Published July 10, 2015

Journal of Environmental Quality ENVIRONMENTAL ISSUES

The Pivotal Role of Phosphorus in a Resilient Water–Energy–Food Security Nexus

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Abstract

We make the case that phosphorus (P) is inextricably linked to an increasingly fragile, interconnected, and interdependent nexus of water, energy, and food security and should be managed accordingly. Although there are many other drivers that influence water, energy, and food security, P plays a unique and under-recognized role within the nexus. The P paradox derives from fundamental challenges in meeting water, energy, and food security for a growing global population. We face simultaneous dilemmas of overcoming scarcity of P to sustain terrestrial food and biofuel production and addressing overabundance of P entering aquatic systems, which impairs water quality and aquatic ecosystems and threatens water security. Historical success in redistributing rock phosphate as fertilizer to enable modern feed and food production systems is a grand societal achievement in overcoming inequality. However, using the United States as the main example, we demonstrate how successes in redistribution of P and reorganization of farming systems have broken local P cycles and have inadvertently created instability that threatens resilience within the nexus. Furthermore, recent expansion of the biofuels sector is placing further pressure on P distribution and availability. Despite these challenges, opportunities exist to intensify and expand food and biofuel production through recycling and better management of land and water resources. Ultimately, a strategic approach to sustainable P management can help address the P paradox, minimize tradeoffs, and catalyze synergies to improve resilience among components of the water, energy, and food security nexus.

The Phosphorus Paradox at the Heart of a Converging Water, Energy, and Food Securities Challenge

The water–energy–food security nexus—the complex interrelationships and interdependencies between three critical resources that underpin human life and civilization—has been identified as one of the greatest challenges for the global economy and sustainable development (World Economic Forum, 2011; Engel and Schaefer, 2013; Olsson, 2013; Perrone and Hornberger, 2014). To date, the role of phosphorus (P) within this nexus has been overlooked. In this "Environmental Issues" contribution, we make the case that P is inextricably linked to an increasingly fragile nexus of water, energy, and food security (Fig. 1). We provide a first assessment of the pivotal role P plays among the often competing demands of food and biofuel production and in safeguarding water quality and security. Phosphorus is an essential element for food and biofuel crop production, but through water quality impairment, P is also a major threat to water security (Elser, 2012; Heathwaite, 2010; Howden et al., 2013; Whitehead et al., 2013). Within the nexus, ecosystem services provide key pillars of support for water, biofuel energy, and food security (Fig. 1), including provisioning services, which supply food, fuel, and water, and regulating services that provide multiple benefits, including water storage, water supply regulation, and water purification (Hoff, 2011; Engel and Schaefer, 2013; Jarvie and Jenkins, 2014). Clearly, P is not alone in its support of these services, but the ubiquity of its contributions has been poorly acknowledged. Although many other factors influence water, energy, and food security, we focus here on the unique role P plays within the nexus.

The water, energy, and food security nexus is under increasing pressures from population growth, urbanization, climate change, and wider socio-economic drivers within an increasingly globalized economy (Fig. 1). Increasingly affluent urban populations, with a preference for protein-based diets, will accelerate demand for meat production by an estimated

J. Environ. Qual. 44:1049–1062 (2015)
doi:10.2134/jeq2015.01.0030
Freely available online through the author-supported open-access option.
Received 22 Jan. 2015.
Accepted 3 May 2015.
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Abbreviations: BMP, beneficial management practice.

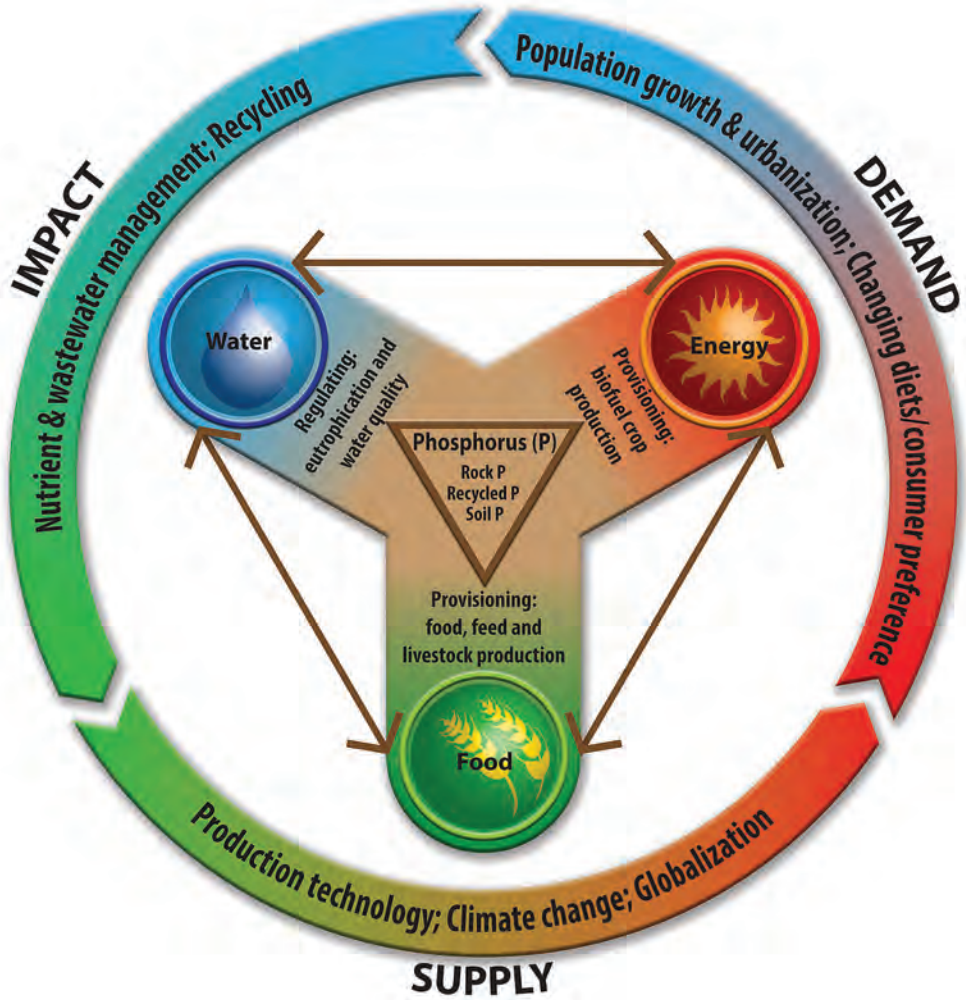

Fig. 1. Conceptual diagram showing the pivotal role of P within the water–energy–food security nexus. Within this P-based nexus, ecosystem services provide key pillars of support for water, energy, and food security. These include provisioning services that underpin food and biofuel production and regulating services such as water purification and water quality regulation, which are provided by aquatic ecosystems. The nexus is dynamic: external drivers such as population growth, climate change, economics, and changing markets within an increasingly globalized economy exert changing pressures on supply, demand, and environmental impact, altering nexus stability.

50% by 2025, driving increased demand for animal feed by 42% (Maligreau et al., 2012). To meet these demands, it is projected that farmers will need to increase grain production by 50% by 2025 (World Economic Forum, 2011). By 2050, the global population will reach 9 billion, and it is expected that demand for P fertilizers will be around 2.4 times the 2000 level (Tilman et al., 2001; Godfray et al., 2010).

Central to meeting the water, energy, and food security demands of a growing and more affluent global population is a fundamental P paradox (Lougheed, 2011): first, scarcity of P as a key limiting resource for food and biofuel production; second, overabundance of P entering aquatic systems from agricultural production and food consumption, which impairs water quality, undermines the health of aquatic ecosystems and threatens water security.

Phosphorus Scarcity for Food and Biofuel Production

The availability and use of P (and N) fertilizers have opened vast tracts of otherwise unproductive farmland, reducing undernourishment, promoting economies of scale, and facilitating a shift to modern urbanized life styles. However, the raw materials for manufacturing these two types of fertilizers are very different. Unlike N_2, which is a renewable atmospheric resource abundantly available across the globe, rock phosphate is a nonrenewable geological resource. There are two facets to P scarcity. First, there are concerns over future P scarcity, including the longevity of phosphate-rock supplies and the fraction of total supply that is economically and geopolitically feasible to extract (Cordell and Neset, 2014; Elser et al., 2014). Economically extractable supplies are geographically very limited, and, although the longevity of supplies is uncertain, recent analyses extend the time frame of current reserves to only around 300 yr using modern mining technologies (Scholz and Wellmer, 2013). The second facet involves current P scarcity. Despite the successes in achieving global P distribution, profound inequalities remain (Vitousek et al., 2009), with P deficits occurring across 30% of global cropland (MacDonald et al., 2011). Indeed, the poverty and food insecurity across the developing world is largely coincident with P deficits in agricultural soils, as illustrated by efforts to quantify P reserves globally (e.g., MacDonald et al., 2011).

Phosphorus Overabundance Impairing Water Quality and Security

As global P fluxes have expanded, the availability of cheap P fertilizers has resulted in patterns of P use that have become increasingly inefficient and dissipative (MacDonald et al., 2011; Scholz et al., 2013). It is estimated that <20% of P mined for fertilizer reaches the food products consumed (Neset and Cordell, 2012), and only around 10% of the P in human wastes is recycled back onto agricultural land (Elser and Bennett, 2011). These inefficiencies have resulted in accelerated losses of P and in an overabundance of P entering and degrading aquatic ecosystems (Carpenter et al., 1998; Jarvie et al., 2013b). Excessive harmful and nuisance algal growth and water-body hypoxia are now a global cause of water quality impairment, threatening water security and environmental and human health (Anderson et al., 2002; Dodds et al., 2009).

Managing both sides of the P paradox more efficiently and sustainably to ensure water, energy, and food security for future generations is set to become a global imperative. Although these challenges are global in extent, they vary regionally, according to differing P availability and use, land and water management, and priorities in food and biofuel production (Vitousek et al., 2009; Haygarth et al., 2014). For example, in China, rapid economic and population growth and urbanization have resulted in dramatic shifts in agricultural food and biofuel production (Koizumi, 2013; Gandhi and Zhou, 2014; Lu et al., 2015). In China, nexus challenges center on the large buildup in soil P and losses to the environment from animal production (Wang et al., 2011). In Europe, which has no significant indigenous phosphate rock reserves, a major focus is addressing potential future P scarcity and reducing dependence on foreign P imports. Efforts are underway to increase efficiency in P use through recovery of P from waste streams and recycling (Withers et al., 2015). In contrast, food and biofuel production across Africa is severely limited by soil P deficiency (Sanchez, 2010; Van der Velde et al., 2014). Although around 80% of estimated global rock phosphate reserves are located in Africa (Jasinski, 2015), poor fertilizer distribution and transport, along with low trade volumes, result in high fertilizer costs and poor accessibility to fertilizers, particularly in sub-Saharan Africa (Syers et al., 2011). Applications of P to fields often do not replenish removal in crop harvest, and around three quarters of African soils are now depleted in nutrients (Henao and Baanante, 2006; Vitousek et al., 2009). Consequently, African crop yields are only around one quarter of the global average, and replenishing soil fertility is recognized as the primary requirement to improve food security across the continent (Henao and Baanante, 2006; Van der Velde et al., 2014).

Here, we provide a first step in delineating and organizing some of the emerging P nexus issues and challenges into a strategic framework. Using data and case study examples, mainly from the United States, we explore (i) how historical success in redistributing rock phosphate to enable modern feed and food production systems has broken local P cycles, inadvertently creating new inequalities that create instability and threaten resilience within the nexus; (ii) how recent expansion of the biofuels sector is creating new pressures on P distribution and availability within the nexus; (iii) how practices that intensify and expand food, biofuel, and fiber production have created tradeoffs but also offer new synergies to better manage land and water resources; and (iv) how sustainable P management can help address the P paradox, minimize tradeoffs, and catalyze new synergies to achieve improved resilience in water, energy, and food security.

Breaking the Phosphorus Cycle: How Redistribution of P Has Created New Inequalities That Threaten Resilience in Water, Energy, and Food Security

Modern fertilizer and feed distribution systems are a marvel of supply chain management. Moving refined forms of P from high-quality, inexpensive sources has been the foundation of all forms of modern agricultural production systems, helping to sustain dramatic yield increases. Importing fertilizer P enabled the reclamation of Brazil's Cerrado Region, the source of the world's largest soybean [*Glycine max* (L,) Merr.] crops, and the expansion of China's agricultural base to improve national food security for the world's largest population (Syers et al., 2011). In the last 40 yr, global food production has more than doubled to meet the demands of rapidly growing and increasingly urban populations (Khan et al., 2009). During this time, global P fertilizer use has increased by 350%, which has led to greater food security but has also required a fundamental restructuring of farming into economically optimized industrial food production systems (MacDonald and McBride, 2009; Potter et al., 2010; MacDonald et al., 2012). Mixed livestock and crop farming systems (where P was recycled locally) have given way to geographically specialized farming systems, dependent on large-scale transfers of P from mineral reserves to geographically distinct areas of grain and animal production and human consumption (Sharpley and Jarvie, 2012; Jarvie et al., 2013a). Consequently, environmental flows of P have accelerated 4-fold over the last 60 yr (Childers et al., 2011), with profound implications for P cycles and wider, long-term nexus stability.

As a regional example, Fig. 2 shows the impacts of this agricultural restructuring on the spatial distributions of P across the United States. Areas of intensive livestock production (Fig. 2a) and cities (Fig. 2b) have become the major hubs of waste P production from manure and human waste. Major foci of manure P production occur in the beef feedlots in California and the Texas panhandle; in the dairy farms of Wisconsin and Idaho; in the integrated poultry operations of Arkansas, Georgia, and Maryland; and in the swine farms of North Carolina, Iowa, and Wisconsin (Fig. 2a). These areas of surplus P from manure are on a par with the large and increasingly concentrated P production of the major cities, which are the focus of human food P consumption and associated sewage and food waste accumulation (Fig. 2b). Because almost 100% of dietary P intake by humans is excreted (Jönsson et al., 2004), wastewater provides a major source of P, with per capita P excretion of approximately 2.7 g P d^{-1} (USEPA, 2002). These areas of human and livestock P production are geographically distinct from areas of greatest demand for inorganic P fertilizers for crop production in the Midwest and Mississippi Valley (Fig. 2c).

When areas of P production (the sum of livestock and human P production) and fertilizer P demand are juxtaposed (Fig. 3), some of the inherent difficulties in recycling P within our food production systems become apparent. Areas of P demand for

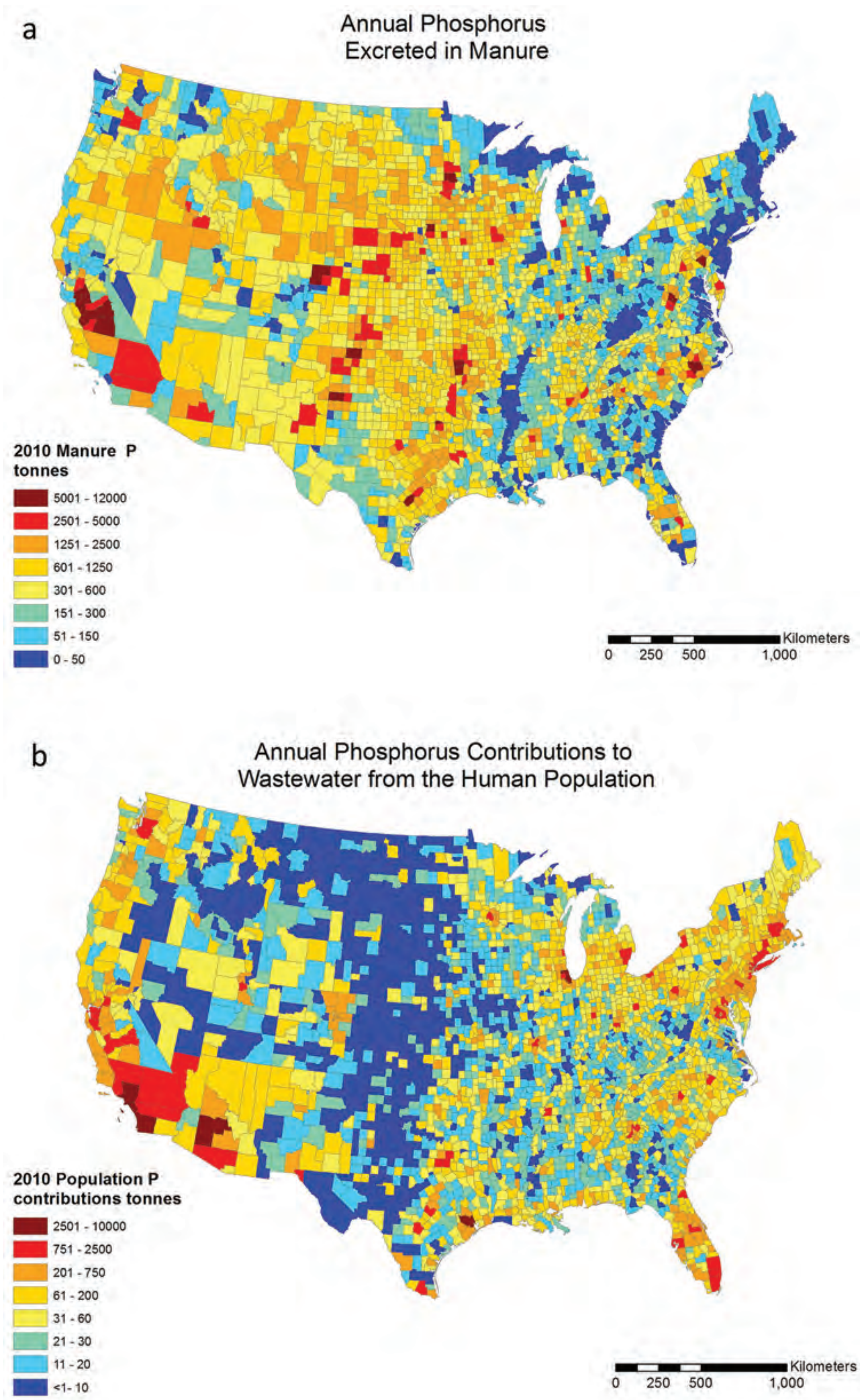

Fig. 2. Spatial distributions of (a) P excreted in livestock manure, (b) P contributions to wastewater from the human population, and (c) inorganic P fertilizer used for farm applications across the contiguous United States. All values are presented in tonnes P at the county level for 2010. County-level livestock manure P, inorganic fertilizer P, and land area data were accessed from the International Plant Nutrition Institute NuGIS database (IPNI, 2012). Human P contributions to wastewater were calculated using the 2010 county-level population census data from the US Census Bureau (2012) and an average annual per capita P contribution of 0.986 kg P (USEPA, 2002). The data were then mapped using ESRI ArcGIS 10.1 software. The P mass loading data for a, b, and c are plotted on different scales to elucidate the spatial patterns in P from manure, human waste, and fertilizer.

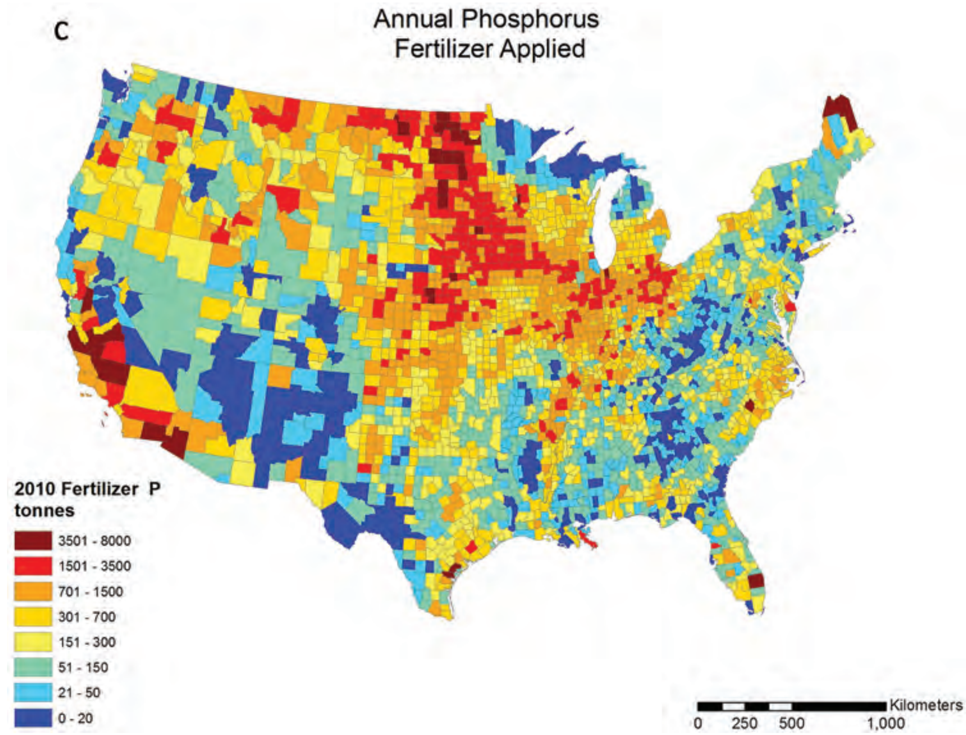

Fig. 2. Continued.

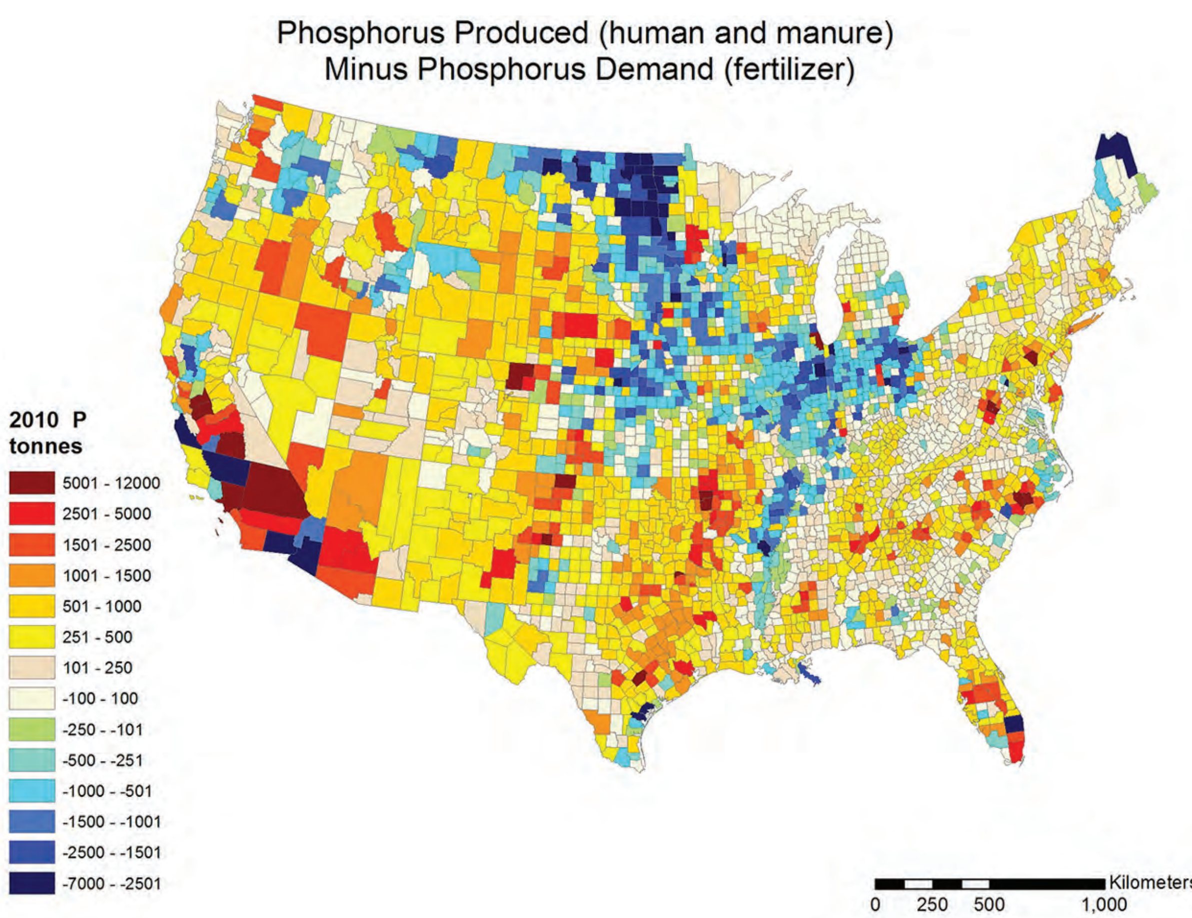

Fig. 3. Map showing the distribution of net P production and net P demand (tonnes P) across the United States in 2010. Values are derived from the difference between the sum of livestock P produced (see Fig. 2a) plus human P contributions (see Fig. 2b) minus inorganic fertilizer P applied (see Fig. 2c). Negative values indicate areas of net P demand, where inputs of P are required to support crop production; positive values show the areas of net P production, with surplus P requiring disposal.

grain production in the Midwest and Mississippi River valley are located hundreds of miles away from the major cities and intensive livestock producing areas where waste P is produced. This means that a large proportion of P in animal manures and urban wastes is no longer recycled back to land where the feed grain was produced (Kleinman et al., 2012). Production of livestock using imported feed now accounts for around half of the grain produced in the United States and 40% of global grain production (Food and Agriculture Organization of the United Nations, 2012). As greater specialization of farming continues, areas of grain production are becoming almost entirely dependent on inorganic P fertilizers, rather than recycled P from manure and human wastes. This reliance on inorganic P fertilizers has implications not only for long-term P security but also for soil carbon and soil health. Recycling of organic carbon–rich manure or biosolids wastes sustains vital underpinning ecosystem services by enhancing microbial activity and nutrient cycling, retaining soil moisture, and reducing soil erosion.

In fact, there is currently ample P produced in manure and human waste in the United States to satisfy P demand for crop production. In 2010, the total P produced by livestock and humans in the United States exceeded the national P fertilizer demand by around 1.3-fold. A myriad of opportunities and barriers exist for recycling waste P produced in the cities and livestock production areas to productive cropland where P is most needed (Kleinman et al., 2012). However, energy costs for transport and recycling P in raw manure and sewage biosolids (relative low-value products with high water content) back to areas of grain production are often prohibitively high (Kleinman et al., 2012; Withers et al., 2014). This has become a major constraint on closing the P cycle at regional, national, and global scales (Schipanski and Bennett, 2012; Sharpley and Jarvie, 2012). Limited practical options exist for the disposal or processing of these P-rich wastes, resulting in local accumulation of P, exceeding crop and pasture needs. Continued land application near production areas at levels of P greater than crop removal is increasing P losses in areas of intensive livestock farming. This impairs water quality, limiting water use and reducing water security (Kingery et al., 1994; Kleinman et al., 2007; Sharpley et al., 2007). These new inequalities in P production and demand are tipping the balance within the nexus toward greater P losses to the environment, reducing water security, and have accelerated demand and dependency on inorganic fertilizers and finite nonrenewable phosphate rock resources.

A Burgeoning Biofuels Industry: Creating New Pressures for Phosphorus Sustainability and Nexus Stability?

Phosphate fertilizers are now supporting and sustaining an increasingly important source of renewable biofuel energy through widespread cultivation of first-generation biofuel crops, including sugarcane (*Saccharum officinarum* L.), wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and sugar beet (*Beta vulgaris* L.) as feedstocks for bioethanol production and rapeseed, soybean, and palm oil for biodiesel production (Balat and Balat, 2009; Hein and Leemans, 2012). Governments across Europe, North and South America, Asia, and Africa have introduced mandates to expand biofuel production to boost national energy security and to reduce reliance on fossil fuels (Robertson et al., 2008; Tilman et al., 2009; Walker, 2009). There are currently ambitious targets for expanding biofuels production and use in the coming decade (Hein and Leemans, 2012). At a global scale, increasing demand for biofuels has outstripped increases in supply, thus squeezing availability for food production (Wright, 2014). Furthermore, although biofuels contribute to energy security, production of biofuel feedstock crops competes with food production for water and land, increasing the commodity process and potentially lowering the resilience of food production systems (Rosegrant et al., 2008; Rathmann et al., 2010; Hein and Leemans, 2012). A growing biofuels sector also has implications for nexus stability through accelerated use of finite inorganic P resources and risks of increased P losses, water quality impairment, and water security (Simpson et al., 2008).

Figure 4a shows national trends for corn and soybean production in the United States (USDA–ERS, 2015). In 2000/2001, bioethanol accounted for approximately 6% of corn production, and biodiesel accounted for only 0.3% of soybean oil production. However, in 2002 a series of new biofuel mandates was introduced: the 2002 Renewable Fuel Standard, the 2005 Energy Policy Act, and the 2007 Energy Security and Independence Act. By 2012/2013, bioethanol had risen to 42% of corn production, and biodiesel had risen to >20% of soybean oil production (Fig. 4a). This corresponds with a >700% increase in the use of corn for bioethanol and a >10,000% increase in soybean oil use for biodiesel between 2000 and 2014. Despite this dramatic surge in biofuel production, there were relatively small increases in acres planted, production, and yields. At most, soybean and corn acreage increased by approximately 4% and approximately 22%, respectively, but with a high degree of interannual variability. Production of soybean oil during this time increased by up to 20% and corn production increased by up to 40%, whereas yields of both crops increased by up to approximately 30% (Fig. 4a, b). Since 2000, there has been no evidence for any major increases in P fertilizer application rates, although there is some indication that P fertilizer applications to soybean may have risen after 2009, after the dip in use of P fertilizers in 2008 caused by the spike in world fertilizer and oil prices (Fig. 4d). The dramatic expansion of corn and soybean use for biofuel feedstocks therefore likely occurred at the expense of production of animal feed and food. The increased demand for corn and soybean for biofuel feedstocks also corresponded with a 270% increase in corn prices and a 230% increase in soybean prices, which peaked in 2012 (Fig. 4c). It is estimated that biofuels may account for at least a third of the recent increase in agricultural commodity prices (Rathmann et al., 2010).

Rising commodity prices can encourage farmers to increase production and yields at the expense of conservation measures, and this can unintentionally accelerate P loss and other adverse environmental consequences. For example, biofuel production also has the potential to accelerate P loss through expansion of tile drainage to increase land productivity and farmable acres. Furthermore, although the increases in corn and soybean acreages have been modest, a proportion of these new acres has been on set-aside or Conservation Reserve Program acres, where Government approval was given to break conservation contracts (Chen and Khanna, 2011; Clark et al., 2013). By nature of being

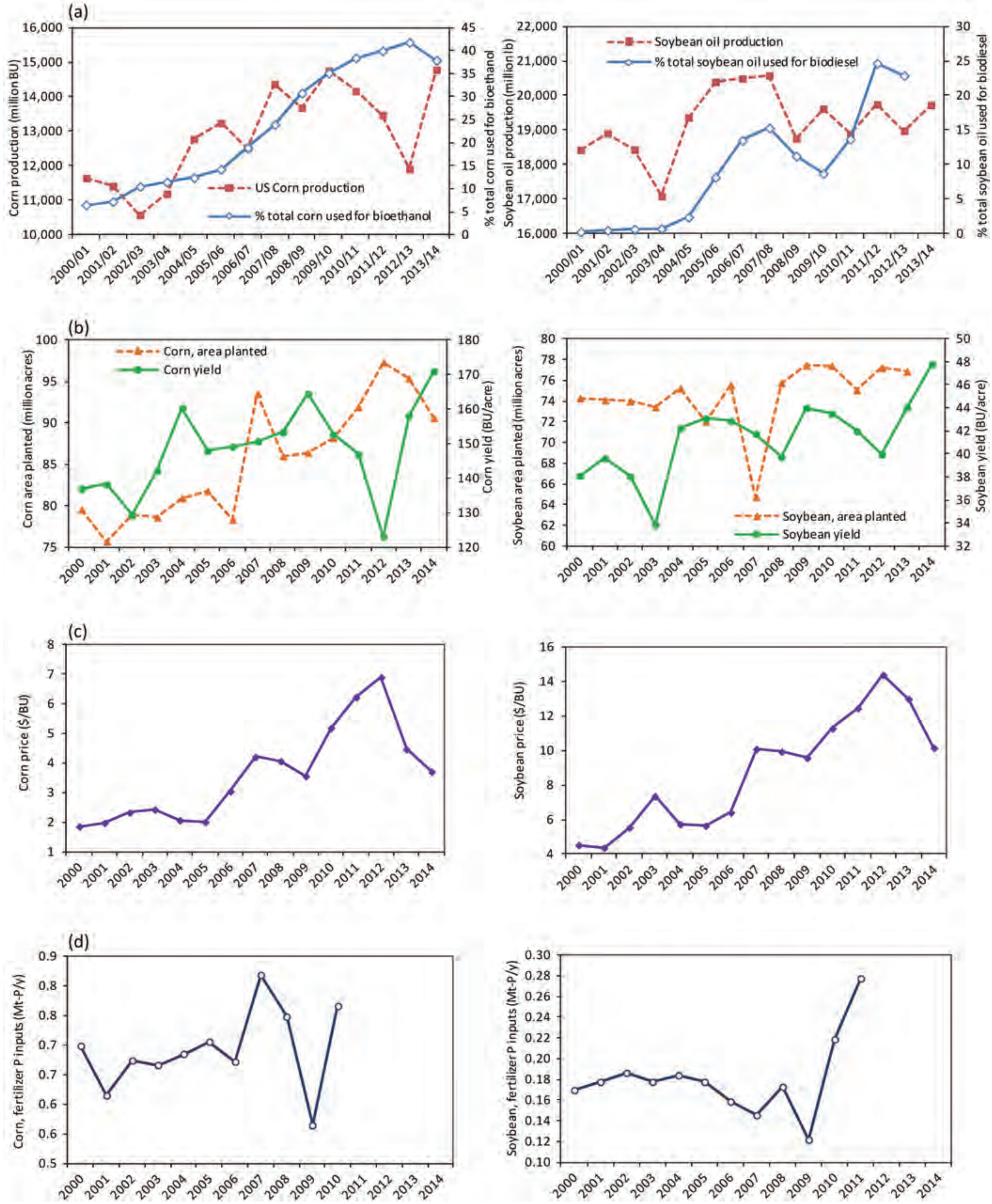

Fig. 4. Time series showing annual US corn and soybean statistics since 2000. (a) Total annual production (million bushels [BU] for corn and million pounds [lb] for soybean soil) and the percentage of total corn and soy bean oil (US domestic production plus net imports) used for biofuels. (b) Annual acreage and yields (BU/acre, bushels per acre). (c) Crop prices ($/BU, dollars per bushel). (d) Fertilizer P applied annually to US corn and soybean crops (Mt/y, megatonne [metric] per year). Data source: USDA–ERS (2015).

set-aside, these new acres generally include environmentally sensitive areas that are more vulnerable to nutrient loss than non-set-aside land (Robertson et al., 2008; Simpson et al., 2008; Tilman et al., 2009). Further, the by-products of processing and solid wastes (e.g., distillers grain) are highly enriched with P (Hein and Leemans, 2012) and require careful management to minimize P losses to surface waters (Simpson et al., 2008) and to avoid unintentionally introducing other contaminants (e.g., metals and biotics) into the ecosystem (Vohla et al., 2011). These by-products also offer opportunities for recycling, which may help to offset the P demands of biofuel crop production. However, the creation of colocated livestock operations with biofuel production to take advantage of distiller's grain as animal feed can also create new areas of localized P accumulation in manures, which have the potential to undermine nexus stability (Simpson et al., 2008).

Maximizing Synergies for Water, Energy, and Food Security through Sustainable Intensification

The concept of an interdependent water–energy–food security nexus requires a radical shift in thinking from separate water, energy, and food policies to a more holistic approach (Olsson, 2013; Ringler et al., 2013; Perrone and Hornberger, 2014). Interventions designed to improve individual security spheres within the nexus can sometimes affect, or worsen, other interventions, resulting in unintended, unexpected, and undesirable consequences or tradeoffs. By considering wider nexus interconnections and interdependencies, there may be opportunities to reduce tradeoffs and find solutions that help optimize water, energy, and food security in a more balanced and coherent manner (Bazilian et al., 2011; Lawford et al., 2013).

A multitude of tradeoffs for water security and sustainable P management have arisen as a result of drives to increase crop yields for food security and biofuel energy (Table 1), many of which are outlined above. However, through "sustainable intensification" (Pretty et al., 2011; Petersen and Snapp, 2015), a range of policy opportunities, techniques, and technologies are emerging that may help to increase agricultural output while reducing negative environmental impacts, and improving ecosystem services (Table 1).

Improved soil and land management will play a central role in increasing P use efficiency and securing synergies across water, energy, and food security sectors. Beneficial management practices (BMPs) are designed to protect and enhance soil

Table 1. The role of phosphorus in the water, energy, and food security nexus connections, and examples of nexus tradeoffs and synergies.

Nexus connection	The role of P	Examples of potential Nexus tradeoffs	Examples of potential Nexus synergies through sustainable intensification
Food and water	Phosphorus fertilizers have increased food security, supporting global population growth and raising living standards. Phosphorus loss throughout the food production chain has caused widespread eutrophication.	From increasing food security: Water quality and security tradeoffs from increased risks of P loss, linked to • Increasing production yields through increased fertilizer applications and land drainage • Expanding agricultural production into marginal areas: increases soil erosion and P loss, with longer-term tradeoffs for soil C, and ecosystem services that support food production and clean water • Industrialization and geographical specialization of agriculture has reduced local P recycling and increased reliance on inorganic P fertilizers.	From more sustainable P management: • Agricultural beneficial management practices can help protect and enhance soil structure and fertility, minimize P losses, and increase water use efficiency. • Recovery and recycling of P from manure and wastewater (e.g., through enhanced value products such as struvite and fortified fertilizers) will help close the P cycle, enhancing food security and reducing reliance on imported inorganic P fertilizers.
Water and energy	Phosphorus fertilizers have increased agricultural energy and water demand through the intensification of grain and meat production. Phosphorus fertilizers now sustain a rapidly growing biofuels industry, based on grain ethanol and biodiesel.	From increasing energy security through biofuel production: Water quality and security tradeoffs can arise from poor P-use efficiency in commercial biofuel operations, including: • Increasing pressure for biofuel corn and soybean production in marginal areas • Overfeeding of P to livestock when by-products from biofuel processing are used as animal feed	From better land management: • Ensuring landscape suitability and sustainability for biofuel grain so that biofuel crops are grown in the right place to maximize yields while minimizing soil erosion and P loss • Capitalizing on wider landscape diversity to support a greater range of biofuel crops (e.g., second-generation perennial cellulosic biofuel crops, such as grasses and woody plants, can help decrease P loading to surface waters and increase soil C in less productive areas)
Food and energy	Food and biofuel energy production are both reliant on inputs of P, which cannot be substituted by any other chemical element.	From competition between food and biofuel crop production and conservation management: • Biofuel crops directly compete with food crops for land and water resources, increasing food prices with tradeoffs for food security in countries reliant on food imports. • Increased commodity prices can incentivize farmers to increase production and yields at the expense of conservation measures, with tradeoffs for soil and water security.	From recycling and utilizing waste as a resource, including: • Colocating concentrated animal feeding operation near biofuel processing plants to utilize waste products of biofuel production (e.g. distiller's grain) as animal feed (without overfeeding P), increases the efficiency of P use, minimizing P losses. • Energy generation from anaerobic digestion of animal wastes as part of the process of sustainable recycling of manures

structure and fertility and minimize P losses, increasing the resilience of provisioning and regulating ecosystem services that support food and biofuel crop production and sustain water quality. Beneficial management practices include a range of carefully targeted conservation and nutrient management programs to address P sources (e.g., rate, method, and timing of applied P) and transport controls (e.g., conservation tillage, contour plowing, and riparian buffers). Critically, there is no single magic bullet, and the site-specific nature, combinations, and implementation of BMPs will vary according to characteristics of the land, climate, farming system, time of year, and farmer preferences. Furthermore, some BMPs that yield beneficial nexus synergies in some settings can result in tradeoffs in other settings. The design and implementation of BMPs must be carefully targeted to local conditions and must take account of other land management practices. For instance, conservation tillage (i.e., no till and reduced till) maintains and enhances organic matter accumulation and soil structure, promoting aeration and water infiltration and thereby reducing surface runoff. This delivers multiple benefits for the provisioning and regulating ecosystem support pillars of the water, energy, and food security nexus. Similarly, cover crops used to protect bare or fallow soils during the winter can contribute to improved soil health by further reducing erosion losses and increasing soil C cycling (Sorensen et al., 2014). However, tradeoffs can arise from conservation tillage if broadcast fertilizer and manure P are allowed to accumulate at the soil surface, which can increase dissolved P runoff (Kleinman et al., 2011b; Sharpley and Smith, 1994). Additionally, risks of subsurface transport of dissolved P are of increasing concern, through vertical leaching of dissolved P via preferential flow pathways, including the macropores and earthworm burrows, which are promoted by reduced tillage. Where subsurface drainage intercepts vertical leaching pathways, the risks of dissolved P loss in subsurface drainage can be dramatically enhanced (Smith et al., 2015a). Also, conservation tillage, cover crops, and perennial forage crops can increase P losses from plant residues after freezing and thawing in cold climates (Tiessen et al., 2010; Bechmann et al., 2005; Riddle and Bergstrő̈m, 2013; Liu et al., 2014).

Opportunities also exist to capitalize on wider landscape diversity to support a greater range of biofuel crops, with multiple ecosystem benefits. For example, second-generation perennial cellulosic biofuel crops (grasses and woody plants) can be grown in less productive areas, such as riparian zones, with minimal fertilizer, pesticide, and fossil energy inputs (Meehan et al., 2013; Werling et al., 2014). These may help provide multiple environmental benefits, including provisioning and regulating ecosystem services. For example, decreasing P loading to surface waters can increase below-ground carbon sequestration, although there may be both positive and negative impacts for biodiversity (Robertson et al., 2008; Tilman et al., 2009).

Recycling offers the greatest opportunities for closing the P cycle and providing multiple nexus benefits. These opportunities include reducing losses to surface waters in cities and areas of intensive livestock production and recycling P to P-deficient soils to improve crop production for food, feed, and biofuel (Withers et al., 2014). Phosphorus security concerns, rising fertilizer costs, and the growing imperative to increase the efficiency of P use and management are stimulating new technologies and synergies in recycling manure, wastewater, food, and biofuel waste (Mehta et al., 2015). Making P recycling cost-effective will depend on achieving economies of scale and optimizing technologies of production and on building markets for these recycled products. Here, tradeoffs associated with P accumulation in areas of intensive livestock production and in urban areas might actually be turned around. For example, economies of scale associated with the spatial concentration and specialization of intensive livestock operations can offer cost-effective opportunities for manure processing and production of higher-value recycling products (DeVuyst et al., 2011; Mehta et al., 2015).

Recycling may be increasingly achieved through integrated livestock and cropping systems and through collaboration and colocation of specialized livestock, crop production, and biofuel processing plants, which create local markets for recycled products. This integration of livestock and crop production systems as a framework for future agricultural development has been espoused over the last decade (Franzluebbers and Steudemann, 2007; Rota and Sperandini 2009; Russelle et al., 2007). For example, by-products from biofuel processing plants, including dry distiller's grain (0.8–0.9% P), are increasingly being recycled as a source of high-energy and high-protein animal feed as an alternative to corn (0.3% P), helping to close the P cycle (DeVuyst et al., 2011; Jesson, 2011). Colocation of concentrated animal feeding operations with biofuel processing industries capitalizes on an abundant supply of high-value recycled feed at low cost, relative to imported corn and soybean meal (Hart and Carriquiry, 2007). Distiller's grain is also sufficiently rich in digestible P that it can substitute for inorganic P supplements in feed, an expensive ingredient in poultry and livestock rations (Hoffman and Baker, 2011). However, attention is needed to balance the use of distiller's grains in animal feed to ensure dietary intake of P does not exceed nutritional requirements. Greater use of these by-products also has the potential to exacerbate regional P imbalances in livestock and poultry production and to increase the concentration and environmental availability of P in manure (Ebeling et al., 2002; Baxter et al., 2003; Maguire et al., 2004; Simpson et al., 2008)

Nexus Challenges for Phosphorus Management: An Example of the Lake Erie Watershed

Over the last decade, the re-eutrophication of Lake Erie has been directly linked to increasing fluxes of dissolved P from the major tributaries including the Maumee and Sandusky Rivers (Michalak et al., 2013; Baker et al., 2014; Kane et al., 2014; Scavia et al., 2014; Smith et al., 2015b). Between the early 1980s and mid-1990s, land in these watersheds was converted to no-tillage to reduce soil erosion and P losses. Initially, no-till was highly effective in decreasing total P losses (Baker and Richards, 2002; Richards et al., 2009). However, river dissolved P fluxes started to rise in the early 2000s and have risen steadily since then, increasing the magnitude and frequency of nuisance and harmful algal blooms in Lake Erie (Baker et al., 2014; Kane et al., 2014; Scavia et al., 2014). As noted above, the effectiveness of no-till and the risks of dissolved P losses are often highly dependent on other land management practices. During this time, other drivers came into play: biofuel mandates increased demand for corn and soybean production, raising commodity prices. Higher prices encouraged farmers to install subsurface tile drains to improve yields. Tile drains increased hydrological connectivity, contributing source areas, and dissolved P flux transmission to the rivers (Richards et al., 2009; Smith et al., 2015a, 2015b). The rising dissolved P fluxes therefore likely reflect a combination of well-intended watershed management practices designed to improve water quality and secure farm profitability but that were poorly coordinated, probably exacerbated by an increase in the intensity and frequency of storm events (Sharpley et al., 2012).

These recent experiences in the Lake Erie watershed illustrate the challenge and importance of developing integrated, coherent policies to address the much broader issue of improving the resilience of water, food, and energy systems. The Lake Erie case study highlights how separate policies intended to support crop production (tile drainage) and conservation to minimize water quality impairment (no-tillage) may interact, leading to unexpected tradeoffs and detrimental impacts (Daloglu et al., 2012; Sharpley et al., 2012). With hindsight, tradeoffs for water quality arising from increasing crop production yields in the Lake Erie watershed might have been anticipated earlier by taking a more integrated view of watershed activities and management practices. Indeed, tradeoffs might have been averted at an earlier stage by small refinements in practice, such as subsurface placement of fertilizer with minimal disturbance of the surface residue, along with occasional tillage, to help reduce soil stratification. Further, there needs to be greater integration of programs among watershed activities to avoid conflicting agendas that give rise to the seemingly unintended environmental consequences recently observed in the Lake Erie Watershed (Kleinman et al., 2015).

Toward Future Sustainable Phosphorus Management: Building Resilience across the Water–Energy–Food Security Nexus

A key challenge facing sustainable P management is that the costs of inefficient P use and losses of P to the aquatic environment, including long-term or off-site environmental impacts, have never been adequately accounted for at the farm level. Annual P losses from agriculture typically represent only a small proportion of the annual P fertilizer applied by farmers and of production costs. In the Lake Erie watershed, environmentally damaging P losses account for less than 1% of the annual P fertilizer applied (Baker and Richards, 2002; Daloglu et al., 2012). Without subsidies or incentives for implementing conservation measures, there is no economic motivation for farmers to address these P losses. Moreover, P fertilizer is commonly applied as "insurance" for maintaining crop yields. It may be hard to convince farmers to voluntarily use less P fertilizer when crop prices have been driven up by demand for biofuel crops and when farmers are highly averse to the risk of compromising yields.

The impacts of P loss on water quality impairment tend to be cumulative at the watershed and river basin scales and as the scale of water quality tradeoffs increases. It therefore becomes increasingly difficult to assign individual responsibility and thereby recoup the costs of water quality impairment (Power, 2010). Rather than attempting to make the polluter pay, it is usually more effective to incentivize improvements in practice through subsidies and support for conservation practices (Shortle et al., 2012). Although there are broad, universal strategies involving the careful use and reuse of P, the best way of implementing these strategies will vary with the characteristics of land management, climate, weather, farming system, and time of year. As highlighted above, remedial strategies need to be carefully targeted and based on local knowledge and conditions (Kleinman et al., 2011a, 2011b; Sharpley et al., 2011). Beneficial management practices and solutions will need to take account of, and adapt to, wider watershed activities to avoid potential antagonism and tradeoffs between land management practices addressing differing priorities and objectives (Collins et al., 2014; Doody et al., 2014). The dramatic increases in dissolved P loss from Lake Erie watersheds and the corresponding impacts on lake eutrophication are a timely warning of how water quality and security benefits can unexpectedly turn to tradeoffs as a result of interactions between separate land use practices designed to minimize soil erosion and improve food and biofuel crop yields.

To address potential disconnects in policy and practice among food and biofuel production and water resource protection, Integrated River Basin Management may offer a way forward (Orr et al., 2007; Nielsen et al., 2013). This provides a platform for bringing together stakeholders from across the spectrum of watershed interests (e.g., agriculture, industry, municipalities, and environmental protection) to develop integrated long-term planning for sustainable management of land and water resources and requires a broad range of biophysical and socio-economic knowledge (Medema et al., 2008; Jordan et al., 2012). Cross-compliance also offers a means of increasing policy coherence between the water, biofuel energy, and food security spheres. Cross-compliance directly ties agricultural production subsidies and support for food and biofuel crop production to defined standards of land and water management. Within the European Union, for example, cross-compliance was introduced in 2003, tying European Union support to farmers to set of rules on "good agricultural and environmental condition" (DEFRA, 2014; Meyer et al., 2014). The criteria for "good agricultural and environmental condition" are designed to protect and enhance key ecosystem services that support and deliver multiple benefits across the water–energy–food security nexus. These include minimizing soil erosion and nutrient loss, maintaining soil organic matter and soil structure, ensuring minimum levels of land maintenance, avoiding the deterioration of habitats, and protecting and managing receiving waters (Aviron et al., 2009). To ensure that policy and management practice are on the right track, adaptive management offers iterative processes of monitoring, anticipating, adapting, and fine-tuning land management practices (Medema et al., 2008; Kominami and Lovell, 2012; Sharpley and Jarvie, 2012). Adaptive management detects and provides an early warning when small, but significant, incompatibilities in agricultural management practices start to produce environmental tradeoffs, such as water quality degradation.

Maximizing the synergies in sustainable P management will involve strengthening connections with the other pillars of support for water, energy, and food security, particularly by sustaining the vital ecosystem services that underpin the nexus. For example, another important factor for soil quality and sustainable crop production is balancing sufficient C input with limited N and P losses. Soil C plays a vital role in soil quality and provisioning services that support food and biofuel crop production and by securing regulating services related to water retention and reduced soil erosion. Achieving synergies will require improved understanding of the interactions and mechanisms that drive and sustain multiple ecosystem services and how these change through space and time (Bennett et al., 2009; Balbi et al., 2015).

Achieving better P use efficiency will necessitate coordinated measures to minimize P losses and water quality impacts while maximizing the productivity and profitability of farming, food, and biofuel production systems. This will involve greater recycling of P in manure and in human and food waste, retaining P within the soil and increasing its availability for plant uptake. Management options will need to be pragmatic, workable, and affordable for farmers who are already under increasing pressures to meet production and environmental targets. The contributions of sustainable P management within the water–energy–food security nexus may perhaps be envisaged as building and strengthening this support network (Fig. 1) through suites of practices that capitalize on P recycling opportunities and build spatially and temporally precise BMPs. These will need to cross-link between the supporting pillars of the nexus, building a network that secures the stability and resilience of water, energy, and food systems while providing the flexibility needed for the growth, development, and adaptation of the nexus to meet future socio-economic and environmental challenges.

Conclusions

Although many factors influence water, energy, and food security, P is pivotal to the nexus of water, energy, and food security, and increasing demands for P to underpin food and biofuel security are threatening the resilience of this nexus. As a result, the balance has shifted toward greater P losses, water quality impairment, and reduced water security and an accelerating dependence on inorganic fertilizers from finite, nonrenewable geological phosphate rock reserves. Using the United States as an example, we have shown how restructuring of agriculture to achieve greater food security has created new inequalities in P production and demand through the decoupling of livestock and crop production. We have highlighted a wide range of water security tradeoffs arising from the breakdown in local P cycles. These tradeoffs are a direct consequence of reduced recycling of P in manure and human wastes back to cropland. Tradeoffs are increasingly compounded by the expansion in biofuel crop production, which has hiked commodity prices, incentivizing farmers to increase production and yields at the expense of conservation measures.

Opportunities are emerging that may help to transform some of these tradeoffs into synergies for improved water, energy, and food security. For example, economies of scale associated with the spatial concentration and specialization of intensive livestock operations can offer cost-effective opportunities for manure processing and production of higher-value recycling products. Overall, the stability and resilience of the water–energy–food security nexus will be determined in large part by understanding the connections between P and the rest of the nexus and then managing those connections accordingly. Policies and initiatives to promote food and energy security, via agricultural intensification, will need to be better coordinated and tied inextricably and financially with P recycling and implementation of land and soil conservation measures to address both elements of the P paradox: the long-term P scarcity and P overabundance impairing water security. Furthermore, policies and initiatives for improved P management will also need to be coordinated with sustainable management practices for a wide range of other factors that support water, energy, and food systems. Improving resilience in water, energy, and food security systems through sustainable intensification and sustainable P management will be critical because the well-being of future generations depends on the continued and affordable availability of each component within the water–energy–food security nexus.

Acknowledgments

This work was supported by the UK Natural Environment Research Council via the Macronutrient Cycles Thematic Programme (grant NE/J011991/1) and via National Capability Research funding (Impacts of Nutrient Management; grant NEC04879). The authors thank Paul Fixen at the International Plant Nutrition Institute for providing access to, and advice on, the NuGIS dataset and Chris Wardle at the British Geological Survey for help with the artwork for Figure 1.

References

Anderson, D.M., P.M. Glibert, and J.M. Burkholder. 2002. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. Estuaries 25:704–726. doi:10.1007/BF02804901

Aviron, S., H. Nitsch, P. Jeanneret, S. Buholzer, H. Luka, L. Pfiffner, S. Pozzi, B. Schuepbach, T. Walter, and F. Herzog. 2009. Ecological cross compliance promotes farmland biodiversity in Switzerland. Front. Ecol. Environ 7:247–252. doi:10.1890/070197

Baker, D.B., and R.P. Richards. 2002. Phosphorus budgets and riverine phosphorus export in northwestern Ohio watersheds. J. Environ. Qual. 31:96–108. doi:10.2134/jeq2002.9600

Baker, D.B., R. Confesor, D.E. Ewing, L.T. Johnson, J.W. Kramer, and B.J. Merryfield. 2014. Phosphorus loading to Lake Erie from the Maumee, Sandusky and Cuyahoga rivers: The importance of bioavailability. J. Great Lakes Res. 40:502–517. doi:10.1016/j.jglr.2014.05.001

Balat, M., and H. Balat. 2009. Recent trends in global production and utilization of bio-ethanol fuel. Appl. Energy 86:2273–2282. doi:10.1016/j.apenergy.2009.03.015

Balbi, S., A. del Prado, P. Gallejones, C.P. Geevan, G. Pardo, E. Pérez-Miñana, R. Manrique, C. Hernandez-Santiago, and F. Villa. 2015. Modeling trade-offs among ecosystem services in agricultural production systems. Environ. Model. Softw. doi:10.1016/j.envsoft.2014.12.017.

Baxter, C.A., B.C. Joern, D. Ragland, J.S. Sands, and O. Adeola. 2003. Phytase, high-available-phosphorus corn, and storage effects on phosphorus levels in pig excreta. J. Environ. Qual. 32:1481–1489. doi:10.2134/jeq2003.1481

Bazilian, M., H. Rogner, M. Howells, S. Hermann, D. Arent, D. Gielen, P. Steduto, A. Mueller, P. Komor, R.S.J. Tol, and K.K. Yumkella. 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. Energy Policy 39:7896–7906. doi:10.1016/j.enpol.2011.09.039

Bechmann, M.E., P.J.A. Kleinman, A.N. Sharpley, and L.S. Saporito. 2005. Freeze–thaw effects on phosphorus loss in runoff from manured and catch-cropped soils. J. Environ. Qual. 34:2301–2309. doi:10.2134/jeq2004.0415

Bennett, E.M., G.D. Peterson, and L.J. Gordon. 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12:1394–1404. doi:10.1111/j.1461-0248.2009.01387.x

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.M. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl. 8:559–568. doi:10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2

Chen, X., and M. Khanna. 2011. Indirect land use effects of corn ethanol in the U.S: Implications for the Conservation Reserve Program. Agricultural and Applied Economics Association's 2014 AAEA annual meeting, Minneapolis, MN, 27–29 July 2014. http://ageconsearch.umn.edu/bitstream/170284/2/2014%20AAEA.pdf (11 May 2015).

Childers, D.L., J. Corman, M. Edwards, and J.J. Elser. 2011. Sustainability challenges of phosphorus and food: Solutions from closing the human phosphorus cycle. Bioscience 61:117–124. doi:10.1525/bio.2011.61.2.6

Clark, C.M., Y. Lin, B.G. Bierwagen, L.M. Eaton, M.H. Langholtz, P.E. Morefield, C.E. Ridley, L. Vimmerstedt, S. Peterson, and B.W. Bush. 2013. Growing a sustainable biofuels industry: Economics, environmental considerations, and the role of the Conservation Reserve Program. Environ. Res. Lett. 8:1–20. doi:10.1088/1748-9326/8/2/025016

Collins, A.L., M. Stutter, and B. Kronvang. 2014. Mitigating diffuse pollution from agriculture: International approaches and experience. Sci. Total Environ. 468–469:1173–1177. doi:10.1016/j.scitotenv.2013.11.001

Cordell, D., and T.S.S. Neset. 2014. Phosphorus vulnerability: A qualitative framework for assessing the vulnerability of national and regional food systems to the multidimensional stressors of phosphorus scarcity. Global Environ. Change 24:108–122. doi:10.1016/j.gloenvcha.2013.11.005

Daloglu, I., K.H. Cho, and D. Scavia. 2012. Evaluating causes of trends in long-term dissolved reactive phosphorus loads to Lake Erie. Environ. Sci. Technol. 46:10660–10666. doi:10.1021/es302315d

DEFRA. 2014. The guide to cross compliance in England 2014. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/320833/The_Guide_to_Cross_Compliance_in_England_2014_complete_edition.pdf (11 May 2015).

DeVuyst, E.A., S.W. Pryor, G. Lardy, W. Eide, and R. Wiederholt. 2011. Cattle, ethanol, and biogas: Does closing the loop make economic sense? Agric. Syst. 104:609–614. doi:10.1016/j.agsy.2011.06.003

Dodds, W.K., W.W. Bouska, J.L. Eitzmann, T.J. Pilger, K.L. Pitts, A.J. Riley, J.T. Schloesser, and D.J. Thornbrugh. 2009. Eutrophication of US freshwaters: Analysis of potential economic damages. Environ. Sci. Technol. 43:12–19. doi:10.1021/es801217q

Doody, D.G., P.J.A. Withers, and R.M. Dils. 2014. Prioritizing waterbodies to balance agricultural production and environmental outcomes. Environ. Sci. Technol. 48:7697–7699. doi:10.1021/es5024509

Ebeling, A.M., L.G. Bundy, J.M. Powell, and T. Andraski. 2002. Dairy diet phosphorus effects on phosphorus losses in runoff from land-applied manure. Soil Sci. Soc. Am. J. 66:284–291. doi:10.2136/sssaj2002.0284

Elser, J.J. 2012. Phosphorus: A limiting nutrient for humanity? Curr. Opin. Biotechnol. 23:833–838. doi:10.1016/j.copbio.2012.03.001

Elser, J.J., and E. Bennett. 2011. A broken biogeochemical cycle. Nature 478:29–31. doi:10.1038/478029a

Elser, J.J., T.J. Elser, S.R. Carpenter, and W.A. Brock. 2014. Regime shift in fertilizer commodities indicates more turbulence ahead for food security. PLoS ONE 9:e93998. doi:10.1371/journal.pone.0093998

Engel, S., and M. Schaefer. 2013. Ecosystem services: A useful concept for addressing water challenges? Curr. Opin. Environ. Sustain. 5:696–707. doi:10.1016/j.cosust.2013.11.010

Food and Agriculture Organization of the United Nations. 2012. Current world fertilizer trends and outlook to 2016. Food and Agriculture Organization of the United Nations, Rome, Italy. ftp://ftp.fao.org/ag/agp/docs/cwfto16.pdf (11 May 2015).

Franzluebbers, A.J., and J.A. Steudemann. 2007. Crop and cattle responses to tillage systems for integrated crop–livestock production in the Southern Piedmont, USA. Renew. Agric. Food Syst. 22(3):168–180. doi:10.1017/S1742170507001706

Gandhi, V.P., and Z.Y. Zhou. 2014. Food demand and the food security challenge with rapid economic growth in the emerging economies of India and China. Food Res. Int. 63:108–124. doi:10.1016/j.foodres.2014.03.015

Godfray, H.C.J., J.R. Beddington, I.R. Crute, L. Haddad, D. Lawrence, J.F. Muir, J. Pretty, S. Robinson, S.M. Thomas, and C. Toulmin. 2010. Food security: The challenge of feeding 9 billion people. Science 327:812–818. doi:10.1126/science.1185383

Hart, C.E., and M. Carriquiry. 2007. Home Iowa Ag Review. Winter 2007, Vol. 13 No. 1. Agricultural situation spotlight: Ethanol-livestock integration. http://www.card.iastate.edu/iowa_ag_review/winter_07/article3.aspx (11 May 2015).

Haygarth, P.M., H.P. Jarvie, S.M. Powers, A.N. Sharpley, J.J. Elser, J. Shen, H.M. Peterson, N.-I. Chan, N.J.K. Howden, T. Burt, F. Worrall, F. Zhang, and X. Liu. 2014. Sustainable phosphorus management and the need for a long-term perspective: The legacy hypothesis. Environ. Sci. Technol. 48:8417–8419. doi:10.1021/es502852s

Henao, J., and C. Baanante. 2006. Agricultural production and soil nutrient mining in Africa: Implications for resource conservation and policy development. Technical Bulletin IFDC T-72 ISBN978-0-88090-157-4. International Center for Soil Fertility and Agricultural Development, Muscle Shoals, AL.

Heathwaite, A.L. 2010. Multiple stressors on water availability at global to catchment scales: Understanding human impact on nutrient cycles to protect water quality and water availability in the long term. Freshwater Biol. 55:241–257. doi:10.1111/j.1365-2427.2009.02368.x

Hein, L., and R. Leemans. 2012. The impact of first-generation biofuels on the depletion of the global phosphorus reserve. Ambio 41:341–349. doi:10.1007/s13280-012-0253-x

Hoff, H. 2011. Understanding the nexus. Background paper for the Bonn 2011 Conference: The water, energy and food security nexus. Stockholm Environment Institute, Stockholm, Sweden. http://www.sei-international.org/mediamanager/documents/Publications/SEI-Paper-Hoff-UnderstandingTheNexus-2011.pdf (11 May 2015).

Hoffman, L.A., and A. Baker. 2011. Estimating the substitution of distillers' grains for corn and soybean meal in the U.S. feed complex. USDA Economic Research Service report FDS-11-I-01, October 2011. http://www.grains.org/sites/default/files/pdfs/ddgs-substitution.pdf (11 May 2015).

Howden, N.J.K., T.P. Burt, F. Worall, S.A. Mathias, and M.J. Whelan. 2013. Farming for water quality: Balancing food security and nitrate pollution in UK river basins. Ann. Assoc. Am. Geogr. 103:397–407. doi:10.1080/00045608.2013.754672

IPNI. 2012. A Nutrient Use Information System (NuGIS) for the U.S. Norcross, GA. 12 Jan. 2012. www.ipni.net/nugis (accessed 11 May 2015).

Jarvie, H.P., and A. Jenkins. 2014. Accounting for ecosystem services in water quality standards compliance. Environ. Sci. Technol. 48:14072–14074. doi:10.1021/es5053057

Jarvie, H.P., A.N. Sharpley, B. Spears, A.R. Buda, L. May, and P.J.A. Kleinman. 2013a. Water quality remediation faces unprecedented challenges from "legacy phosphorus." Environ. Sci. Technol. 47:8997–8998. doi:10.1021/es403160a

Jarvie, H.P., A.N. Sharpley, P.J.A. Withers, J.T. Scott, B.E. Haggard, and C. Neal. 2013b. Phosphorus mitigation to control river eutrophication: Murky waters, inconvenient truths, and "postnormal" science. J. Environ. Qual. 42:295–304. doi:10.2134/jeq2012.0085

Jasinski, S. 2015. Phosphate rock. In: mineral commodity summaries. US Department of the Interior and USGS. http://minerals.usgs.gov/minerals/pubs/mcs/2014/mcs2014.pdf (11 May 2015).

Jesson, H. 2011. Cattle + ethanol = a good match. Ethanol Producer Magazine, Grand Forks, ND. 6 June 2011. http://www.ethanolproducer.com/articles/7833/cattleethanola-good-match (11 May 2015).

Jönsson, H., A.R. Stintzing, B. Vinneras, and E. Salomon. 2004. Guidelines on the use of urine and faeces in crop production. EcoSanRes, Stockholm Environment Institute, Stockholm, Sweden. http://www.ecosanres.org/pdf_files/ESR_Publications_2004/ESR2web.pdf (11 May 2015).

Jordan, P., P.M. Haygarth, G. Shortle, and R.C. Harris. 2012. Catchment science and policy for agriculture and water quality. Environ. Sci. Policy 24:1–3. doi:10.1016/j.envsci.2012.09.009

Kane, D.D., J.D. Conroy, R.P. Richards, D.B. Baker, and D.A. Culver. 2014. Re-eutrophication of Lake Erie: Correlations between tributary nutrient loads and phytoplankton biomass. J. Great Lakes Res. 40:496–501. doi:10.1016/j.jglr.2014.04.004

Khan, S., M.A. Khan, M.A. Hanjra, and J. Mu. 2009. Pathways to reduce the environmental footprints of water and energy inputs in food production. Food Policy 34:141–149. doi:10.1016/j.foodpol.2008.11.002

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally-related soil properties. J. Environ. Qual. 23:139–147. doi:10.2134/jeq1994.00472425002300010022x

Kleinman, P.J.A., A.N. Sharpley, A.R. Buda, R.W. McDowell, and A.L. Allen. 2011a. Soil controls of phosphorus in runoff: Management barriers and opportunities. Can. J. Soil Sci. 91:329–338. doi:10.4141/cjss09106

Kleinman, P.J.A., A.N. Sharpley, P.J.A. Withers, L. Bergstrom, L.T. Johnson, and D.G. Doody. 2015. Implementing agricultural phosphorus science and management to combat eutrophication. Ambio 44(S2):297–310. doi:10.1007/s13280-015-0631-2

Kleinman, P.J.A., A.L. Allen, B.A. Needelman, A.N. Sharpley, P.A. Vadas, L.S. Saporito, G.J. Folmar, and R.B. Bryant. 2007. Dynamics of phosphorus transfers from heavily manured Coastal Plain soils to drainage ditches. J. Soil Water Conserv. 62:225–235.

Kleinman, P.J.A., A.N. Sharpley, R.W. McDowell, D.N. Flaten, A.R. Buda, L. Tao, L. Bergstrom, and Q. Zhu. 2011b. Managing agricultural phosphorus for water quality protection: Principles for progress. Plant Soil 349:169–182. doi:10.1007/s11104-011-0832-9

Kleinman, P.J.A., K.S. Blunk, R. Bryant, L. Saporito, D. Beegle, K. Czymmek, Q. Ketterings, T. Sims, J. Shortle, J. McGrath, F. Coale, M. Dubin, D. Dostie, R. Maguire, R. Meinen, A. Allen, K. O'Neill, L. Garber, M. Davis, B. Clark, K. Sellner, and M. Smith. 2012. Managing manure for sustainable livestock production in the Chesapeake Bay Watershed. J. Soil Water Conserv. 67:54A–61A. doi:10.2489/jswc.67.2.54A

Koizumi, T. 2013. Biofuel and food security in China and Japan. Renew. Sustain. Energy Rev. 21:102–109. doi:10.1016/j.rser.2012.12.047

Kominami, H., and S.T. Lovell. 2012. An adaptive management approach to improve water quality at a model dairy farm in Vermont, USA. Ecol. Eng. 40:131–143. doi:10.1016/j.ecoleng.2011.12.003

Lawford, R., J. Bogardi, S. Marx, S. Jain, C.P. Wostl, K. Knueppe, C. Ringler, F. Lansigan, and F. Meza. 2013. Basin perspectives on the water-energy-food security nexus. Curr. Opin. Environ. Sustain. 5:607–616. doi:10.1016/j.cosust.2013.11.005

Liu, K., J.A. Elliott, D.A. Lobb, D.N. Flaten, and J. Yarotski. 2014. Nutrient and sediment losses in snowmelt runoff from perennial forage and annual cropland in the Canadian Prairies. J. Environ. Qual. 43:1644–1655. doi:10.2134/jeq2014.01.0040

Lu, Y., A. Jenkins, R.C. Ferrier, M. Bailey, I.J. Gordon, S. Song, J. Huang, S. Jia, F. Zhang, X. Liu, Z. Feng, and Z. Zhang. 2015. Addressing China's grand challenge of achieving food security while ensuring environmental sustainability. Sci. Adv. 1:e1400039. doi:10.1126/sciadv.1400039

Lougheed, T. 2011. Phosphorus paradox: Scarcity and overabundance of a key nutrient. Environ. Health Perspect. 119:A208–A213. doi:10.1289/ehp.119-a208

MacDonald, J.M., and W.D. McBride. 2009. The transformation of U.S. livestock agriculture: Scale efficiency, and risks. USDA Economic Research Service. http://www.ers.usda.gov/publications/eib-economic-information-bulletin/eib43.aspx (11 May 2015).

MacDonald, G.K., E.M. Bennett, and S.R. Carpenter. 2012. Embodied phosphorus and the global connections of United States agriculture. Environ. Res. Lett. 7. doi:10.1088/1748-9326/7/4/044024

MacDonald, G.K., E.M. Bennett, P.A. Potter, and N. Ramankutty. 2011. Agronomic phosphorus imbalances across the world's croplands. Proc. Natl. Acad. Sci. USA 108:3086–3091. doi:10.1073/pnas.1010808108

Maguire, R.O., J.T. Sims, W.W. Saylor, B.L. Turner, R. Angel, and T.J. Applegate. 2004. Influence of phytase addition to poultry diets on phosphorus forms and solubility in litters and amended soils. J. Environ. Qual. 33:2306–2316. doi:10.2134/jeq2004.2306

Maligreau, J.-P., H. Eva, and A. Maggio. 2012. NPK: Will there be enough plant nutrients to feed a world of 9 billion in 2050. Foresight and Horizon Scanning Series. JRC Science and Policy Reports European Commission. http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/25770/1/npk%20final%20report%20_%20publication%20be%20pdf.pdf (11 May 2015).

Medema, W., B.S. McIntosh, and P.J. Jeffrey. 2008. From premise to practice: A critical assessment of integrated water resources management and adaptive management approaches in the water sector. Ecol. Soc. 13:29.

Meehan, T.D., C. Gratton, E. Diehl, N.D. Hunt, D.F. Mooney, S.J. Ventura, B.L. Barham, and R.D. Jackson. 2013. Ecosystem-service tradeoffs associated with switching from annual to perennial energy crops in riparian zones of the US Midwest. PLoS One 8. doi:10.1371/journal.pone.0080093

Mehta, C.M., W.O. Khunjar, V. Nguyen, S. Tait, and D.J. Batstone. 2015. Technologies to recover nutrients from waste streams: A critical review. Crit. Rev. Environ. Sci. Technol. 45:385–427. doi:10.1080/10643389.2013.866621

Meyer, C., B. Matzdorf, K. Muller, and C. Schleyer. 2014. Cross compliance as payment for public goods? Understanding EU and US agricultural policies. Ecol. Econ. 107:185–194. doi:10.1016/j.ecolecon.2014.08.010

Michalak, A.M., E.J. Anderson, D. Beletsky, S. Boland, N.S. Bosch, T.B. Bridgeman, J.D. Chaffin, K. Cho, R. Confesor, I. Daloglu, J.V. DePinto, M.A. Evans, G.L. Fahnenstiel, L. He, J.C. Ho, L. Jenkins, T.H. Johengen, Kuo K.C., E. LaPorte, X. Liu, M.R. McWilliams, M.R. Moore, D.J. Posselt, R.P. Richards, D. Scavia, A.L. Steiner, E. Verhamme, D.M. Wright, and M.A. Zagorski. 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Proc. Natl. Acad. Sci. U.S.A. 110:6448–6452. doi:10.1073/pnas.1216006110

Neset, T.-S.S., and D. Cordell. 2012. Global phosphorus scarcity: Identifying synergies for a sustainable future. J. Sci. Food Agric. 92:2–6. doi:10.1002/jsfa.4650

Nielsen, H.O., P. Frederiksen, H. Saarikoski, A.M. Rytkonen, and A.B. Pedersen. 2013. How different institutional arrangements promote integrated river basin management: Evidence from the Baltic Sea Region. Land Use Policy 30:437–445. doi:10.1016/j.landusepol.2012.04.011

Olsson, G. 2013. Water, energy and food interactions: Challenges and opportunities. Front. Environ. Sci. Eng. 7:787–793. doi:10.1007/s11783-013-0526-z

Orr, P., J. Colvin, and D. King. 2007. Involving stakeholders in integrated river basin planning in England and Wales. Water Resour. Manage. 21:331–349. doi:10.1007/s11269-006-9056-9

Perrone, D., and G.M. Hornberger. 2014. Water, food, and energy security: Scrambling for resources or solutions? Wiley Interdiscip. Rev.: Water 1:49–68. doi:10.1002/wat2.1004

Petersen, B., and S. Snapp. 2015. What is sustainable intensification? Views from experts. Land Use Policy 46:1–10. doi:10.1016/j.landusepol.2015.02.002

Potter, P., N. Ramankutty, E.M. Bennett, and S.D. Donner. 2010. Characterizing the spatial patterns of global fertilizer application and manure production. Earth Interact. 14:1–22.

Power, A.G. 2010. Ecosystem services and agriculture: Tradeoffs and synergies. Philos. Trans. R. Soc. Lond. B Biol. Sci. 365:2959–2971. doi:10.1098/rstb.2010.0143

Pretty, J., C. Toulmin, and S. Williams. 2011. Sustainable intensification in African agriculture. Int. J. Agric. Sustainability 9:5–24. doi:10.3763/ijas.2010.0583

Rathmann, R., A. Szklo, and R. Schaeffer. 2010. Land use competition for production of food and liquid biofuels: An analysis of the arguments in the current debate. Renew. Energy 35:14–22. doi:10.1016/j.renene.2009.02.025

Richards, R.P., D.B. Baker, and J.P. Crumrine. 2009. Improved water quality in Ohio tributaries to Lake Erie: A consequence of conservation practices. J. Soil Water Conserv. 64:200–211. doi:10.2489/jswc.64.3.200

Riddle, M.U., and L. Bergström. 2013. Phosphorus leaching from two soils with catch crops exposed to freeze–thaw cycles. Agron. J. 105:803–811. doi:10.2134/agronj2012.0052

Ringler, C., A. Bhaduri, and R. Lawford. 2013. The nexus across water, energy, land and food (WELF): Potential for improved resource use efficiency? Curr. Opin. Environ. Sustain. 5:617–624. doi:10.1016/j.cosust.2013.11.002

Robertson, G.P., V.H. Dale, O.C. Doering, S.P. Hamburg, J.M. Melillo, M.M. Wander, W.J. Parton, P.R. Adler, J.N. Barney, R.M. Cruse, C.S. Duke, P.M. Fearnside, R.F. Follett, H.K. Gibbs, J. Goldemberg, D.J. Mladenoff, D. Ojima, M.W. Palmer, A. Sharpley, L. Wallace, K.C. Weathers, J.A. Wiens, and W.W. Wilhelm. 2008. Agriculture: Sustainable biofuels redux. Science 322:49–50. doi:10.1126/science.1161525

Rosegrant, M.W., T. Zhu, S. Msangi, and T. Sulser. 2008. Global scenarios for biofuels: Impacts and implications. Rev. Agric. Econ. 30:495–505. doi:10.1111/j.1467-9353.2008.00424.x

Rota, A., and S. Sperandini. 2009. Integrated crop-livestock farming systems. In: Livestock thematic papers tools for project design. International Fund for Agricultural Development (IFAD). http://www.ifad.org/lrkm/factsheet/integratedcrop.pdf (11 May 2015).

Russelle, M.P., M.H. Entz, and A.J. Franzluebbers. 2007. Reconsidering integrated crop–livestock systems in North America. Agron. J. 99(2):325–334. doi:10.2134/agronj2006.0139

Sanchez, P.A. 2010. Tripling crop yields in tropical Africa. Nat. Geosci. 3:299–300. doi:10.1038/ngeo853

Scavia, D., J.D. Allan, K.K. Arend, S. Bartell, D. Beletsky, N.S. Bosch, S.B. Brandt, R.D. Briland, I. Daloglu, J.V. DePinto, D.M. Dolan, M.A. Evans, T.M. Farmer, D. Goto, H.J. Han, T.O. Hook, R. Knight, S.A. Ludsin, D. Mason, A.M. Michalak, R.P. Richards, J.J. Roberts, D.K. Rucinski, E. Rutherford, D.J. Schwab, T.M. Sesterhenn, H.Y. Zhang, and Y.T. Zhou. 2014. Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. J. Great Lakes Res. 40:226–246. doi:10.1016/j.jglr.2014.02.004

Schipanski, M.E., and E.M. Bennett. 2012. The influence of agricultural trade and livestock production on the global phosphorus cycle. Ecosystems 15:256–268. doi:10.1007/s10021-011-9507-x

Scholz, R.W., and F.-W. Wellmer. 2013. Approaching a dynamic view on the availability of mineral resources: What we may learn from the case of phosphorus? Global Environ. Change 23:11–27. doi:10.1016/j.gloenvcha.2012.10.013

Scholz, R.W., A.E. Ulrich, M. Eilittae, and A. Roy. 2013. Sustainable use of phosphorus: A finite resource. Sci. Total Environ. 461–462:799–803. doi:10.1016/j.scitotenv.2013.05.043

Sharpley, A.N., and H.P. Jarvie. 2012. Agricultural management, water quality and ecology: Putting practice into policy. In: A. Eaglesham, editor, National Agricultural Biotechnology Council Conference Proceedings 24. Boyce Thompson Institute, Ithaca, NY. Library of Congress # 2012954078. p. 87–116.

Sharpley, A.N., and S.J. Smith. 1994. Wheat tillage and water quality in the Southern Plains. Soil Tillage Res. 30:33–48. doi:10.1016/0167-1987(94)90149-X

Sharpley, A.N., S. Herron, and T. Daniel. 2007. Overcoming the challenges of phosphorus-based management in poultry farming. J. Soil Water Conserv. 62:375–389.

Sharpley, A.N., P.J.A. Kleinman, D.N. Flaten, and A.R. Buda. 2011. Critical source area management of agricultural phosphorus: Experiences, challenges and opportunities. Water Sci. Technol. 64:945–952. doi:10.2166/wst.2011.712

Sharpley, A.N., P. Richards, S. Herron, and D. Baker. 2012. Case study comparison between litigated and voluntary nutrient management strategies. J. Soil Water Conserv. 67:442–450. doi:10.2489/jswc.67.5.442

Shortle, J.S., M. Ribaudo, R.D. Horan, and D. Blandfor. 2012. Reforming agricultural nonpoint pollution policy in an increasingly budget-constrained environment. Environ. Sci. Technol. 46:1316–1325. doi:10.1021/es2020499

Simpson, T.W., A.N. Sharpley, R.W. Howarth, H.W. Paerl, and K.R. Mankin. 2008. The new gold rush: Fueling ethanol production while protecting water quality. J. Environ. Qual. 37:318–324. doi:10.2134/jeq2007.0599

Smith, D.R., K.W. King, L. Johnson, W. Francesconi, P. Richards, D. Baker, and A.N. Sharpley. 2015a. Surface runoff and tile drainage transport of phosphorus in the midwestern United States. J. Environ. Qual. 44:495–502.

Smith, D.R., K.W. King, and M.R. Williams. 2015b. What is causing the harmful algal blooms in Lake Erie? J. Soil Water Conserv. 70:27A–29A. doi:10.2489/jswc.70.2.27A

Sorensen, C.G., N. Halberg, F.W. Oudshoorn, B.M. Petersen, and R. Dalgaard. 2014. Energy inputs and GHG emissions of tillage systems. Biosystems Eng. 120:2–14. doi:10.1016/j.biosystemseng.2014.01.004

Syers, K., M. Bekunda, D. Cordell, J. Corman, J. Johnston, A. Rosemarin, and I. Salcedo. 2011. Phosphorus and food production In: UNEP Year Book 2011: Emerging issues in our global environment. United Nations Environment Programme, Nairobi. p. 35–45, http://www.unep.org/yearbook/2011/pdfs/UNEP_YEARBOOK_Fullreport.pdf (11 May 2015).

Tiessen, K.H.D., J.A. Elliott, J. Yarotski, D.A. Lobb, D.N. Flaten, and N.E. Glozier. 2010. Conventional and conservation tillage: Influence on seasonal runoff, sediment, and nutrient losses in the Canadian prairies. J. Environ. Qual. 39:964–980. doi:10.2134/jeq2009.0219

Tilman, D., J. Fargione, B. Wolff, C. D'Antonio, A. Dobson, R. Howarth, D. Schindler, W.H. Schlesinger, D. Simberloff, and D. Swackhamer. 2001. Forecasting agriculturally driven global environmental change. Science 292:281–284. doi:10.1126/science.1057544

Tilman, D., R. Socolow, J.A. Foley, J. Hill, E. Larson, L. Lynd, S. Pacala, J. Reilly, T. Searchinger, C. Somerville, and R. Williams. 2009. Beneficial biofuels: The food, energy, and environment trilemma. Science 325:270–271. doi:10.1126/science.1177970

US Census Bureau. 2012. Population estimates: County totals datasets. Population, population change and estimated components of population change: April 1 2010 to July 1, 2012. http://www.census.gov/popest/data/counties/totals/2012/CO-EST2012-alldata.html (accessed 11 May 2015).

USDA–ERS. 2015. Bioenergy. http://www.ers.usda.gov/topics/farm-economy/bioenergy.aspx (11 May 2015).

USEPA. 2002. Onsite wastewater treatment systems manual. EPA/625/R-00/008. http://www.epa.gov/owm/septic/pubs/septic_2002_osdm_all.pdf (11 May 2015).

Van der Velde, M., C. Folberth, J. Balkovic, P. Ciais, S. Fritz, I.A. Janssens, M. Obersteiner, L. See, R. Skalsky, W. Xiong, and J. Penuelas. 2014. African crop yield reductions due to increasingly unbalanced nitrogen and phosphorus consumption. Glob. Change Biol. 20:1278–1288. doi:10.1111/gcb.12481

Vitousek, P.M., R. Naylor, T. Crews, M.B. David, L.E. Drinkwater, E. Holland, P.J. Johnes, J. Katzenberger, L.A. Martinelli, P.A. Matson, G. Nziguheba, D. Ojima, C.A. Palm, G.P. Robertson, P.A. Sanchez, A.R. Townsend, and F.S. Zhang. 2009. Nutrient imbalances in agricultural development. Science 324:1519–1520. doi:10.1126/science.1170261

Vohla, C., M. Koiv, H.J. Bavor, F. Chazarenc, and U. Mander. 2011. Filter materials for phosphorus removal from wastewater in treatment wetlands: A review. Ecol. Eng. 37:70–89. doi:10.1016/j.ecoleng.2009.08.003

Walker, D.A. 2009. Biofuels, facts, fantasy, and feasibility. J. Appl. Phycol. 21:509–517. doi:10.1007/s10811-009-9446-5

Wang, F., J.T. Sims, L. Ma, W. Ma, Z. Dou, and F. Zhang. 2011. The phosphorus footprint of China's food chain: Implications for food security, natural resource management, and environmental quality. J. Environ. Qual. 40:1081–1089. doi:10.2134/jeq2010.0444

Werling, B.P., T.L. Dickson, R. Isaacs, H. Gaines, C. Gratton, K.L. Gross, H. Liere, C.M. Malmstrom, T.D. Meehan, L. Ruan, B.A. Robertson, G.P. Robertson, T.M. Schmidt, A.C. Schrotenboer, T.K. Teal, J.K. Wilson, and D.A. Landis. 2014. Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. Proc. Natl. Acad. Sci. USA 111:1652–1657. doi:10.1073/pnas.1309492111

Whitehead, P.G., J. Crossman, B.B. Balana, M.N. Futter, S. Comber, L. Jin, D. Skuras, A.J. Wade, M.J. Bowes, and D.S. Read. 2013. A cost-effectiveness analysis of water security and water quality: Impacts of climate and land-use change on the River Thames system. Philos. Trans. R. Soc. A 371. doi:10.1098/rsta.2012.0413

Withers, P.J.A., R. Sylvester-Bradley, D.L. Jones, J.R. Healey, and P.J. Talboys. 2014. Feed the crop not the soil: Rethinking phosphorus management in the food chain. Environ. Sci. Technol. 48:6523–6530. doi:10.1021/es501670j

Withers, P.J.A., K.C. van Dijk, T.S.S. Neset, T. Nesme, O. Oenema, G.H. Rubaek, O.F. Schoumans, B. Smit, and S. Pellerin. 2015. Stewardship to tackle global phosphorus inefficiency: The case of Europe. Ambio 44:193–206. doi:10.1007/s13280-014-0614-8

World Economic Forum. 2011. Water security: The water-food-energy-climate nexus. Island Press, Washington, DC.

Wright, B. 2014. Global biofuels: Key to the puzzle of grain market behavior. J. Econ. Perspect. 28:73–97. doi:10.1257/jep.28.1.73