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REPORT

The Impact of First-Generation Biofuels on the Depletion of the Global Phosphorus Reserve

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Abstract The large majority of biofuels to date is "first-generation" biofuel made from agricultural commodities. All first-generation biofuel production systems require phosphorus (P) fertilization. P is an essential plant nutrient, yet global reserves are finite. We argue that committing scarce P to biofuel production involves a trade-off between climate change mitigation and future food production. We examine biofuel production from seven types of feedstock, and find that biofuels at present consume around 2% of the global inorganic P fertilizer production. For all examined biofuels, with the possible exception of sugarcane, the contribution to P depletion exceeds the contribution to mitigating climate change. The relative benefits of biofuels can be increased through enhanced recycling of P, but high increases in P efficiency are required to balance climate change mitigation and P depletion impacts. We conclude that, with the current production systems, the production of first-generation biofuels compromises food production in the future.

Keywords Biofuels · Phosphorus · Climate change · Trade-off

INTRODUCTION

Biofuels have been strongly promoted by many governments in order to reduce CO_2 emissions and support the diversification of energy sources. The large majority of bioethanol and biodiesel produced to date is "first-generation" biofuel made from agricultural commodities using conventional technology. The global production of bio-ethanol alone increased from 17 thousand million liters in 2000 (Balat 2007) to 65 thousand million liters in 2008 (Biofuels Platform 2010). The most important feedstocks for bio-ethanol are sugarcane, wheat, corn, and sugarbeet, and for biodiesel these are rapeseed, soybean, and palm oil (Balat and Balat 2009).

In order to further promote the production and use of biofuels, a range of countries have established targets for blending biofuel components in the overall fuel mix. Biofuel blending mandates and/or targets have now been established in, among others, Brazil, Canada, China, the EU, India, Japan, Malaysia, South Africa, Thailand, and the US (Bringezu et al. 2009). Two key energy markets, the US and the EU, have particularly ambitious targets for biofuel use. The U.S. Department of Energy targets to replace 30% of the fossil transportation fuel mix with biofuels and 25% of industrial organic chemicals with biomass-derived chemicals by 2025 (Ragauskas et al. 2006). The 2003 EU "Biofuels Directive" (The European Parliament and the Council of the European Union 2003) required 5.75% of all transport fuels to be derived from biomass as of December 2010, and further targets for biofuels for 2020 are being discussed. Consequently, the production of biofuels will strongly increase in the coming decade (European Environment Agency 2009).

There are a number of environmental concerns related to first-generation biofuel production, which depend on feedstock type, production location, agronomical practices, etc. (e.g., Patzek 2004; Tilman et al. 2009; Cushion et al. 2010; Haberl et al. 2010). One of the key issues is that some biofuel production pathways increase rather than decrease greenhouse gas emissions, due to associated N_2O emissions (Crutzen et al. 2007) or, in the case of palm oil cultivated on peatland soils, because of peat oxidation (Wicke et al. 2008). There is also concern regarding the impacts on food prices of using food crops for biodiesel and bio-ethanol production (Rosegrant 2008). Further externalities relate to water use, pesticide use, nutrient run-off, and eutrophication of downstream water bodies

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(Leemans et al. 1996; Cushion et al. 2010; de Vries et al. 2010).

An additional aspect of first-generation biofuel production is that all feedstock production pathways require the application of phosphorus (P) fertilizers. It is increasingly recognized that the depletion of P is a prime concern for mankind, because P is essential for global food production, it cannot be substituted and the world's P stocks are finite (Steen 1998; Cordell et al. 2009; Tiessen et al. 2011). Consequently, the production of first-generation biofuels involves a trade-off between avoiding CO_2 emissions and mitigating climate change on the one hand, and depleting P reserves on the other hand. Given that depletion of P reserves would have major implications for global food supply and food prices, there is a need to examine if finite P stocks should be used for the production of first-generation biofuel feedstock or rather be preserved for future food production.

The objective of this article is to analyze the use of P for biofuel feedstock production. In particular, we (i) examine the current P fertilizer use for the main first-generation biofuel crops; (ii) illustrate the relative impacts on P depletion and CO_2 mitigation of seven main types of first-generation biofuel; and (iii) analyze the scope for recycling P in the production of biofuels. Based on our analysis, we examine the potential implications of the allocation of P to biofuel production. We acknowledge the uncertainties in our analysis and examine them in the "Discussion" section.

METHODS

Current Global P Use for First-Generation Biofuel Production

We analyze the current use of inorganic P for the production of first-generation biofuel, acknowledging that in some parts of the world total P application rates may be higher or lower than what is required for replacing soil P contents (Scheiner et al. 1996; Lavado and Taboada 2009; Bouwman et al. 2011). We only consider the use of inorganic fertilizers since only these contribute to depletion of the global P reserves. Note that, however, the availability of organic P and inorganic P is correlated; the supply of manure to fertilize crops depends partly on the application of inorganic P fertilizers to produce animal feed.

We analyze the use of inorganic P for biofuel feedstock production based on agricultural production statistics from FAOSTAT (crop data) and fertilizer data by crop and by country from the International Fertilizer Industry Association (Heffer 2009). The seven crops currently most widely used for biofuels production have been selected for the analysis, i.e., sugarcane, wheat, corn, sugarbeet, rapeseed, soybean, and palmoil (Balat and Balat 2009).

A critical step in calculating P use for biofuel production is to deduct P use that can be attributed to the production of co-products, such as corn gluten feed or soy meal. We allocated P use over the production of biofuels and co-products in equal proportion with the economic value of biofuel feedstock and the co-products (i.e., the share of P use for biofuels production = value of biofuel production/value of the total production). The following by products have been distinguished in the article: animal feed (corn gluten, soy meal, rape feed), dried distillers grains with solubles (a co-product of ethanol production used as animal feed), and palm kernel (used for a variety of products including as surfactant in detergent production). Table 1 shows the share of P fertilization that can be attributed to biofuels when corrected for co-products.

The Relative Impacts of Biofuels on Climate Change Mitigation and P Depletion

To illustrate the trade-off between P depletion and mitigation of climate change in a quantitative manner, we analyze P use required for the production of 1 GJ biofuel energy and avoided CO_2 emissions per GJ biofuel energy. Both P use and CO_2 emissions per GJ are subsequently compared to a benchmark.

We compare the avoided CO_2 emissions per GJ of biofuel to the amount of CO_2 that can still be emitted while restricting climate change to a potentially acceptable level. Several authors have argued that global temperature increases should not exceed 2°C (Leemans and Eickhout 2004; Smith et al. 2009) to avoid significant impacts on agricultural production and ecosystems. A 3.5°C threshold has also been suggested (Schneider 2001). The most recent IPCC assessment forecasted a potential temperature increase in 2100 relative to pre-industrial of 1.8–5.8°C (Solomon et al. 2007). Increasing temperatures will cause increasing damages on the planet's ecosystems (Parry et al. 2007). In this article, CO_2 mitigation impacts from the use of biofuels are compared with a benchmark of 2, 3, and 4°C relative to pre-industrial. Based on Matthews et al. (2009), we assume that the CO_2 emissions from 2009 onward need to be restricted to a best estimate of 2.9 tT CO_2 in order to avoid a 2°C temperature increase. Allen et al. (2009) indicate most likely maximum emissions of 5.9 and 11.0 tT CO_2 required to restrict global temperature increase from 3 to 4°C, respectively.

The avoided CO_2 per GJ of biofuel energy is based on the values reported by the UK Renewable Fuels Agency (2010) that has the UK Government mandate to allocate Renewable Transport Fuel Certificates to suppliers of biofuels in the UK. The emission factors published by the

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Table 1 Share of P use that can be attributed to biofuels production

Crop	Price of biofuel, mid 2010[a] (US$/ton)	Main co-products	Ton co-product/ton product[b]	Price of the co-products (mid 2010) (US$/ton)	Part of fertilizer use attributable to biofuels production (%)
Ethanol					
Sugarcane	356	None	0		100
Maize	356	Corn gluten feed	0.66	101[c]	67
		DDGS	0.96	114[c]	
Wheat	356	DDGS	1.14	114[c]	73
Sugarbeet	356	Pulp sold as animal feed	1.25	140[c]	67
Biodiesel					
Rapeseed	702	Rape meal	1.32	225[d]	70
Soybean	702	Soy meal for animal feed	4.32	288[c]	36
Palm oil (fruits)	702	Palm kernel	0.30	307[e]	88

DDGS dried distillers grains with solubles

[a] Agricultural Marketing Service (2010), [b] USDA Agricultural Statistics Board (2007), [c] USDA Economics Research Service (2010), [d] Dairy Development Centre (2010), [e] Malaysian Palm Oil Board (2010)

Renewable Fuels Agency represent well-to-wheel figures reflecting the associated greenhouse gas emissions related to crop production, feedstock transport, conversion to bioethanol or biodiesel, fuel transport, and emissions from a bioethanol or biodiesel storage depot and the filling station. For the trade-off analysis, the “typical” values for the emission factors have been selected, including the average actual emissions due to land use conversion (Renewable Fuels Agency 2010). These reflect that some of the land used for biofuel production is recently deforested land.

In the case of P depletion, the P fertilizer use per GJ of biofuel energy produced was calculated, and compared with the total global reserve of mineable P. There are a number of estimates available for the remaining P reserves (Chernoff and Orris 2002; Stewart 2002; Kauwenbergh 2010). The estimate of the remaining stocks of rock phosphate, the principal source of P, has been revised upward in the past year, from an estimated reserve of 16 thousand million metric ton of phosphate rock (Jasinski 2010) to 65 thousand million ton in the 2011 USGS review (Jasinski 2011). The 2011 review is supported by industry data and in line with IFDC estimates published by Kauwenbergh (2010). Nevertheless, the magnitude of the increase following years of declining reserves is remarkable. In one case, Syria, reserves increased from 0.1 thousand million ton in 2010 (Jasinski 2010) to 1.8 thousand million ton in 2011 (Jasinski 2011). Furthermore, the estimates are highly dependent on company data from the Western Saharan mines that account for around 75% of the global reserve (Jasinski 2011) and the reliability of these data has been questioned (Nature 2010). Hence, there appears to be considerable uncertainty on the world’s remaining P reserves. Therefore, in this article, the impacts of P use for biofuel production are compared with two benchmarks, which may provide a low and a high estimate of available P reserves: 16 and 65 thousand million ton rock phosphate, based on the 2010 and 2011 USGS estimate, respectively. Phosphate rocks contains on average 30% P_2O_5, which in turn contains 44% P (Smil 2000). Hence, 16 thousand million ton rock phosphate corresponds to 2112 million ton P; 65 thousand million ton rock phosphate to 8580 million ton P.

We calculate P use required for the production of 1 GJ of energy from biofuel based on the average P fertilizer use for biofuel crops (from Heffer 2009), the average yield of biofuel crops (from FAOSTAT) and their average net energy content following processing to biofuel (from Renewable Fuels Agency 2010). As explained above, we correct for the production of co-products by allocating P over biofuel products and co-products based on their relative economic value (Table 1).

Scope for Recycling of P in the Production of Biofuels

In principle, there is significant scope for recycling of P in the biofuel production chain, since the biofuels themselves contain very little P as per the fuels specifications in the US and the EU. Recycling of P would improve the performance of biofuels in terms of P use. Figure 1 presents the flow of P in relation to the production of biofuels from first-generation feedstock. We examine each of the five steps where P leaves the biofuels production chain. Based on a literature review, the approximate magnitude of P losses and possibilities for recycling P are indicated.

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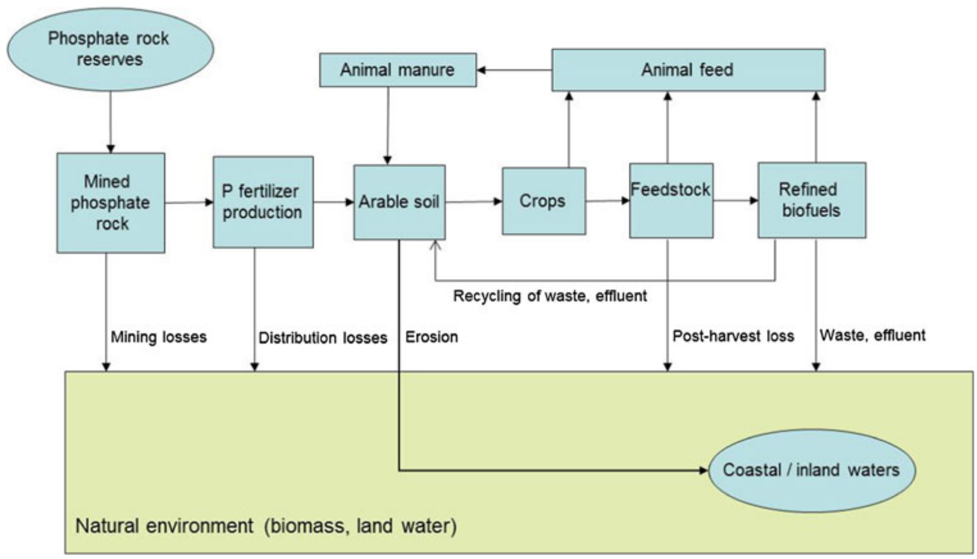
Fig. 1 Phosphorus flows in relation to biofuels production. *Circles* depict the main reservoirs of P on the planet, the *arrows* present the main flows of P in relation to the various steps (*squares*) in the production of first-generation biofuels



RESULTS

Current Global P Use for First-Generation Biofuels

Around 89% of the total P global production is used for food production, with the remainder used mainly for industrial purposes, such as the production of detergents (Cordell et al. 2009). The total global agricultural consumption of P for fertilizer production is around 16 million ton of P per year (Heffer 2009). The global average per ha P application of biofuel crops varies between the different feedstock crops, from 12 kg ha^{-1} $year^{-1}$ for wheat to 26 kg ha^{-1} $year^{-1}$ for sugarbeet (Heffer 2009).

Table 2 shows the global use of P for the production of biofuels in 2007, corrected for the production of co-products. The total P consumption related to the production of feedstock for biofuel in 2007 amounts to 329 Gg P, or around 2% of the global use of P for agricultural fertilizers (Table 2).

Comparison of Climate Change Mitigation and P Depletion in Relation to Biofuels

We illustrate how biofuels' positive impacts on climate change mitigation compare with the negative impacts related to P depletion. Table 3 shows the P use per GJ of biofuel produced, and the avoided CO_2 emission per GJ of biofuel produced. Table 4 subsequently compares the P use per GJ biofuel with the global P reserves, and the avoided CO_2 per GJ biofuel with the CO_2 that can still be emitted while limiting global temperature increase to a certain level. Because both climate change and P depletion impacts are expressed as GJ^{-1} there is the possibility to compare their relative impacts.

Table 4 shows how the relative benefits of first-generation biofuels vary with the assumed benchmark for maximum allowable global temperature increase. If it is assumed that critical climate change involves a 4°C temperature change, the relative benefits of CO_2 mitigation are smaller than in case it is assumed that critical climate change involves a 2°C temperature change. Likewise, the smaller the assumed global P reserve, the higher the negative impacts of P depletion per unit of biofuel produced are.

Our calculations show that for most combinations of assumed critical temperature change and magnitude of the global P reserve the relative contribution to P depletion exceeds the relative contribution to mitigating climate change. Only in case of a 2°C temperature change threshold, and a global reserve of 65 thousand million ton rock phosphate (i.e., 8185 million ton P) there is one biofuel feedstock that shows a favorable comparison (positive impacts exceeding negative impacts), i.e., sugarcane. For all other biofuel feedstocks and assumptions, the negative contribution to P depletion outweighs the positive contribution to mitigating climate change. Wheat and rapeseed make for the worst biofuels, their contribution to P depletion exceeds their contribution to climate change mitigation with at least a factor 4, depending on the assumptions made. As discussed below, climate change mitigation and P depletion are not the only impacts of biofuel production and a wider perspective is required to inform policy making.

Scope for Recycling of P in the Production of Biofuels

The negative impacts of P depletion in the production of first-generation biofuels can be reduced by more efficient use or recycling of P. The main possibilities for increasing the

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Table 2 Annual global inorganic P use for biofuel feedstock; 2007 or the 2007/2008 cropping season

Crop	Key crop producers for biofuel purposes	Production (million ton)[a]	Share of global crop production used for biofuel (%)	Biofuel feedstock production (million ton)[f]	P fertilizer use for feedstock production (million kg P)[g]	Share of P fertilizer attributable to biofuels production (%)[h]	P fertilizer use for biofuel production (million kg P)
Ethanol production							
Sugarcane	Brazil	1627	16[b]	256	67	100	67
Maize	USA	788	11[b]	89	226	67	151
Wheat	EU	611	1[b]	4	15	73	11
Sugarbeet	EU	247	4[b]	9	5	67	3
Biodiesel production							
Rapeseed	EU, China, Canada	51	23[c]	12	111	70	78
Soybean	USA, Brazil, Argentina	220	4[d]	8	46	36	16
Palm oil (fruit)	Malaysia, Indonesia	193	2[e]	4	3	88	2
Total		3544		382	472		329

[a] FAOSTAT, [b] OECD 2008, p. 78, [c] World Bank 2009, p. 190, [d] ERS, USDA 2009, [e] Product Board MVO 2009, [f] Multiplication of previous columns, [g] Multiplying global fertilizer use per crop (Heffer 2009) with the share of global crop production used for biofuels (column 4), [h] from Table 1

Table 3 P use and avoided CO_2 per GJ biofuel

Crop	Inorganic P application (kg ha^{-1})[a]	Energy production (GJ ha^{-1})[b]	Part of fertilizer use attributable to biofuels production (%)[c]	Attributable P use (kg P GJ^{-1})[d]	CO_2 avoided (kg CO_2 GJ^{-1})[e]
Ethanol					
Sugarcane	18	132.6	100	0.14	63
Maize	13	63.9	67	0.13	39
Wheat	12	22.2	73	0.40	30
Sugarbeet	26	102.4	67	0.17	55
Biodiesel					
Rapeseed	16	24.3	70	0.47	37
Soybean	13	16.2	36	0.30	33
Palm oil (fruits)	10	111.8	88	0.08	27

[a] Heffer (2009), [b] Multiplication of energy content (GJ kg $feedstock^{-1}$) from (Renewable Fuels Agency 2010) with yields (kg feedstock ha^{-1}) from FAOSTAT, [c] see Table 1, [d] combining the previous columns, [e] Renewable Fuels Agency (2010)

efficiency of P use in biofuel feedstock production are (i) reducing mining losses; (ii) reducing distribution losses; (iii) reducing erosion rates; (iv) reducing post-harvest losses; and (v) recycling P contained in waste, ashes, and residues from the biofuels production process (see Fig. 1). Cordell et al. (2009) indicates that 6% of the P fertilizer production is lost through *distribution* losses, and a further 5% is lost in the *mining* process, but there are no data available on potential efficiency gains and the costs of achieving these (Herring and Fantel 1993; Kauwenbergh 2010).

P use efficiency can also be increased by reducing *erosion* rates in the fields where feedstock is cultivated (Pushparajah and Magat 1990; Roy et al. 2006). A review of erosion rates on different slopes and soil types, in different countries (US and Brazil), and for different feedstock types (including maize and sugarcane) reveals that erosion rates typically vary between 0.1 and 5 kg P ha^{-1} $year^{-1}$ (Sharpley 1995; Giampietro et al. 1997; Sparovek and Schnug 2001a, b; Pimentel et al. 2008; Boddey et al. 2008). Erosion can be reduced with better land management (Pimentel et al. 1995), but this requires investment, which may not be economical with current fertilizer prices (Sparovek and Schnug 2001a, b).

Post-harvest losses occur due to deficient storage or transport and may involve physical, fungi, and/or insect damage, and have been reported to amount to at least 10% for cereals and 10–20% for roots and tubers (Aidoo 1993; Kader 2005). Sugarcane and oil palm need to be processed

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Table 4 CO_2 benefits versus P depletion

Crop	Relative contribution to climate change mitigation (10^{-15} GJ^{-1})			Relative contribution to P depletion (10^{-15} GJ^{-1})	
	+2°C, 2.9 tT CO_2	+3°C, 5.9 tT CO_2	+4°C, 11.0 tT CO_2	Reserve: 2.1 Gt P	Reserve: 8.6 Gt P
Ethanol					
Sugarcane	21	11	6	66	16
Maize	13	7	4	62	15
Wheat	10	5	3	190	47
Sugarbeet	19	9	5	81	20
Biodiesel					
Rapeseed	13	6	3	223	55
Soybean	11	6	3	142	35
Palm oil	9	5	2	37	10

CO_2 avoided per GJ is divided by the allowable CO_2 emission, and P use per GJ is divided by the global P reserve; all columns present impacts per GJ and can therefore be compared

rapidly after harvest to prevent deterioration of the feedstock quality, and production losses of 1–5% have been reported (Jelsma et al. 2009; Solomon 2009).

The amount of P contained in the biofuels themselves, as prescribed by biofuel specifications, is small and the largest part of P used for biofuel feedstock production is released in the *processing and refining steps*. P is transformed to byproducts, solid waste, and effluents. For some feedstock types, such as soy and rapeseed, part of the P contained in feedstock ends up in animal feed and is returned to farmers' fields in the form of manure. Not all of this P is efficiently recycled, some manure is deposited in areas subject to excess fertilization. Most of the waste from biofuel production is in liquid form (Giampietro et al. 1997; Simpson et al. 2009). Several new technologies to transform effluent into products that can be used as fertilizers have been developed, but their cost-effectiveness varies as a function of the biofuel type and the characteristics of the facility (Driver et al. 1999; Schuchardt et al. 2008).

Hence, there are various pathways through which P leaves the biofuel production chain, the most important one being the last step where feedstock is processed to biofuel. Technical options for enhanced recycling of P exist, but many of them are not cost-effective at current P prices. Table 5 presents the increase in P efficiency (either through more efficient use or through recycling of P) required to balance P depletion and climate change impacts of first-generation biofuels, assuming a climate change threshold of 3°C and a global P reserve of 8.6 Gt P (65 thousand million ton rock phosphate, Jasinski 2011).

Table 5 P recycling percentage required to balance climate change and P depletion impacts of biofuel feedstock, assuming a 3°C threshold and a global P reserve of 8.6 Gt P

Feedstock	Recycling percentage
Ethanol	
Sugarcane	31
Maize	53
Wheat	89
Sugarbeet	55
Biodiesel	
Rapeseed	89
Soybean	83
Palm oil	50

DISCUSSION

An analysis of the net welfare implications of biofuels use needs to include the whole range of benefits (including energy source diversification, farmers' support, climate change mitigation) and costs (including associated greenhouse gas emissions, impacts on food prices, impacts on land cover and biodiversity, eutrophication due to effluent discharge, pesticide use and P depletion). This article zooms in on P use for biofuels production because it is an as yet insufficiently recognized implication of biofuels policies, because P use is fundamental to all first-generation biofuel production systems and because the impacts of P depletion will be as far reaching as those of climate change. We show that currently around 2% of global P use is for the production of first-generation biofuels. Given current policy targets for biofuel blending in many countries, the use of first-generation biofuels will increase rapidly in the coming decades, as will the use of P fertilizer for feedstock production (Ragauskas et al. 2006; European Environment Agency 2009).

Our analysis indicates that the relative contribution of biofuels to depleting P reserves exceeds the relative contribution to mitigating climate change, with the exception of biofuels from sugarcane in case of a maximum 2°C

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temperature increase. The relatively good performance of sugarcane is related to the productivity of the crop and may also be influenced by the widespread application of waste recycling techniques in Brazil, reducing the need for inorganic fertilizers (Ometto et al. 2009; Simpson et al., 2009). However, if a 3 or 4°C threshold is used for acceptable climate change, the negative impact of P depletion exceeds the positive impact of climate change mitigation also for sugarcane. Additional policy measures to promote efficient use of P in the production of first-generation biofuels (e.g., Ometto et al. 2009) are highly important, given the lack of market incentives. However, very high increases in the efficiency of P use are required to balance P depletion and climate change mitigation impacts, ranging from 31% for sugarcane to 89% for wheat and rapeseed, in case of a 3°C temperature increase threshold and the perhaps optimistic estimate of global P reserves (65 thousand million ton rock phosphate) of Jasinski (2011).

There are substantial uncertainties in our analysis, which relate to the global P reserves, the CO_2 that can be emitted while avoiding certain levels of climate change (compare Matthews et al. 2009; Meinshausen et al. 2009; Allen et al. 2009) and the relative impacts of depleting P reserves versus climate change. Also, we attributed P to biofuel feedstock versus co-products on the basis of their relative economic value, even though this does not necessarily represent the distribution of P over these products. In the face of these various uncertainties, it is clear that our analysis only provides a first illustration of the relative impacts of biofuels on P depletion versus climate change mitigation. Our analysis nevertheless shows the potential significance of P depletion as an additional concern in relation to biofuels.

In particular, P depletion will have global implications for food security. When P prices increase as a consequence of scarcity, global food production will be affected. Global P reserves may last for another 7–10 decades (Herring and Fantel 1993; Cordell et al. 2009) based on the 2010 USGS estimate of the global P reserve (Jasinski 2010) or possibly 3–4 times longer based on the 2011 USGS estimate (Jasinski 2011). However, price increases of P fertilizer and therefore of food crops due to increasing P scarcity may occur well before. There are a range of technical options for more efficient use and recycling of P in waste flows (Molinos-Senante et al. 2011) and in biofuel production systems (see above), but P recovery comes at a significant costs. Hence, even if recycling is applied, there will be a residual cost that will translate into higher food prices. The potential fast pace of such price increases is demonstrated by the 700% price increase of rock phosphate between February 2007 and April 2008 (e.g., Cordell et al. 2009). In addition, the increasing scarcity of P reserves also has geopolitical implications since P stocks are unevenly distributed in the world. For instance, Western Europe has no reserves (Stewart 2005). It is conceivable that countries with P reserves will prioritize safeguarding their own supply, which means that P supplies may be even more constrained for countries without P reserves.

Further research in this field needs to consider (i) the costs of rising food prices in the face of increasing P scarcity; (ii) the costs of climate change; (iii) cost curves for P mining and recycling (including the potential of P stocks currently not economical to mine); and (iv) costs of alternative renewable energy sources. In relation to biofuels, a critical issue is that there are no substitutes for P required to feed the world, but that there are several alternative sources of renewable energy that could mitigate climate change at costs in some case not exceeding those of biofuels (Martinot 2005; de Vries et al. 2007). Moreover, it is not unlikely that it will be easier for the world to adapt to a 2°C or even a 4°C global temperature increase than to deal with the depletion of P reserves and the subsequent disruption of global food supply.

CONCLUSIONS

The mitigation of climate change is one of the key objectives of the biofuels policies that have been put in place in many countries in the last decade. Our analysis points to a fundamental trade-off: first-generation biofuels require P fertilizers and their cultivation therefore contributes to P depletion that will affect global food production in the course of the coming centuries. This article shows that the current share of first-generation biofuel feedstock in global fertilizer consumption is around 2%, and that this percentage is likely to further increase in the coming years. Under current production systems, the negative impacts from biofuel production on P depletion appear to exceed the positive impacts on climate change mitigation, with the possible exception of sugarcane ethanol. Wheat and rapeseed are the worst biofuels if only the contribution to P depletion and to mitigating climate change are considered. The relative performance of biofuels can be improved through enhanced recycling of P, but very high efficiency gains in P use are required to balance P depletion and climate change impacts. Our analysis shows that current targets for biofuels, which can only be fulfilled with first-generation biofuel sources (International Energy Agency 2008), will affect future food security and may have a net negative impact on future welfare.

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