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The critical role of phosphorus in world production of cereal grains and legume seeds

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Abstract The production of food for the nearly 7 billion people on the earth today requires a large input of phosphorus (P), a non-renewable resource. Over the 14 year period 1995–2008, the global production of dry cereal grains plus legume seeds has not increased per capita and the area farmed to obtain these yields has declined steadily. There is great concern about the availability of food, the rising cost of food and the availability of P to maintain crop yields of key food staples. Known P reserves are finite. We report the rates of change in the area of agricultural land, the production of food staples, the use of fertilizer P and the export of elemental P in the major cereal and legume crops on a per capita basis. We seek to draw attention to the urgent need to utilize world P reserves more wisely so as to delay the impact of dwindling amounts of P and increasing costs of P on world food security. We strongly urge agriculturalists to pursue more P-efficient crop genotypes and land management which reduces losses of P from agricultural ecosystems and we support the engineering of P-recycling schemes which convert the current P-loss system nearer to a closed P-cycle system. Unless these avenues are developed in the immediate future there are likely to be severe consequences for food security in the longer term.

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Introduction

The International Food Policy Research Institute (IFPRI 2008) drew attention to the world situation which produces sufficient food for all, but still saw 800 million people chronically undernourished in 2008. They listed the steps needed to alleviate hunger and prevent recurrence of famine and starvation. Yet by October 2009, the FAO Committee on World Food Security (2009) reported that one billion people were very malnourished or starving. The rise in the cost of food followed by the recent financial and economic crises has resulted in unacceptable levels of malnutrition and structural poverty around the world (FAO Committee on World Food Security 2009). It is evident that having an increasingly large percentage of the population as poor and malnourished humans could undermine security and tranquility, be it in small towns, cities, countries, continents or globally. Food, water and energy security are needed for political and social stability (cf Lott et al. 2009).

As the world population grows, there will be further pressure on food supplies and on the natural resources which underpin their production. Soil erosion, drought, land degradation (due to factors such as salinization, poor land use decisions and other factors) have resulted in significant areas of former croplands becoming unproductive (Campbell 1998; The Global Education Project 2010). The production, processing and distribution of food all rely heavily on petroleum products and thus the supply and price of oil is a very significant input cost. The cost of oil is likely to increase as demand increases due to: 1) an increase

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in world population, 2) an increase in the use of automobiles for transport, especially in countries such as China and India which have rapidly increasing disposable incomes, and 3) a decrease in low cost petroleum reserves—the so called peak oil (e.g. Hirsch 2005) which various commentators say has already occurred or may occur in the next decade or two. One of the serious consequences of higher oil prices and/or reduced availability of oil will be higher fertilizer prices (not only oil- or natural gas-derived nitrogenous fertilizers) coupled with higher costs of transport and processing of food products.

The three macronutrients, N, P and K are usually considered the most important nutrients for plant production. We have focused on P as it is a non-renewable resource whereas N is produced by chemical means or by symbiotic associations e.g. legume-*Rhizobium*. Potassium deficiencies are not as widespread as P or N deficiencies. In this manuscript, we concentrate upon the role of phosphorus (P) in the production of the major plant crops, dry cereal grains and dry legume seeds, in the context of human population growth.

The role of P is an important factor in food security but we recognize that numerous other factors are involved including: 1) human population growth, 2) energy price and availability, 3) climatic factors, 4) water availability, 5) pests and diseases of crops and stored foods, 6) economic and political factors including trade barriers, subsidies and commodity prices, 7) dietary choices toward more meat consumption resulting in more grain/seeds being used as animal feeds and rations 8) the rate of diversion of potential food grains/seeds to manufacture of biofuels and other industrial products, 9) soil fertility and the ways crops are grown, 10) the availability and price of fertilizers, 11) the area of land available for crop production, 12) the species and cultivars of plant crops grown, 13) the problem of obesity in a world where a billion are undernourished, and 14) disruptions due to wars and other natural disasters.

The importance of phosphorus to world food security is dictated by the fact that phosphorus is a major plant-essential nutrient (Epstein 1972) which realistically cannot be replaced by another element to sustain plant life (Dessibourg 2010) and it is a non-renewable resource (Steen 1998). The role of phosphorus in food production, its role in global food security, and reasons why we should be very concerned about an emerging phosphorus crisis have been documented by Cordell and co-workers (see Syers et al. 2011) The use of P fertilizer is a key component for high yielding food crops and most of the mineral P used annually on the planet is for food production.

The importance placed on a non-renewable resource is related to the number of years that the known and anticipated economically extractable reserves are expected to meet the demand for that resource. Demand for P fertilizers, mostly derived from phosphate rock that is under the control of a small number of countries, is increasing rapidly. At the same time phosphate rock reserves, especially high quality ones, are being depleted. Like oil, P is a non-renewable resource and some commercial reserves will be depleted in the next century. Some reports estimate that “peak phosphorus” production will be reached in the next 30 years, after which P production for fertilizers will decline, prices for P will rise rapidly, food will inevitably become more expensive due to increased cost of P fertilizers and reduced crop yields, and international tensions may increase (White and Cordell 2010). However, estimates placed on world P-reserves vary widely. Contrary to the views published by White and Cordell (2010), Van Vuuren et al. (2010) and Van Kauwenbergh (2010) suggested that rapid depletion of extractable phosphate rock is not very likely in the near term. The models Van Vuuren et al. (2010) used indicated that at best 20–35%, and at worst 40–60%, of the current resource base would be extracted by 2100. A recent report commissioned by the IFDC (Van Kauwenbergh 2010) claimed that peak phosphorus is not expected for 300 to 400 years. This claim is refuted by White and Cordell (2010) who argue that, while reliable estimates of world P stocks are difficult to define, peak P is likely to occur within several decades. They argue that there are increasing demands for P from agriculture and the energy industry in addition to exhaustion of high quality (less expensive) P reserves and the risk of politically-motivated exclusion of P from world trade.

The most economical sources of P are found in Africa, China, the United States, Russia and the Middle East; however, by 2050, Africa will be producing 50% of the total P and the USA negligible amounts (Van Vuuren et al. 2010). These production areas are distant from the areas of greatest demand and some may well be in politically unstable regions. The European Union has expressed concern that agricultural production in Europe is almost entirely dependent upon imported phosphorus (Scope Newsletter 2011).

The decline in reserves will be associated with a decline in the quality of available rock for fertilizer manufacture and may also involve higher extraction costs. The concentration of elemental P in the rock sourced for fertilizer manufacture will decline (Cordell et al. 2009). These changes are expected to occur as oil production declines and so both the cost per unit of P (either mined or recycled) that is used and the cost to transport it to farmers is likely to increase. Given that P is a non-renewable resource that generally ends up in ocean sediments, it seems to us important to start now to improve our use and re-use of P so as to delay future crises, rather than debating when severe shortages will occur.

Seeds/grains of virtually all species store mineral nutrients such as P, K, Mg, Ca, Mn, and Zn. Most of the P occurs in the form of phytic acid (PA), a *myo*-inositol hexa*kis*phosphate (Raboy 2007). The potential negative charges on the phosphate groups of PA bind various cations, especially K^+ and Mg^{2+}, to form a salt called phytate (Raboy 2007). Humans, swine, poultry and other monogastric animals cannot digest phytate resulting in reduced bioavailability of mineral nutrients, and major release of P in manure leading to eutrophication of waterways (Raboy 2007; Lott et al. 2009). A global estimate of the P and PA removed from agricultural lands with crop grains, seeds and fruits (Lott et al. 2000, 2002) revealed that 4.1 billion metric tonnes (t) of these crop foods produced annually contained over 12.1 million t of P and 33 million t of PA. The dry cereal grains plus dry legume seed crops contained 7.9 million t of elemental P (Lott et al. 2009). Dry cereal grain plus dry legume seed crops thus accounted for 77% of the total production and 90% of the PA. The P in this PA equalled well over half (56–71%) of the elemental P in mineral fertilizers used for all purposes worldwide (Lott et al. 2002). In most circumstances the value of minerals including P removed in harvested seed/grain crops is greatly undervalued: Campbell (1998) estimated that it is about $25/tonne of wheat grain and this has likely risen largely due to the increased price of fertilizer.

Recently we estimated the production, area farmed, yield, P content, and the PA content of the world's most important dry cereals (barley, maize, rice, wheat) and the major dry legume seed (soybean), as well as total dry cereal grains and total dry legume seeds (Lott et al. 2009). These data were presented for the world and for the six continents/regions (Africa, Asia, Europe, North-Central America, Oceania, and South America) used by the United Nations. Nine years of data (1995–2003) were evaluated. We also related the P removed from the land when these crops were harvested to the elemental P used in fertilizer from all mineral sources. In relation to crop production, Asia consumed considerably more mineral P fertilizer than any other region, using nearly 54% of the world total. North-Central America generally had the highest yields and Africa the lowest (Lott et al. 2009).

While there is common recognition of future difficulties due to oil supplies being depleted, there is relatively little appreciation of the importance of P to global food security and little recognition of the value of the P contained in the food that is harvested from agricultural lands. In the research presented in the current paper, we concentrated upon total dry cereal grains and total dry cereal grains plus total dry legume seeds for the same six regions and globally, but present findings on a per capita basis to highlight the importance of P to world food security. Here we compared the production of these key food grains/seeds in relation to the human populations in the world's six continents/regions, arable land per capita used in these major geographic regions of the world to grow these crops, elemental P per capita removed when these crops are harvested, and the elemental P from mineral sources used for fertilizer per capita.

Methods

Data for mean total dry cereal grain and mean total dry legume seed production (in metric tonnes), mean area farmed to produce those crops (in hectares), and mean elemental P in the crops (in t) for the years 1995–2003 were obtained from the complete set of data produced by Lott et al. (2009). Means and standard deviations were computed from the regional values for each parameter over specified time periods (1995–2003; 2004–2008 and 1995–2008). Total cereals include dry grains of wheat, maize, rice, barley, rye, oats, millet, sorghum, and other cereals produced in smaller quantities such as triticale. Total legumes include soybean, broad beans, peas, beans (*Phaseolus* sp.), lentils, groundnuts, and others produced in smaller quantities such as vetches. Mean data and standard deviations were presented for the world and the six continents/regions (Africa, America-North and Central, America-South, Asia, Europe, Oceania) used by the Food and Agriculture Organization of the United Nations. Data for 1995–2003 for production and area farmed to grow these crops were obtained from FAO Production Yearbooks (1997, 1999, 2000, 2003, and 2004). Data for total P in these crops were calculated using the values given in Lott et al. (2000). Data for 2004–2008 for production and area farmed to grow these crops were obtained from the FAO web site (FAOSTAT 2011a).

For the human population of the various continents/regions we used mid-year estimates for both sexes and all ages given in Table 1 in the Demographic Yearbooks (1995, 1996, 1997, 1998, 1999, 2001, 2002, 2003, 2004, 2005, 2006, 2007 and 2008). The Demographic Yearbook (2000) data for population had serious flaws. The best population data available for the year 2000 were from Table 1 in the Demographic Yearbook (2001) and that was what we used. There were very small differences (maximum 3.2 million) between the world total populations given in the Demographic Yearbooks and the sums of the totals given for all six continents. No attempt was made to alter any of these differences. Means and standard deviations were calculated using PASW Statistics (v 18, SPSS Inc. Chicago, ILL, USA). It was important to determine if the data we needed to use from the FAO Production Yearbooks for a given continent/region could be compared with human population

Table 1 Summary of data for 1995–2003 and 2004–2008 for the human population of the world and for the six continents/regions of the world. The production per capita, area farmed per capita, and the elemental phosphorus removed at harvest (mean±standard deviation) are given for the total dry cereal grain crop and the total dry cereal crop plus the dry legume seed crop for the same time period and regions. The numbers in parentheses are for 2004–2008. An [a] indicates that the standard deviation was above 10% of the mean. As the production/capita does not change ($p>0.05$) between the two periods then the amount of elemental P removed with crop per capita will not change between periods and thus only a single value is presented

Continent/region	Mean population (millions)	Grain/seed	Production (t) per capita per annum	Area farmed (ha) per capita	Elemental P (kg) removed with crop per capita per annum
AFRICA	783.44±47.11 (940.80)	Cereals total	0.15±0.01 (0.15±0.01)	0.12±0.01 (0.11±0.00)	0.5±0.0
		Cereals + legumes total	0.17±0.01 (0.17±0.01)	0.15±0.00 (0.14±0.00)	0.6±0.0
AMERICA NORTH/ CENTRAL	480.22±17.87 (523.60)	Cereals total	0.86±0.06 (0.90±0.06)	0.19±0.02[a] (0.16±0.01)	2.7±0.2
		Cereals + legumes total	1.03±0.07 (1.07±0.05)	0.26±0.02 (0.23±0.01)	3.8±0.3
AMERICA SOUTH	340.56±15.61 (377.80)	Cereals total	0.30±0.02 (0.34±0.03)	0.10±0.01 (0.10±0.00)	0.9±0.1
		Cereals + legumes total	0.48±0.06[a] (0.61±0.05)	0.19±0.01 (0.22±0.00)	2.1±0.3[a]
ASIA	3633.56±126.38 (3977.20)	Cereals total	0.27±0.01 (0.28±0.01)	0.09±0.00 (0.08±0.00)	0.8±0.0
		Cereals + legumes total	0.29±0.01 (0.30±0.01)	0.11±0.01 (0.10±0.00)	0.9±0.0
EUROPE	728.33±0.87 (730.80)	Cereals total	0.55±0.04 (0.60±0.06)	0.17±0.01 (0.17±0.01)	2.0±0.2
		Cereals + legumes total	0.56±0.04 (0.59±0.06)[a]	0.18±0.01 (0.17±0.00)	2.0±0.2
OCEANIA	30.21±1.35 (33.84)	Cereals total	1.09±0.20[a] (0.94±0.26)[a]	0.56±0.02 (0.59±0.03)	4.1±0.7[a]
		Cereals + legumes total	1.17±0.21[a] (0.96±0.27)[a]	0.63±0.02 (0.64±0.03)	4.4±0.8[a]
WORLD	5996.67±207.25 (6542)	Cereals total	0.34±0.01 (0.35±0.01)	0.11±0.01 (0.11±0.00)	1.1±0.0
		Cereals + legumes total	0.38±0.01 (0.40±0.01)	0.14±0.01 (0.13±0.00)	1.3±0.0

data obtained from the Demographic Yearbooks produced by the United Nations for the same continents/regions for the years 1995 to 2008. The demographic data include more detail on sub-regions within a continent but a comparison of the countries in each showed that they were essentially the same, with exceptions for the Americas. In our study we obtained the population of North/Central America by adding together figures for the population in the Caribbean, Central America and North America. The population of South America was taken from the South America sub-section of a category called Latin America and the Caribbean.

As detailed in Lott et al. (2009) the consumption of P fertilizers for all purposes in the various continents/regions for the 9 years 1994/1995 to 2002/2003 was obtained from Table 29 in the FAO Fertilizer Yearbook 2003 (2004). Data for the years 2004 to 2008 were obtained from FAOSTAT (2011b). The FAO have revised the data collection protocol in recent years and a new questionnaire format was adopted in 2006 (Mayo 2008). The FAO data used for 2004–2008 for consumption of phosphate fertilizers (P_2O_5 total nutrients) were converted to elemental P. The countries making up the regions used in the FAO Yearbook on Fertilizer were compared to the countries used in the demographic yearbooks and the FAO Production Yearbooks. There were differences but they were very minor and no attempt was made to correct them. For example, the demographic data include populations of many small islands that did not report any P fertilizer usage or any cereal/legume production. While much of the P fertilizer used for all purposes is used on cereal and legume crops, the most important plant crops worldwide, some is also used on other seed, fruit, vegetable, and forage crops as well as in horticulture; these products largely enter the food chain directly or indirectly. Worldwide, about 90% of the demand for P is for use in food production (Cordell et al. 2009). As we have no accurate information that would have allowed us to adjust the values we give for P used for non-grain/seed crops, we presented our data as P fertilizer used for all purposes per capita, knowing that a large fraction of the P fertilizer is applied to the most important grain/seed crops. FAO data (incomplete for any one year) on fertilizer use statistics indicate that about 6% of P used is applied to fodder and horticultural crops globally.

The data were plotted over the time spans studied (1995–2003, 2004–2008) and an evaluation was made to determine if there were any statistically significant trends using PASW Statistics (v 18, SPSS Inc. Chicago, ILL, USA). We used the available data to assess three aspects of change: namely, in human population, per capita production of legume plus cereal grains/seeds, and area farmed per capita to grow these cereal plus legume crops. For 1995 to 2003 we estimated elemental P removed per capita with total seed crop, and elemental P fertilizer used for all purposes on a per capita basis. The total P in dry grains/seeds of each different crop (e.g. wheat, rice, oats, millets, beans, peas, groundnuts, soybean, etc.) in the categories “dry cereal grains” and “dry legume seeds” was estimated using the method of Lott et al. (2000). Based on published values for total P concentration of each grain or seed type, the tonnes of P in each crop was estimated and summed to obtain the category total. Where needed, corrections were made (e.g. for groundnut shells). The analyses were performed separately for each of the six regions as well as for the whole world to determine trends with time (1995–2008). For land used, the UN data are based on double-cropped areas being counted only once.

Results

P removal

For 1995–2003, on a per capita basis the amount of P removed with dry cereal grains or dry cereal grains plus dry legume seeds was by far the highest in Oceania (4.1 and 4.4 kg/person per annum respectively), over three times the world mean (1.1 and 1.3 kg/person per annum respectively; Table 1). North/Central America also removed a large amount of P per capita with these crops. Africa and Asia removed well below the world mean amount of P in these crops on a per capita basis (Table 1). For South America, the P removed per capita with cereal grain crops was below the world mean but well above the world mean for cereal grains plus legume seeds per capita. Because the production per capita was very similar for 1995–2003 and 2004–2008 (Table 1), it is reasonable to assume that P removal per capita was similar in both time periods.

P input

For both 1995–2003 and 2004–2008, the amount of P fertilizer used for all purposes on a per capita basis was very high in Oceania (20 to 21 kg elemental P), nearly nine times the world mean (2.4 to 2.7 kg) and forty times that of Africa (0.5 kg; Table 2). The P fertilizer use per capita was also above the world mean for North/Central America and South America. Africa and Asia were below the world mean P fertilizer usage per capita. Africa had less than a quarter of the world mean P usage per capita (Table 2). The high per capita usage of P in Oceania and North/Central America may reflect that both regions are net exporters of grain for food consumption elsewhere in the world. The mean use of P fertilizer in South America on a per capita basis increased over 50% when 2004–2008 is compared to 1995–2003 (Table 2).

Population

The mean population data for the nine year period (1995–2003) showed that just over 60% of the world’s population lived in Asia (Table 1). Africa was the next most populous continent (13% of world total), followed by Europe (12%), North/Central America (8%), South America (5.7%) and Oceania (0.5%). The world population in 2003 was 6.3 billion and reached more than 6.5 billion in 2008. A

Table 2 Means±standard deviations for 1995–2003 and 2004–2008 of data are given for elemental phosphorus (in millions of tonnes) obtained from mineral sources and used in fertilizer for all purposes globally and in each of the six continents/regions of the world. For the same time period and the same regions data are given for the amount of elemental P from mineral sources used for all purposes on a per capita basis. Numbers in parentheses are for 2004–2008. An [a] indicates means with a standard deviation >10%

Continent/region	Elemental P (mt per annum) in fertilizer used for all purposes	Elemental fertilizer P usage (kg) per capita per annum
AFRICA	0.41±0.001 (0.4±0.003)	0.5±0.03 (0.5±0.04)
AMERICA NORTH/ CENTRAL	2.3±0.007 (2.3±0.008)	4.7±0.27 (4.5±0.54[a])
AMERICA SOUTH	1.2±0.2[a] (2.1±0.3[a])	3.6±0.55[a] (5.7±0.73[a])
ASIA	7.5±0.5 (10.2±0.3)	2.1±0.11 (2.6±0.10)
EUROPE	2.0±0.2 (1.8±0.06)	2.7±0.25 (2.5±0.19)
OCEANIA	0.6±0.04 (0.7±0.1[a])	21±0.74 (20.1±3.78[a])
WORLD	14.1±0.6 (17.6±0.2)	2.4±0.07 (2.7±0.15)

comparison of human population increases between 1995 and 2008 revealed that over that 14 year period the world population increased 20% with the greatest increase in Africa (40%) and the lowest increase (1%) in Europe (Table 3a).

Production and area farmed

For the period 1995–2003, the production on a per capita basis of total dry cereal grains or total dry cereal grains plus dry legume seeds was highest in Oceania and lowest in Africa (Table 1). Production per capita in Africa was about 15% of the production per capita in Oceania. Mean production per capita in Oceania fell in 2004–2008 compared to 1995–2003 (Table 1) due to prolonged drought. North/Central American and European production per capita of cereals and cereals plus legume grains/seeds was well above the per capita world mean (Table 1). South America's production of total cereal grains plus legume seeds per capita was above the world mean, yet total cereal grain production per capita was below the world mean. The same pattern for South America occurred in area farmed per capita. Oceania used the biggest areas per capita to farm cereals and cereals plus legume seeds/grains whereas Asia used the smallest areas per capita (Table 1). This reflects the differences in broad acre farming in Oceania (largely Australia) in contrast to small holdings of farmers in Asia. Both Europe and North/Central America used more area

Table 3 Trends (by linear regression of the data for the specified time period) in data for the total dry cereal grains plus total dry legume seeds for the 14 year time span (1995–2008) for four variables for the world and six continents/regions. Variables studied were: a) human population in millions, b) total production of dry cereal grains plus dry legume seeds in t per capita, c) area (in ha) farmed to grow these crops per capita, and d) the elemental P in kg in mineral fertilizer used for all purposes expressed on a per capita basis. a = no change over the 14 year time span ($p>0.05$)

Variable (Theme)	Continent / Region	Base year 1995 (million)	ß (standardised coefficient)	Rate of change per annum over 14 years	Percentage change over 14 years	R^2	P
a) Human population	Africa	728	0.986	21.02	40	0.973	<0.0005
	America North/Central	455	0.999	6.28	19	0.997	<0.0005
	America South	320	0.995	5.34	23	0.991	<0.0005
	Asia	3458	0.999	48.44	20	0.998	<0.0005
	Europe	727	0.728	0.266	1	0.53	<0.003
	Oceania	28.5	0.997	0.513	25	0.993	<0.0005
	World	5716	0.998	81.82	20	0.996	<0.0005
b) Production of cereals and legumes / capita	Africa	0.15	0.227	0	a	0.017	>0.05
	America North/Central	0.94	0.219	0.003	a	0.048	>0.05
	America South	0.43	0.964	0.02	65	0.929	<0.0005
	Asia	0.29	0.040	0	a	0.002	>0.05
	Europe	0.53	0.424	0.006	a	0.18	>0.05
	Oceania	1.11	−0.415	−0.024	a	0.172	>0.05
	World	0.37	0.435	0.002	a	0.19	>0.05
c) Area farmed for cereals and legumes / capita	Africa	0.1528	−0.839	−0.001	a	0.536	>0.05
	America North/Central	0.2695	−0.908	−0.004	−21	0.824	<0.0005
	America South	0.188	0.858	0.003	22	0.736	<0.0005
	Asia	0.114	−0.943	−0.001	−12	0.888	<0.0005
	Europe	0.1929	−0.737	−0.002	−15	0.543	0.003
	Oceania	0.6193	−0.008	0	a	0	>0.05
	World	0.148	−0.931	−0.001	−9	0.867	<0.0005
d) Elemental P fertilizer used for all purposes on a per capita basis	Africa	0.567	−0.892	−0.01	−25	0.745	0.001
	America North/Central	4.965	−0.788	−0.081	−23	0.622	0.001
	America South	3.367	0.874	0.238	99	0.764	<0.0005
	Asia	1.871	0.817	0.049	37	0.668	<0.0005
	Europe	2.899	−0.870	−0.057	−28	0.758	<0.0005
	Oceania	20.159	−0.259	−0.137	a	0.067	>0.05
	World	2.257	0.619	0.025	16	0.383	0.018

per capita to grow these crops than the world mean. This difference may be partly due to cold winters in temperate zones, whereas in much of tropical Asia production continues through the year.

Trends—1995–2003

In addition to presenting nine year mean data we also looked at possible trends over that nine year period for total dry cereal grains plus dry legume seeds for five variables (data not presented). With the sole exception of Europe, the human population increased significantly in all regions and globally. Over the nine years studied, the percent change in population ranged from a 0.3% increase in Europe to a 19.2% increase in Africa. Over the 9 year time span 1995–2003, the production of total dry cereal grains plus dry legume seeds per capita increased only in South America and declined only in Asia. The area farmed per capita to grow these major crops decreased significantly in Asia, Europe, North-Central America and globally and did not increase significantly in any region. Over the nine years studied the amount of elemental P removed with the total dry cereal grain plus dry legume seed crops on a per capita basis decreased significantly in Asia but increased in South America. The amount of elemental P in fertilizers, used for all purposes, increased greatly in South America (31%) on a per capita basis but declined in Africa, Europe and North-Central America.

Trends—1995–2008

Trends for 1995–2003 based on production of dry legume seeds plus dry cereal grains and area farmed taken from one data source were extended to cover the 14 year period 1995–2008 using two data sources for production and area farmed and expressed on a per capita basis (Table 3). Over the time span 1995 to 2008 population expansion in Africa outpaced world and other southern hemisphere regions almost twofold, whereas Europe in the northern hemisphere was basically static in population growth (Table 3a). Production of cereal plus legume seeds per capita over the 14 year span showed no significant change in five continents but, in South America, there was a major increase of 65% (Table 3b). The area farmed to grow dry cereal grains plus legume seeds per capita increased only in South America (22%), showed no change over the 14 years in Africa and Oceania, and decreased in North/Central America (−21%), Europe (−15%), Asia (−12%) and globally (−9%, Table 3c). The use of P fertilizers for all purposes on a per capita basis over the 14 years studied showed that usage rates in Oceania did not change significantly (Table 3d). P fertilizer usage per capita decreased in Europe (−28%), Africa (−25%) and North/Central America (−23%) whereas usage in Asia increased by 37% and South America doubled its usage (Table 3d). Mean production per capita was similar for the periods 1995–2003 and 2004–2008 for each region and for the world (Table 1) so we can conclude that the amount of P removed in these crops on a per capita basis is a stable value. Therefore the amount of P removed in crops is directly proportional to the population. For the relatively short time periods reported here the changes in area per capita cannot be regarded as significant except in South America where there has been a major increase in the area sown to legumes. Oceania has a high variability in production per capita due to the highly variable climate and the inclusion of data taken during the period of the prolonged drought.

Discussion

It is of concern that the production of dry cereal grains plus legume seeds on a per capita basis showed no change globally and in five continents at a time when a small but increasing amount of the production is being diverted to non-food purposes such as biofuel manufacture and when hunger/starvation is affecting increasing numbers of humans. Only in South America was there a large increase in cereal plus legume production, but based on 1995–2003 data in Lott et al. (2009) South American production of these crops represented less than 8% of the world total. In the period 2004–2008, South American production had risen to account for 9% of world production (data not presented).

Globally and in most of the continents/regions, the area farmed to produce cereal grains plus legume seeds on a per capita basis had no change or declined from 1995 to 2008. South America was the only exception where there was an increase (22%) in the area farmed per capita even at a time when the population of the continent increased 23%. South America has experienced major deforestation in the Amazon basin and other areas. For South America, the considerable difference between production of total cereal grains plus legume seeds per capita (which was above the world mean) and the per capita production of cereal grains alone (which was below the world mean) was due to the major production of soybeans. In all regions except South America, the major crop grown was a cereal (wheat in Europe and Oceania, rice in Asia, or maize in Africa and North/Central America) but, in South America, soybean accounted for 38% of that continent's total cereal plus legume production slightly exceeding the 37% of the South American production total for maize (Lott et al. 2009). South America devoted considerably more of the area used to grow total cereals plus total legumes to soybean than maize (Lott et al. 2009). Because dry soybean seeds have higher P than dry cereal grains (0.68% P on a dry weight basis for soybean seeds versus about half that for the key cereals: Lott et al. 2000), the amount of P removed with cereal plus legume crops per capita markedly increased in South America compared to other continents. The elemental P removed with soybean seed harvest in South America was the second highest of all the 6 world regions for 1995–2003 and represented 37% of the world total for P in soybeans (Lott et al. 2009) but that was only 5% of the elemental P removed globally in all the dry cereal grain plus legume seed crops.

South America and Asia were the only continents where the use of mineral P fertilizers for all purposes on a per capita basis increased from 1995 to 2008 (99% and 37% respectively), while Oceania had no change and Africa, North/Central America and Europe had considerable decreases. The decline in fertilizer usage in North America and Europe may be due to previous over-fertilization of soils that have high residual values for P. In this context, the soil P bank can be utilized for some years without deficiencies occurring. Thereafter, P fertilizer inputs will be required to maintain productivity. The combination of more area farmed to grow cereal plus legume crops and increased mineral P fertilizer usage must have contributed greatly to the reason that South America stands out as being the only continent having a large increase (65%) in production per capita over the 14 year time span studied. Although we do not know if the P fertilizer use rates in South America were below, at, or above efficient agronomic levels, this analysis still shows that P fertilizer is well correlated with increased production. Given the costs of P fertilizer in most countries, it is unlikely that excessive applications of P occured in recent years. Soils that bind P-compounds have a great influence upon the availability of P to plants (Lynch 1999). A map of the world presented in Lynch (1999) shows the distribution of soils prone to lead to P deficiency. Low soil P affects large areas of the surface of the planet including many of the most densely populated and heavily vegetated. Clearly efficient use of P fertilizers must consider the local soil conditions.

It is informative to analyze the same data set from two points of view (i) the actual values for production, area farmed, P contained in harvested dry cereal grains plus legume seeds, etc (as in Lott et al. 2009) and (ii) that same data expressed on a per capita basis (this paper). For total dry cereal grains plus dry legume seeds the continents/regions ranked as a percentage of the world mean total from highest to lowest are as follows: *Production*—Asia, North/Central America, Europe, South America, Africa, Oceania; *Area farmed to grow these crops*—Asia, Europe, North/Central America, Africa, South America, Oceania; *P removed with these crops at harvest*—Asia, North/Central America, Europe, South America, Africa, Oceania: *Elemental P in mineral fertilizers used for all purposes*—Asia, North/Central America, Europe, South America, Oceania, Africa. Using data for total cereal grains plus legume seeds presented in this manuscript, the same topics ranked on a per capita basis as a percentage of the world mean from highest to lowest are: *Production per capita*—Oceania, North/Central America, Europe, South America, Asia, Africa; *Area farmed to grow these crops per capita*—Oceania, North/Central America, South America, Europe, Africa, Asia; *P removed with crop per capita*—Oceania, North/Central America, South America, Europe, Asia, Africa; *Elemental P in mineral fertilizers used for all purposes per capita*—Oceania, North/Central America, South America, Europe, Asia, Africa. Thus Asia is the biggest continent/region in terms of production of cereal grains plus legume seeds, uses the largest amount of land to grow these crops, removes the greatest amount of P in the harvest, and uses by far the greatest amount of mineral P fertilizer. Because Asia has over 60% of the world human population, when expressed on a per capita basis Asia ranks at or near the lowest in all four categories. Per capita, Africa ranks lowest in three of four categories and Oceania ranks first in all.

The FAO Committee on World Food Security (2009) now estimates that more than a billion humans are suffering from under-nourishment. World food stores are low and with increasing concerns over global warming, unsustainable degradation of tropical ecosystems, population growth and variability in yields, there should be a widespread attempt to store additional grain/seed foods to help moderate temporary disruptions in food supplies. Globally production of dry cereal grains plus legume seeds has not increased per capita over the 14 year period 1995–2008 and the area farmed to grow these crops world wide continued to decline steadily (−9% over 14 years). Thus any improvements in yields have been negated by population growth. The rapid increase in the human population, a global 18% increase since 1995, is clearly a huge issue for food security. Stabilizing or reducing the human population would play a big role in providing adequate food to all. Diet shifts that reduce meat consumption would assist having more grain for food but the trend in developing countries that are getting richer is to increase meat consumption. Developing new crop genotypes that use less P per tonne of grain/seeds and/or low phytate crops would help as would growing more food from plants that use less P per t produced (e.g. more maize and less soybean) but this may be at the expense of more calories and less protein. Expansion of agriculture onto marginal lands will require higher than normal P inputs (cf Awad et al. 1990). The continued increase in population combined with what appears to be larger fluctuations in climate, and hence decreased reliability of food production, is expected to result in sub-optimal supplies of food for large segments of the human population more frequently. South America is unusual in that it showed an increase in production per capita that is driven by an increase in the area farmed. While some see that there are huge areas which could be converted to agricultural production others are concerned that the deforestation would be at the unacceptable expense of the loss of the valuable natural resources.

Based on the14 year set of data we used to obtain trends, evidence that human population growth has continued to increase, increased diversion of grain to biofuel production, larger climate change problems, etc. all lead us to believe that the trends we outline here are strong evidence that food security for many people is at great risk. We have not estimated how much P fertilizer was used or not used to produce cereal and legume crops. We consider the use of P on other crops, vegetables and pastures to be important to the long-term supply of P and to food security but these uses are unlikely to change the large regional differences we observed.

Since plant food production and fertilizer applications are inextricably linked, there is a very long term need for N, P, and K fertilizers to protect and improve the fertility of the plant crop farmlands worldwide (FAO 2007). Our data show that world P fertilizer usage was increasing at a rate of about 357,000 t/ annum, i.e. an annual increase of 2.4% for the 14 year period. The expected growth in demand for P fertilizers is about 3% per annum until 2010/2011 with over 60% of this increase being in Asia (FAO 2007). For the period 2008 to 2012 P-fertilizer consumption worldwide is estimated to grow 2.8% (FAO 2008). Fortunately reserves of phosphate rock occur fairly widely across the globe but geopolitical considerations for long term availability need to be assessed. The biggest producers, representing more than 70% of the world production in 1999, were the United States of America, China, Morocco including the Western Sahara, and the Russian Federation (McClellan and Van Kauwenbergh 2004). However, China has moved to restrict P exports through export tariffs, Moroccan occupation of the Western Sahara with its phosphate rock resources is condemned by many governments, and the USA has about 25 years of reserves left (Cordell et al. 2009). Even though there may be reserves of phosphate rock to last one or more centuries, the reserves of high-grade deposits are dwindling and prices of phosphate rock derived fertilizers are likely to rise (Morrison 2009). Phosphate rock is a non-renewable resource, just like petroleum, so very long term food security dictates that every attempt be made to recognize the geochemical realities that limited P reserves will have on future food production and the potential that widespread food shortages have for major unrest in many areas of the world (Cordell et al. 2009, 2011).

Due to the decline in the availability and increases in the cost of processing and transporting P, the price of P to farmers can be expected to increase. This would lead to lower inputs of P and consequently lower yields per ha and per capita. Measures to counter this threat to food production and the related food security implications must be undertaken urgently. Plant-selection and breeding, probably utilizing plant genetic engineering approaches to improve the utilization of world P supplies will only be successful if there is a dedicated and ongoing desire to achieve more food per kg P used. In addition, the current P-use chain, which frequently results in major movement of nutrients when seed/grain crops are moved from areas of production to areas of consumption, must be replaced by a P-use cycle (cf Campbell 1998). It is vitally important for stable long-term food production and food security that the stocks of P in the world, both in reserves and in the food chain, are better accounted for and steps are taken to mine it, distribute it and reuse it more efficiently.

The accumulation of P in seeds and grains increases when P is applied to raise yields (Batten and Khan 1987). Cultivars of wheat and rice which produce high yields with lower grain % P have been identified (Batten 1986a; Marr et al. 1999; Rose et al. 2010). Additions of P accumulate largely in phytate (Lott et al. 2000). Seeds/grains with lower total P will also be lower in phytate (Batten 1986b). The dual gains from producing food which is lower in P and phytate are that consumers are provided with food which is preferable for micronutrient retention in humans and other monogastric animals and from the reduction in the rate of export of P in crops produced from agricultural land. To date the advantages of grains with lower P have not been utilized by farmers.

More efficient use of the P reserves of the world is possible. At this time, no allowance is made for the replacement value of the minerals in staple foods. In 2009–10, the world production of coarse grains alone was 1.1 billion tonnes with about 106 million tonnes being traded (ABARE 2010). There have been several calls for the real cost of production to include an allowance for the minerals in plant products (Lipsett and Dann 1983; Campbell 1998) but the value placed on foods takes no account of the depletion of non-renewable resources such as P which are mined to produce the food. If the replacement value of minerals in food was part of the price paid for a commodity, it would lead to more efficient use of this non-renewable resource. However, we acknowledge that policies for such a strategy must be developed to mitigate the increased cost of food for the world's poor.

The ultimate solution to the problem of P-exhaustion is to change the movement of P from a one-way path to a P-cycle. A detailed review of non-plant approaches to improving P utilization is that by Cordell et al. (2011). We propose some strategies: 1) maximizing recycling of P from biosolids back to farmland, 2) minimize P loss from productive farmland in run-off and soil erosion since these losses can be reduced (cf de Kliein et al 2010), 3) maximize recycling of mineral nutrient containing residues from biofuel production back to the land that produced the plant materials used in the process, 4) use of microorganisms to solubilize P and other strategies to release P from rock and P-fixing soils, 5) improve P fertilizer application strategies (cf Malley et al 2007) to rapidly and economically assess soil fertility above ground (cf Ben-Dor et al. 2009), in the root zone (cf Christy 2008) and the crop itself (cf Bowman et al. 2007), 6) use of P efficient genotypes, 7) research P capture from ocean sediments, and, 8) locate animal industries closer to the sources of their seed/grain feed.

Conclusions

The diversion of grains to industrial uses (e.g. to produce ethanol) led to increases in the prices of some foods in 2008. Localized disasters such as drought or floods in major food producing regions (e.g., Russia and Pakistan in 2010) receive attention from the world media and may result in increases in food prices in the short term. However, the depletion of high grade phosphate fertilizers and the resulting increase in cost per kg of elemental P available for fertilizing food crops, which attracts almost no attention, is a more serious long term, irreversible happening. This paper demonstrates the need to value the P removed in cereal and legume crops much more carefully and the importance of managing P reserves far more judiciously.

Irrespective of how many years rock P reserves are able to support agricultural production based on current predictions, steps to counter the negative effects of declining supply, declining quality and rising costs must be initiated as soon as possible. These will result in lower costs of production and an increase in food security as well as reduced risk of P-induced pollution. The identification and implementation of more efficient utilization of P may include the use of crop genotypes which produce more food or fibre per kg P applied as fertilizer and per kg P accessed by the plant or a lower P concentration in crop products, and recycling of P taken up by plants (after being used by humans) to reduce the demand on mining of rock-P reserves. There is a lag of one to two decades between identifying a P-efficient trait in a plant and it being utilized commercially. If these approaches or any other approach are to have a significant impact there will need to be many years of research and development. It is important that a major commitment to this research is not delayed. Food security should not and need not be further compromised by lack of P.

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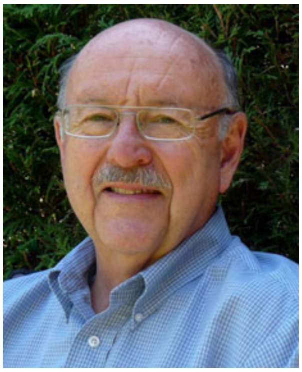

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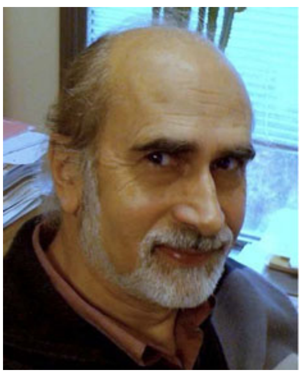

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