrawal encompasses regional variability that ranges from a small sink to a source of N (Herridge *et al* 2008). In order to explore to what extent the mismatches between nutrient withdrawals and fertilization rates were related to divergences in the monetary value of crops, we used global average farm-gate prices as reported by FAO for 2007 (2012) (see supplementary table 2).

We complemented the stoichiometric and agronomic perspectives presented above with a global figure of the absolute amount of nutrient withdrawals and dietary supply associated with each crop and animal product group and its allocation to food and other uses. In this analysis, we included an estimate of non-edible energy outputs for those crops with important non-food uses. We calculated the chemical composition of the sub-products of a given crop or livestock item whenever they were differentially allocated to food, feed, energy, other uses, or waste in order to obtain a good accounting of nutrient routing along these allocation pathways. We used FAO data (2012) on annual consumption of crop products and sub products in the categories of food, feed, seed, processing, other uses, and waste available for 2008–2009 and we calculated the allocation fraction for each one of these uses. Since consumption may not match production on a given period, we applied the consumption fractions to the absolute production values of the triennium 2008–2010. Since FAO reports do not include bioenergy uses, we compiled data on its annual consumption from alternative sources (see supplementary information table 2). The absolute amounts consumed for bioenergy production were discounted from the 'other uses' category in FAO data and included as a new category. In addition to the previous analysis, we provide a global balance of N, P, and K in agricultural land (see supplementary information)

Seeking an integrative perspective of the effects that crop stoichiometric contrasts actually have on soil nutrient withdrawals and dietary supply, we performed a decomposition analysis of the global food system changes over the last two decades (Kastner *et al* 2012). We isolated the effects of crop cs from those driven solely by area expansion (ae) and yield increase (yi) on global soil N, P and K withdrawals and global edible energy, protein and fat outputs during the 1990–2010 period. We performed three alternative 20-year projections using the average records of the 1989–1991 triennium as 'initial' conditions and calculating 'current' soil nutrient withdrawals and edible energy/protein/fat outputs for each year from 1990 to 2010 in three different ways. The first projection (ae only) assumed that the only aspect of the food system that changed was the cultivated area, whereas yields and the fraction of the cultivated area occupied by each crop group remained constant. In this case the 'initial' area proportion dedicated to each group of crops and their 'initial' yields where applied to the 'current' total cultivated area recorded in each calendar year. The second projection (ae + yi), used the 'initial' area proportion dedicated to each crop group, but adjusted their yields using 'current' records for each year together with 'current' total cultivated area values. The last projection is the one that actually took place (ae + yi + cs) and considered the 'current' records of total area, yield and crop composition. The difference between each one of these three projections shows the isolated effect that each component had dictating the observed trends.

Calculations were performed using the following equations:

$$\text{ae only: } \text{TOTAL}_{\text{ae}} = \Sigma\ \text{yield}_{\text{initial}} * \text{proportion}_{\text{initial}} * \text{total area}_{\text{current}}$$

$$\text{ae + yi: } \text{TOTAL}_{\text{ae+yi}} = \Sigma\ \text{yield}_{\text{current}} * \text{proportion}_{\text{initial}} * \text{total area}_{\text{current}}$$

$$\text{ae + yi + cs: } \text{TOTAL}_{\text{ae+yi+cs}} = \Sigma\ \text{yield}_{\text{current}} * \text{proportion}_{\text{current}} * \text{total area}_{\text{current}},$$

where TOTAL refers to the aggregated output of calories, proteins or fat, and withdrawal of N, P and K across the eleven crop groups (ten groups in table 1 plus 'others'). For each crop group 'yield' represents the average yield, 'proportion' describes the fraction of the aggregated area occupied by all agricultural crops, represented as 'total area'. The effect of compositional shifts was calculated as:

$$\text{TOTAL}_{\text{cs}} = \text{TOTAL}_{\text{ae+yi+cs}} - \text{TOTAL}_{\text{ae+yi}}$$

With a similar rationale, we addressed what fraction of the increase in plant energy, protein and fat outputs of global croplands over the last two decades is responding to population growth versus shifts in per capita consumption habits including food, feed or others uses. In this case, we first

projected 'initial' per capita food/feed/others consumption values for the 1989–1991 triennium following the population numbers of each 'current' year (from FAO, 2012). Next, we considered not only 'current' population values but also 'current' per capita consumption levels for food, then for food + feed, and finally for food + feed + others. The difference between all these projections allowed us to attribute global consumption growth to pure demographic changes and to shifts in individual consumption patterns.

3. Results and discussion

3.1. Stoichiometric contrasts

Mineral nutrients embedded in harvested products, which offer a conservative estimate of their soil-nutrient demand, displayed very large variations across crop types (table 1, see also supplementary information table 2). Nutrient withdrawals for dietary energy output ranged 0.4–6.2, 0.4–1.1 and 0.8–5.8 mg $Kcal^{-1}$, for N, P and K respectively. Dietary energy from cereals including wheat, maize and rice has approximately twice higher N and P demand than non-grain plant products such as sugar crops, roots and tubers, and fruits and vegetables (4.9 versus 2.3 mg N $Kcal^{-1}$ and 0.93 versus 0.50 mg P $Kcal^{-1}$, averages from table 1). Remarkably, high P storage in grains is mostly accounted for by phytic acid, which cannot be digested by humans and non-ruminant livestock (Raboy *et al* 2001). High phytic acid content in grains creates the triple problem of intense withdrawal from soils, nutritional deficits in consumers (particularly livestock, which often receive mineral supplements), and pollution by their excreta (Lott *et al* 2000, Raboy *et al* 2001). From another point of view, phytic acid offers an emerging avenue for plant and animal genetic transformations, respectively focused on decreased concentrations and increased digestive capacity (Raboy *et al* 2001, Golovan *et al* 2001, Veneklaas *et al* 2012). Non-grain crops such as oil palm, sugar crops and roots and tubers are the most efficient energy producers per unit of N (only after legumes) and P; yet they are particularly K-demanding relative to grains (>3.2 versus <1.8 mg $Kcal^{-1}$). Fresh tissues, in which highly mobile K is abundant, are harvested in non-grain crops (Marschner and Marschner 2012).

In the case of dietary protein production, soybean has, together with pulses, the lowest P demand (table 1); yet the opposite is true in terms of dietary energy, likely as a result of the energetic costs of symbiotic N_2-fixation (table 1). Not only crop choices but animal choices as well affect nutrient withdrawals. Nutrients embedded in animal products are also quite variable, with the amount of P withdrawals per unit of dietary protein shifting more than two-fold when eggs and milk are compared to meats, and (table 1). Besides the inefficiency that livestock production introduces on the overall global-food system, and which is only partially overcome through excreta recycling; meat consumption involves a high P cost associated with the construction of animal skeletons. Milk and eggs minimize this cost yielding higher outputs per animal (and skeleton) (Steinfeld *et al* 2006), yet milk has the highest K intensity of all animal items. Poultry protein almost halves the P intensity of beef (table 1). The range of farm-gate monetary values of dietary energy and protein exceeded the range of land and nutrient requirements across agricultural products, varying substantially not only in the case of animal versus plant products, but within each of these groups (table 1). Lowest monetary values per unit of dietary energy and protein are respectively those for maize and soybean, which are the two crops with highest allocation to livestock feeding.

3.2. Agronomic contrasts

Across major crops, there is a poor relationship between global average nutrient fertilization and harvesting withdrawal rates (figure 1). This mismatch suggests that changes in crop composition could affect global fertilization differently than predicted by their actual nutrient requirements. In the case of N, all analyzed crops show a positive balance between global harvesting withdrawals and fertilization (values below the 1:1 line in figure 1(a)). Soybean represents a special case given its biological N-fixing ability, receiving only 5% of its N from fertilizers. P balances are less positive or even negative for a larger fraction of crops (figure 1(b)). This may be explained by crops relying on soil reserves in recently cultivated land with fertile soils (e.g. drained wetlands of Asia or loessic plains in South America), the legacy of overfertilization before the study period (e.g. Western Europe), or the addition of organic fertilizers unrecorded in our data sources (e.g. small-scale mixed grazing-farming systems world-wide). It is important to highlight that the previous situations coexist with the opposing effects of subsidies favoring P overfertilization (e.g. China) and extra P needs for the onset of cultivation in P-fixing soils (e.g. Brazilian Cerrado) (MacDonald *et al* 2012). In contrast with N and P, potassium (K) displays a tight relationship between fertilization and withdrawals with the only exception of sugar cane, where large fertilization deficit seems to take place (figure 1(c)).

Across crops different fertilization inputs appear to depend more on market values than on actual withdrawals from soils. As gross income per hectare grows, so does fertilizer surplus (figure 1(d)), suggesting that declining share of fertilizer on the total production costs encourages higher fertilization rates and their associated negative environmental impact (Weinbaum *et al* 1992). This is remarkable in the case of fruits and vegetables, whose contribution to the global dietary energy intake is only 6.4%, but their use of fertilizers is 18, 20 and 25% for N, P, and K, and their share of global farm-gate income from plant products is 39%. Aggregate crop nutrient balances show a surplus for N with fertilization generally exceeding withdrawals, whereas P and K fertilization seem to match withdrawals more closely (see supplementary information table 3). While this globally averaged picture hides large regional contrasts driven by the diversity of human and biophysical contexts of agricultural production, it reveals a predominant situation of high decoupling of

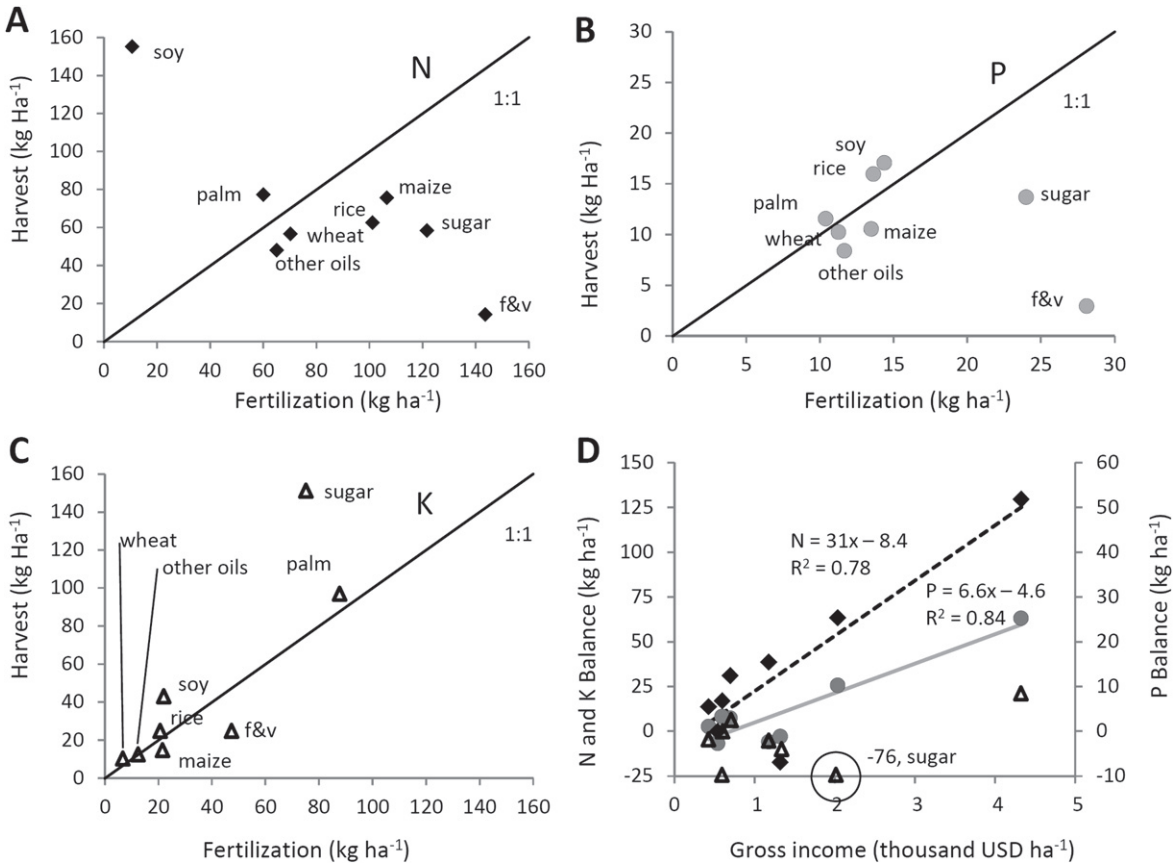

Figure 1. Nutrient withdrawals versus additions for major crop species/groups. Values for nitrogen (A), phosphorus (B) and potassium (C) are shown on an area basis (1:1 line depicts input = output). There is a significant association between withdrawals and fertilization for K (linear regression, $p < 0.01$), but not for N ($p = 0.19$) and P ($p = 0.31$). The association between nutrient balance (fertilization—withdrawals) and farm-gate value across crops (D) is significant for N and P ($p < 0.01$) but not for K ($p = 0.76$). Sugar crops (circled) have a highly negative K balance that falls below the scale of the plot (value shown at the right of the circle).

nutrient withdrawals versus additions across crop groups and chemical elements.

3.3. Global harvest

Global nutrient withdrawals and dietary energy supply differ substantially among agricultural products (figure 2). These differences reflect how the biological constraints presented above scale-up at the global level determining nutrient costs even before any fertilization and livestock feeding inefficiencies are considered. The three major cereals represent 57% of global edible energy, accounting for proportionally higher N (76%) and P (64%), and lower K (34%) withdrawals (figure 2). All harvested grains account for 88% of soil P withdrawals. Acknowledging that ~80% of their P is stored as phytic acid (Lott *et al* 2000), that sole molecule involves ~10.4 Tg P yr^{-1}, a global flux that has been dramatically amplified as our granivorous civilization expanded the area, primary productivity and allocation to seeds of its favorite crops. Representing about half of all animal protein outputs, meats account for 78% of the P embedded in all animal products, 85% of which (~2.4 Tg yr^{-1}) is non-edible and retained mainly in bones (figure 2). Together P harvested in phytic acid and bones represent half of global fertilization (see supplementary information table 4). In the case of K, non-edible harvested materials such as bagasse and mill residues are responsible for one fourth of total K withdrawals (figure 2).

3.4. Impact of crop css

During the last 20 years, dramatic increases in global soil nutrient withdrawals driven by increases in cultivated area and yield have been either partially offset or enhanced by crop composition shifts depending on the nutrient being considered (figure 3). Soil N withdrawals increased in the last 20 years (triennium 2008–2010 versus 1988–1990) from 38.6 to 53.7 Tg yr^{-1} (+39%). Of the additional 14.1 Tg yr^{-1} of N that are now withdrawn from soils, approximately one third (+4.3 Tg yr^{-1}) would have resulted just from the expansion of agriculture over newly cultivated land (figure 3). Increasing soil N withdrawals resulting from rising yields were partially offset by composition changes (+16.1 versus −2.0 Tg yr^{-1}, figure 3), particularly following the emergence of soybean as a dominant global crop. Hence, crop composition shifts over the last 20 years have saved 17% of the increments in global soil N withdrawals that would have taken place just through yield intensification, without diluting but actually increasing slightly the overall protein content of the global harvest (figure 4). In the case of soil P withdrawals, the effects of crop

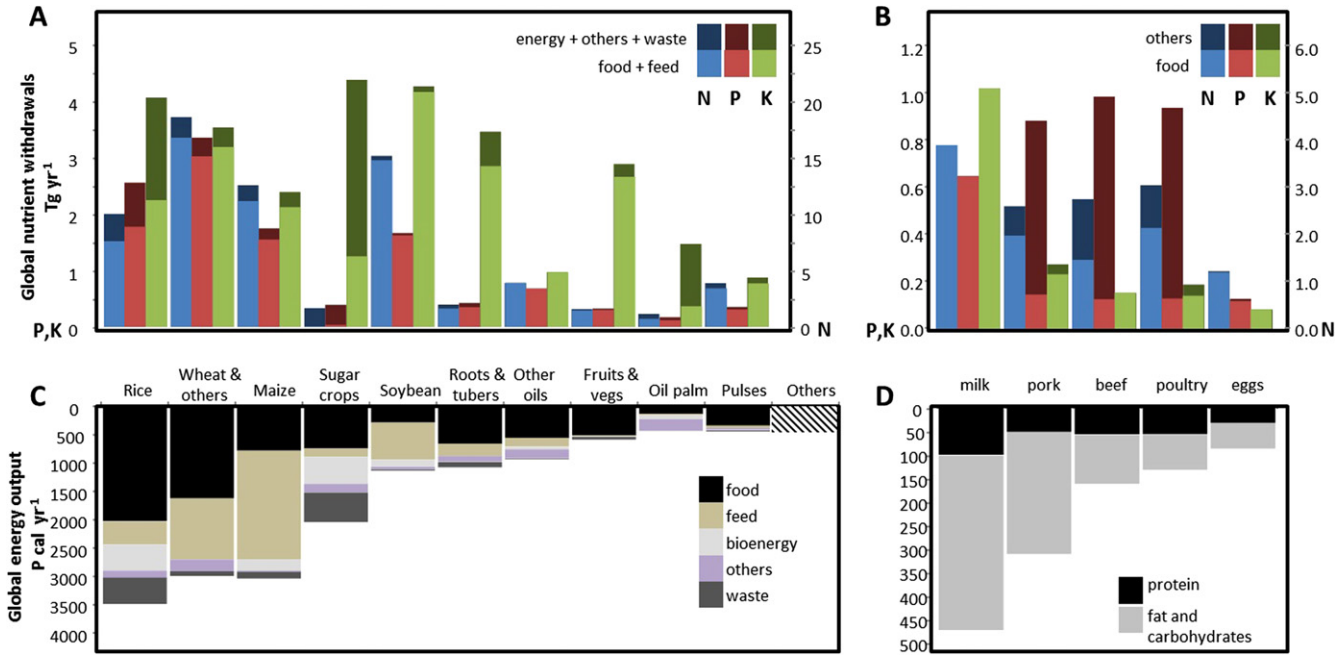

Figure 2. Average annual global harvest of mineral nutrients and energy outputs across plant and animal products for the 2008–2010 triennium. (A) Amount of nitrogen, phosphorus and potassium (note different scales) embedded in plant food and feed versus other uses. (B) Embedded nutrients in animal products divided into edible and non-edible fractions. (C) Crop energy contributions to food, feed and other uses. (D) Livestock edible energy from protein and non-protein components.

composition changes have been negligible. Global soil P withdrawals grew from 8.1 to 11.6 Tg yr^{-1} (+43%) over the last 20 years, with ae, yield intensification, and composition shifts respectively contributing +0.9, +2.4, and +0.06 Tg yr^{-1} to these increases (figure 3). In the case of K, global soil withdrawals have been dramatically increased by crop composition shifts. Over the last 20 years net soil K withdrawals climbed from 18.0 to 28.0 Tg yr^{-1} (+55%), with ae, yield intensification, and composition shifts respectively contributing with +2.0, +5.2, and +2.4 Tg yr^{-1} (figure 3). In contrast with the savings that crop composition shifts created on global soil N, soil K withdrawals are now 46% higher than what would be expected just as a result of increasing yields. A growing harvest of soybean, oil palm and fruits and vegetables explains this trend.

While global soil N, P, and K withdrawals respectively grew by 39, 43 and 55% over the last 20 years, the output of edible energy, proteins and fats from the global crop harvest, respectively increased by 47, 50 and 80% (figure 4). This involves stoichiometric changes in the global food systems with declines in its overall ratios of both energy and protein outputs with regard to N and P withdrawals, but raising ratios with regard to K withdrawals. While yield increases were the dominant component of driving output gains (Kastner *et al* 2012, Tilman *et al* 2011), crop composition shifts played a major role raising plant fat production, mainly through the join contributions of soybean, oil palm and other oil crops. Increases in per capita consumption elevated the global demand of crop products beyond what would have been expected just from population growth. The growth of per capita consumption over the last two decades was highest for plant fat and was driven by increasing non-edible uses (e.g. cosmetics and biofuels) followed by food use (figure 4). Proteins came next with most of their consumption increase being corresponding to livestock feeding. Finally a raising per capita consumption of calories was explained by non-edible uses (mainly biofuels) and secondarily by food/feed uses (figure 4).

Potentially high N and P savings brought by crop composition shifts are illustrated by the replacement of wheat & others fine grains by corn and soybean. This change has already taken place in the case of grains used for livestock feeding and is starting to happen for those used as human food (see supplementary information figure 1). To replace the calories and proteins offered by one ton of wheat and other fine grains, only 0.76 and 0.14 tons of corn and soybean are needed (calculated from table 1). Such replacement would involve 44 and 31% lower N and P and 18% higher K withdrawals and 40% less agricultural land, assuming current mean yields remaining constant (table 1). These figures illustrate savings under a hypothetical extreme replacement of crop species that certainly would be limited by agroecological, nutritional and cultural constraints. Incomplete overlap in the suitable territory of alternative crop species imposes an ecological limit to crop composition shifts, yet one that evolving breeding and agronomic technologies are lowering for many species (Frei 2000). Beyond energy or protein supply, crop composition influences the supply of essential amino-acids, vitamins and micronutrients, none of which were considered in this analysis. Cultural preferences still shape the demand of many staple crops consumed around the world and their shift is subject to a myriad of economic and

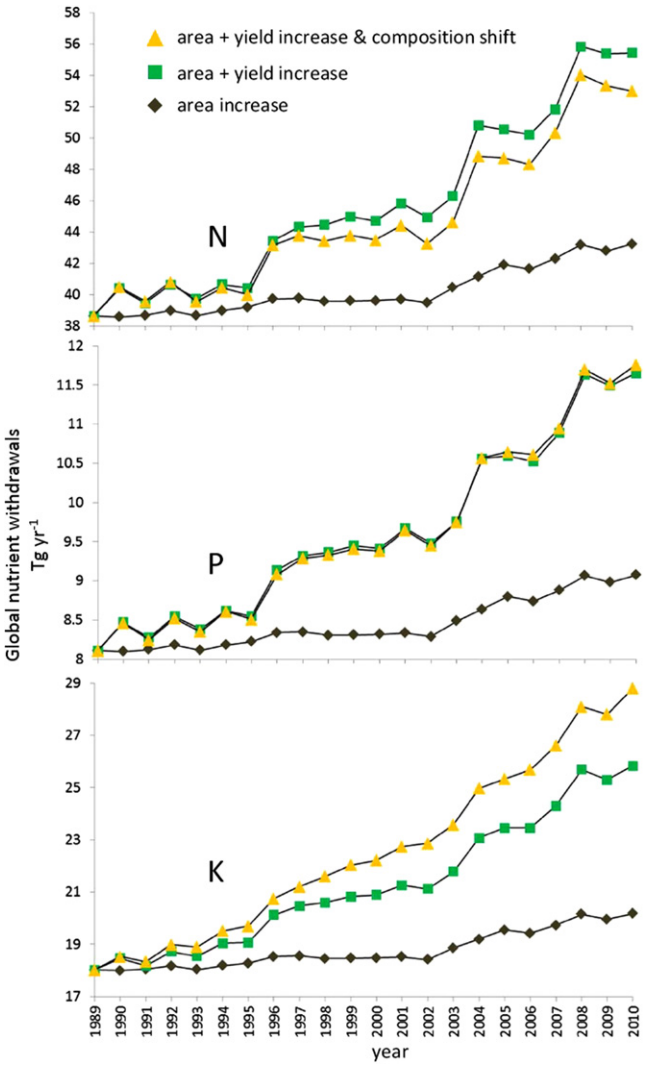

Figure 3. Effect of area expansion, yield increase and composition shift on annual global nutrient withdrawals by agricultural crops. Brown diamonds represent withdrawals due to area expansion alone, assuming that the crop yields and composition of the triennium 1988–1990 remained constant. Green squares combine area expansion and yield increases ignoring compositional shifts over this period. Yellow triangles illustrate actual withdrawals figures and encompass the three factors. The difference between green squares and yellow triangles represents the contribution of compositional shifts to nutrient withdrawals.

social forces that escape our analysis, yet they should rather be seen as highly flexible and dynamic and not fixed in time and space as trends over the last 20 years illustrate (see supplementary figure 1).

3.5. Avenues for reducing nutrient demand

Focusing on the mineral and dietary nutrient content of major crops, we showed that global crop composition shifts can contribute to achieve significant land and nutrient savings complementing ongoing yield increases and partially compensating raising animal consumption. The increasing demand of soil N and P brought by grain-fed livestock production over the last two decades would have been higher if

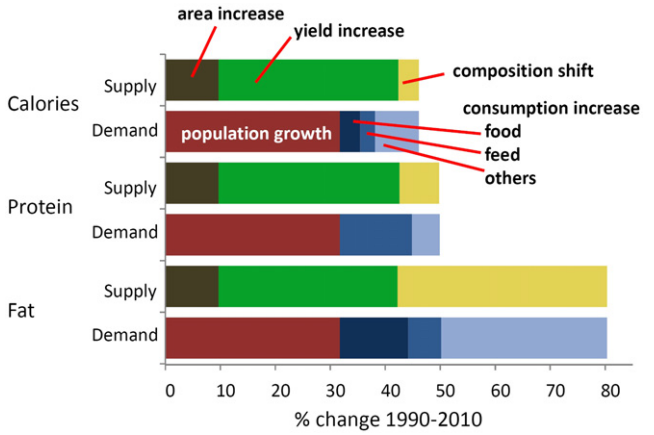

Figure 4. Contribution of different components of the increase in the supply and demand of global crop energy, protein and fat over the last two decades. Bars represent percent change and the relative contribution of area expansion, yield increase and composition shift in the case of supply. The contribution of population growth to global demand raises was estimated by projecting initial (1988–1990) per capita consumption rates to the current (2008–2010) population. The relative contribution of per capita consumption shifts was calculated as the difference between the actual demand and that estimated based solely on population growth. This last figure was partitioned according the relative contribution of food, feed and other uses to average per capita consumption increases.

not supported by the most efficient energy (maize) and protein (soybean) traditional crops. This involves both bad and good news for the potential trophic savings that could be achieved in the global-food system (Cassidy *et al* 2013). The bad news is that the land and nutrients that we allocate to the crops that feed our livestock will yield lower edible outputs if used for the crops that we currently prefer to eat. The good news is that livestock grain feeding has led to the development of extremely efficient crop systems that, if allocated to direct human consumption, could offer major land and nutrient savings. Allocating more maize and soybean to human consumption, however, brings additional challenges considering the high industrial processing that accompany their current food uses and its associated resource cost (e.g. energy for processing, paper for packaging) and nutritional concerns (e.g. high use of artificial preservatives and flavorings).

In addition to crop css, there may be room for improving nutrient efficiency within crop species as well, particularly in the case of P. Breeding during the last century has diluted nutrient contents in wheat grains (Calderini *et al* 1995); and many crops show potential for higher P-use efficiency both through traditional breeding and genetic engineering (Veneklaas *et al* 2012). In addition, nutrient withdrawals can respond to soil fertility management, with luxury P consumption by plants being a likely cause of unnecessary P withdrawals (Sadras 2006).

While soil nutrient withdrawals are partly associated with crop type, fertilization rates and their associated environmental problems are tied to the economy of crops. In this sense, increasing global affluence is elevating the

consumption of 'luxury' crops such as fruits and vegetables, which is the most expensive crop group in our analysis. Amidst its importance for a healthy human diet, fruits and vegetables are the most overfertilized component of the global-food system. Under current fertilization rates, doubling the production of this group would increase global N, P and K fertilizer demands by 16, 18 and 21%, respectively. This group should be a priority target for low-input agronomic and regulatory strategies in the near future.

4. Conclusions

This work leads to three major conclusions: (1) the efficiency of the global food production system should not only be assessed as a function of the area of agricultural land that it is demanding but also as a function of the amount of nutrients that it is withdrawing from soil and putting back on them through fertilization. (2) Changes in crop composition strongly affect how much soil nutrients need to be withdrawn per unit of food output, with particularly contrasting effects on N and P versus K. Acknowledging these contrasts can help to alleviate nutrient needs in the future. (3) While soil nutrient needs shift in response to basic biological attributes of crops; fertilizer additions are more dependent on the economic context of crop production. Understanding the causes and possible regulatory solutions for this decoupling represents a key step to making a more sustainable use of fertilizers.

Although increasing yields and plant/animal ratios in our food system are fundamental and well acknowledged avenues to support a continuously growing demand under a limiting availability of land and nutrients, the resource savings that they may generate are strongly dependent on crop choices. Over the last two decades, raising yields have been the leading force pushing soil nutrient withdrawals, yet crop composition shifts have substantially mitigated these withdrawals in the case of N and aggravated them in the case of K, creating a strong stoichiometric shift in the global-food system. In the same period, our growing consumption of animal products has relied on the most efficient grain crops (maize and soybean) and grain-fed livestock species (chicken). If this trend is reverted and the supporting soil nutrient and land resources are reallocated to the crops that we currently prefer to eat, crop yields will be substantially lower than those achieved with feed grains. Finally, from the perspective of human health, a desirable trophic descent of humanity should rely strongly on higher fruit and vegetable consumption, what under the current conditions will involve raising overfertilization and pollution problems. Dealing with these challenges requires a broader analysis of the global-food system that considers crop choice together with yield gains and trophic adjustments.

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