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Grappling with the success and trade-offs of global nutrient redistribution

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Abstract

Inputs of fertilizer nutrients in agriculture are estimated to have contributed to > 40% increase in crop production over the past century, resulting in widespread benefits to food security and prosperity. However, fertilizer nutrient redistribution has fundamentally altered global and local nutrient cycles alike, yielding trade-offs in socioeconomic and environmental outcomes. David Pimentel's body of work on the management of energy, water, and soil resources in agriculture, along with his perspectives on agronomy and sustainable resource management, resonates with a critical understanding of the consequences of nutrient redistribution in agriculture. With Pimentel's legacy in mind, we consider trade-offs of global nutrient redistribution, improved recycling of nutrients in agricultural systems, as well as the challenges of, and opportunities for, transformations that seek to adjust nutrient cycles in modern agriculture. Pimentel's legacy and contributions provide valuable insight into agriculture's wicked nutrient challenge, as he framed the costs and opportunities of production systems across different scales of food production, developed foundational understanding of global resource challenges, promoted often marginalized or underemployed management strategies to enhance agriculture's ecosystem services, confronted conventional wisdom and popular trends, and appropriately, attacked the use of "silver bullets" as singular solutions to ecological challenges and instead promoted systems-level analyses.

Keywords Nutrients · Nitrogen · Phosphorus · Eutrophication · David Pimentel · Agriculture

1 Introduction

The restructuring of resource flows to support earth's expanding human population has brought unprecedented prosperity to many corners of the globe but has also wrought profound, unintended outcomes to our "planetary boundaries" (Rockström et al., 2009;

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Steffen et al., 2015). In terms of nutrient resources, application of the Haber–Bosch process to produce nitrogen (N) fertilizer, combined with the efficient mining and concentration of rock phosphorus (P) into high analysis fertilizer, became pillars of the Green Revolution (Guignard et al., 2017; Sánchez, 2010). More recently, modern fertilizer supply chains have successfully confronted natural inequities in the global distribution of nutrients and have underpinned expansion of food, fiber, and biofuel production in regions where endemic resources were insufficient to support the intensification of agriculture to meet growing demand (Cassman et al., 2003; Erisman et al., 2008; Zhang et al., 2015).

Across the earth, nutrient redistribution to intensify food, fuel, fiber, and feed production on arable lands, along with by-product redistribution from industrial development (e.g., N and sulfur emission by-products from coal-burning power plants), has fundamentally altered global nutrient cycles (Galloway et al., 2003; Jarvie et al., 2015). This alteration has manifest in imbalances in resource availability (Gitau, 2022; Vitousek et al., 2009), reliance on energy-intensive processes (Smith et al., 2020), and widespread accelerated eutrophication of freshwater and estuarine systems (Howarth et al., 2021). The dichotomy related to global N and P redistribution is evident in the tremendous human achievement and associated wicked problems. Now, humankind must achieve seemingly incongruent goals: (1) increasing agricultural production to feed, clothe, and fuel the growing population and (2) mitigating adverse ecological and economic impacts of N and P redistribution.

Although David Pimentel's research focused less on fertilizer nutrients than on the management of energy, water, and soil resources, his perspectives on agronomy and sustainable resource management, including analyses of nutritional outcomes associated with different productions systems, resonate with a critical understanding of the consequences of global nutrient redistribution, offering a vision for system-level change. Over the span of six decades, Pimentel focused on promoting sustainable forms of agriculture, scanning case studies and large datasets alike to understand the outcomes of various systems. His framing of the costs and opportunities of production systems across different scales of food production are foundational to understanding the history and future of global nutrient challenges (e.g., Pimentel et al., 1993, 1995, 1997). Pimentel's broad application of science to unveil the aggregate (and often unintended) consequences of modern agricultural systems can serve as a benchmark for scientists and decision-makers in the agricultural research community. Regardless of the degree to which one accepts Pimentel's proposals, his work challenged all to consider the consequences of the status quo and to weigh the possibilities for alternative forms of agriculture.

As such, we aim herein to discuss pertinent topics in tribute to Pimentel's impact and inspiration, organized as following:

1. Trade-offs of global nutrient redistribution
2. Improved recycling of nutrients in agricultural systems
   - 2.1 Nutrient cycling of ancient systems
   - 2.2 Addressing the specialization and intensification of crop and livestock systems
3. Challenges of and opportunities for transformation.
   - 3.1 Transformation across the farm gate
   - 3.2 Fertilizer innovations

3.3 On-farm management

2 Trade-offs of global nutrient redistribution

David Pimentel strove to elucidate the collateral consequences, often unintended, of modern farming systems. In 2021, global commercial fertilizer demand was estimated at greater than 110 million tons of fertilizer N and roughly 48 million tons of fertilizer P (reported as P_2O_5; International Fertilizer Association, 2022), supplied via pan-global manufacturing and distribution networks that link raw materials and manufacturing capacity to warehousing, retail, and utilization. The expanded use of fertilizer nutrients in agriculture is estimated to have contributed to > 40% increase in crop production during the past century (Stewart & Roberts, 2012)—an accomplishment with unquestioned benefits to humankind.

However, modern reliance upon fertilizers comes at a cost, and trade-offs in socioeconomic outcomes are clear. Fertilizer resource distribution of global magnitude relies on economies of scale; however, only modern mechanized production systems—but not traditional or marginal small-holder systems—are able to seize upon the production and efficiency benefits (Harmel et al., 2020). The distribution infrastructure and business systems necessary for efficient transport, storage, and delivery of fertilizers are simply not available in many parts of the developing world, leaving widespread yield gaps and food insecurity as a persistent phenomenon roughly three quarters of century after the Green Revolution's onset (Bjornlund et al., 2020).

Further, dependence upon global supply chains represents a major stressor to modern farming economies, especially under the instability of current markets (Bjorn, 2022), and has fueled long-standing geopolitical conflicts over raw material (e.g., Kasprac, 2016). In addition, the energy-intensive nature of fertilizer production drives swings in fertilizer cost and availability that constrain modern agricultural systems and economies. The linkage between energy use and fertilizer production is now understood to be a major contributor to agriculture's greenhouse gas footprint (10.6% according to Menegat et al., 2022), a reality not unnoticed by Pimentel who was prescient in quantifying the contributions of farm inputs to agriculture's energy and environmental footprints (e.g., Pimentel et al., 2005).

Regional intensification and specialization of agriculture since World War II is now observable at a global scale, manifest as fertilizer nutrient hotspots and emblemized by excess P whose signature is clearly preserved in soils (Fig. 1a). In some cases (e.g., China), these hot spots are a function of national strategies toward food security, while in other cases they represent the manifestation of economic optimization and the concentration of specialized forms of agricultural production in different regions, as explained subsequently. Most relevant to Pimentel's legacy, the transfer of fertilizer resources within global agroecosystems coincides with a long-term environmental footprint: the expansion and acceleration of eutrophication in both freshwater and major estuarine systems (Fig. 1b) (Malone & Newton, 2020; Smith, 2003). Of note is the steady increase in harmful algal blooms across the globe, from eutrophic to oligotrophic systems, whose expansion is hypothesized as foundational change in aquatic stoichiometries related to changes in major nutrient forms (Gilbert, 2012). It is important to note that agriculture, alone, is not responsible for these impacts. Because accelerated eutrophication stems from a complex web of biogeochemical processes and socioeconomic drivers (Elser et al., 2007), comprehensive mitigation strategies are required (Carpenter et al., 1998). Thus, broad-scale, systemic transformations must be considered (Jarvie et al., 2015).

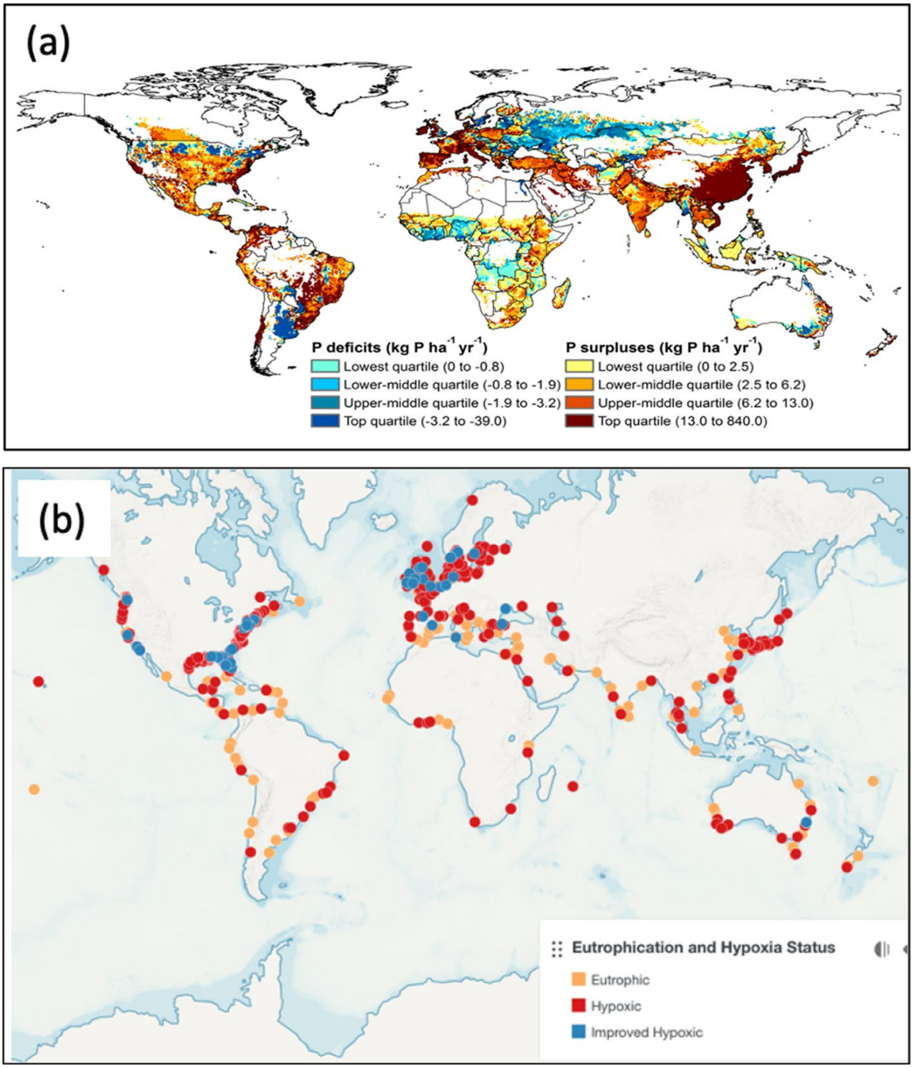

Fig. 1 The geographic concentration of phosphorus in the world's soils, largely a function of global fertilizer supply chains: **a** adapted from MacDonald et al., 2011), and the globalization of cultural eutrophication, as manifest by major eutrophic and hypoxic coastal water bodies, and **b** adapted from World Resources Institute (www.wri.org/data/interactive-map-eutrophication-hypoxia)

Across the globe, the geographic build-up of nutrients are manifest across profoundly different spatial and temporal scales: from field to region and from short to long term. Even in the low-intensity, pasture-based systems of New Zealand, conscientious management of hot spots within fields is required to ensure that nutrients do not eutrophy local water bodies (McDowell, 2008). Inefficiencies in nutrient use efficiency are often taken for granted in agricultural nutrient management, either as a result of the dynamic nature of the element (e.g., N with its multitude of pathways of environmental fate) or as a result of profound buffering (e.g., P binding by soils that renders the element unavailable to commercial crops). These nutrient use inefficiencies have often been confronted via systematic over-application of amendments, including commercial fertilizers, such as in the reclamation of Brazil's Cerrado areas (Withers et al., 2018). As a result, strategies to mitigate the unintended outcomes of agricultural nutrient management are seldom simple, and require simultaneous application of best practices by farmers, as well as system-level adjustments that may conflict with the status quo, themes that transcend Pimentel's library of work.

3 Improved recycling of nutrients in agricultural systems

Pimentel promoted management strategies that enhance ecosystem services provided by agriculture. His prioritization of environmental protection and resource conservation sometimes elevated management practices that are marginalized or underemployed today. These ranged from alternative cropping systems (Pimentel et al., 2005) to unconventional management practices (Pimentel et al., 1993). Often, Pimentel's views confronted conventional wisdom, or current trends, highlighting trade-offs and unintended consequences. This gadfly perspective, however, resonates well with modern agriculture's search for solutions to the paradoxical challenge of nutrient management (e.g., Lougheed, 2011). That is how to increase the availability of terrestrial nutrients needed for crop production without excessive losses of nutrients through leaching, runoff, and emissions.

Although Pimentel regularly called for transformational change in agriculture, he could be critical of using simplified solutions to address complex resource challenges (sensu Smith et al., 2019), exemplified by his long-standing critique of bio-ethanol as an energy source and associated biofuel programs (Pimentel, 2003, 2010). Silver-bullet solutions, and their unintended outcomes, are a familiar aspect of public programs that attempt to tackle complex issues (Merton, 1936). Margaret Catley–Carlson eloquently articulates that development of technical solutions without understanding underlying socioeconomic factors and without vetting the advantages and disadvantages of alternatives rarely produces effective solutions (Harmel et al., 2020). In nutrient management, comprehensive sets of solutions are needed that not only offer options and flexibility to agricultural producers, but engage production across supply chains, transcend regional and national boundaries, and reconsider historical precedent that contribute to many of the systemic traits observed today (Jarvie et al, 2015; Reis et al., 2016).

3.1 Nutrient cycling of ancient systems

Pimentel and colleagues wrote directly on nutrient recycling in their consideration of the sustainability of traditional forms of slash-and-burn farming in the tropics (Kleinman et al., 1995 and 1996). Complementing a well-intended global campaign against slash-and-burn as a major driver of deforestation (FAO's Alternative to Slash and Burn Program, Palm et al., 2005), Kleinman et al. (1995) endeavored to remind the global development community of the historical sustainability of this ancient system, that is if and only if as practiced by indigenous communities with low population densities and ample land resources to allow for long periods of fallow between periods of cultivation. They argued that traditional slash-and-burn systems with long periods of fallow indeed recycle nutrient

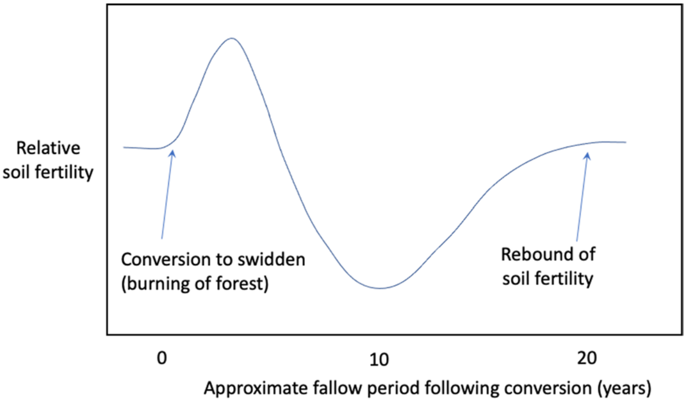

Fig. 2 The cyclical model of soil fertility in traditional (long fallow) slash-and-burn farming systems in which nutrients enabling crop production are derived entirely from soil and biomass (adapted from Kleinman et al., 1995)

resources, unlike input-intensive systems (Fig. 2). This work highlights the central role of nutrient recycling in sustainable agriculture, a precursor to the premium placed upon circular economies (e.g., Velasco-Munoz et al., 2021).

3.2 Addressing the specialization and intensification of crop and livestock systems

Low-input farming systems that rely upon local nutrient cycles alone cannot meet the commodity demands of today's global population of 8 billion (United Nations, 2022) who are in turn fed by fewer than 625 million farms (Erenstein et al., 2021). Nowhere are the inequities of local nutrient supplies more strongly exhibited than in the spatially disconnected nutrient flows of modern crop and livestock production. Many of the nutrient hotpots depicted in Fig. 1b derive from concentrated livestock production, a function of regionally separated crop and livestock production in which unmetabolized feed nutrients in animal manure are not returned to croplands to provide needed N, P, and micronutrients. The specialization and intensification of animal production has brought great economic and production efficiencies in delivering protein to consumers but also adverse environmental outcomes that were regularly the subject of Pimentel's pen (e.g., Pimentel & Pimentel, 2003). Indeed, eutrophication is a widespread concern in watersheds where animal production is concentrated (Carpenter et al., 1998; Sharpley et al., 2003a). As such, nutrient management represents an environmental challenge that is nearly ubiquitous in animal production (e.g., Ma et al., 2014; Holly et al., 2018; Thorsøe et al., 2022). Pimentel and colleagues pointed to the demographic shift in wealthier global populations as the ultimate driver (Giampietro & Pimentel, 1993), highlighting the benefits of livestock grazing systems that more directly cycle nutrients (Pimentel, 1997; Pimentel et al., 1980).

Today, there are consistent calls by those concerned with resource conservation and environmental outcomes to recouple crop and livestock production (e.g., Sanderson et al., 2013), reintroducing nutrient cycling between crop and livestock production systems at scales that are compatible with modern economies (Fig. 3; Spiegal et al., 2020). Opportunities exist to better cycle nutrients between crop and livestock operations, but these require

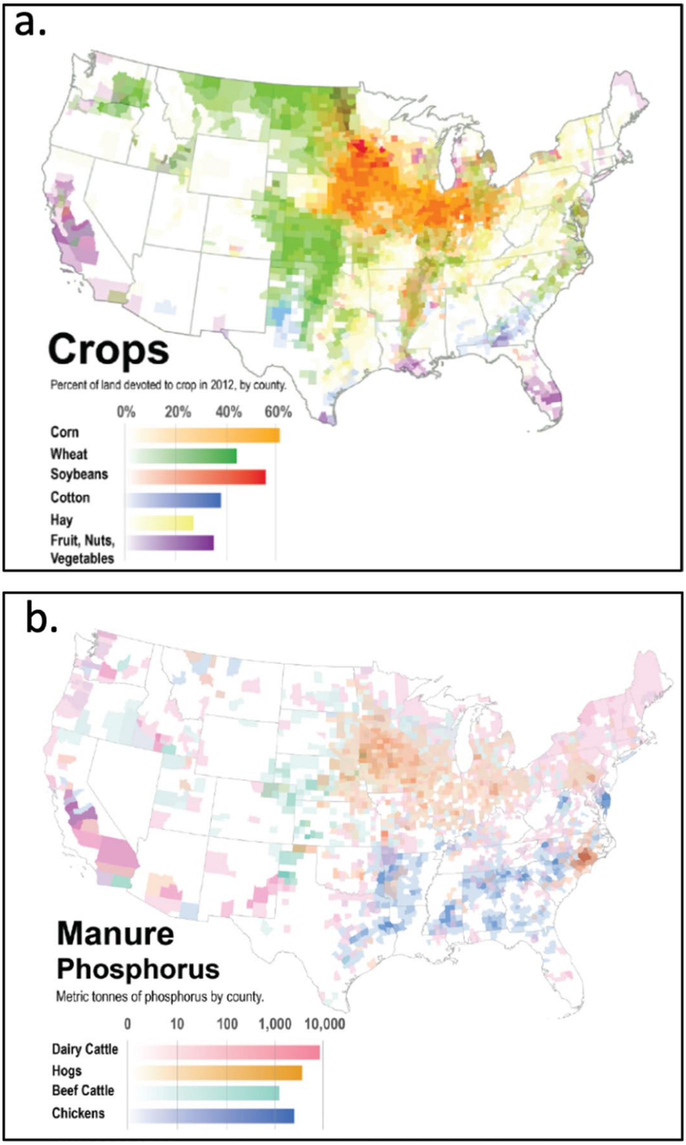

Fig. 3 The distribution of crop and animal agriculture in the United States, as depicted using U.S. county-level data for major crops produced (**a**), and phosphorus in animal manure (**b**). Whereas concentration of crops and of manure phosphorus represent a signature of the specialization and intensification of agricultural systems (adapted from Spiegal et al., 2020)

action within farming systems as well as beyond the farmgate (Kleinman et al., 2022b; Kronberg et al., 2021; Peterson et al., 2020). These visions comport with strategies that promote conservation and changes in commodity consumption, a regular call of Pimentel's (e.g., Pimentel & Pimentel, 2003, 2007). They also require system re-integration (Peterson et al., 2020), new technologies, supply chain coordination (Spiegal et al., 2022), and participation of communities beyond the agricultural industry (Hidalgo et al., 2021).

Notably, given long-standing efforts to redistribute fertilizer nutrients, generalizations regarding nutrient imbalances as a function of mechanization, degree of labor use, and stage of agricultural development are difficult to uphold. National programs to improve the sufficiency of crop production can result in fertilizer nutrient imbalances comparable to those arising in industrialized farming systems. Such has been the case in China where programs to build soil fertility resulted in wide availability of fertilizers to the country's 300+ million small-holder farmers while extension programs lagged, resulting in systematic over-application of commercial fertilizers that threatens environmental quality (Sims et al., 2013). Similarly, modern organic cropping systems that are reliant upon manure routinely result in nutrient imbalances, particularly for P, that are not observed in cropping systems that are reliant on mineral, or commercial, fertilizers (Cooper et al., 2018).

4 Challenges of and opportunities for transformation

While the aggregate impacts of globalized nutrient flows are now well recognized (Vitousek et al., 2009; Elser & Bennet, 2011), as are concerns over numerous global environmental phenomena (especially climate change), challenges abound in how to mitigate the effect of systems that are now foundational to the modern economy. Translating awareness of greenhouse gas emissions, eutrophication, groundwater contamination, and resource depletion into viable action will require humankind to confront a myriad of contributing factors, not the least of which are local "realities" that must be addressed for change to occur (Sharpley et al., 2016).

An important contributor that has hindered collaborative progress on agriculture's contribution to excess N and P in water is the avoidance of uncomfortable truths on relevant topics such as edge-of-field regulation (Harmel et al., 2018) and multiple actor fault in water quality problems (Smith et al., 2018). Avoiding these uncomfortable topics in research, debate, and decision-making tends to prevent compromise and willingness to find common ground and to breed mistrust between parties and often belief in misinformation (Kleinman et al., 2015).

How then, can we promote efficient nutrient cycling in systems whose mass balances no longer resemble natural cycles? Solutions must: (1) be able to apply across a range of highly specialized and varied production systems; (2) address nutrient cycling beyond the farm gate; and (3) account for socioeconomic, environmental, and management factors that influence both implementation and outcomes.

4.1 Transformation across the farm gate

Historical nutrient management approaches addressing environmental concerns have reasonably prioritized the adoption of on-farm management strategies (Öborn et al., 2003; Sharpley et al., 2003b). While many opportunities remain to change on-farm nutrient management (Johnston and Bruulsma, 2014; Hedley, 2015), the aspiration of reintroducing circularity into agricultural nutrient flows requires a recoupling of disconnected production systems that extend across regions and even nations (Nesme & Withers, 2016; Spiegal et al., 2022).

Such an agroecological ambition is represented in the vision of "manureshed" management, i.e., the strategic use of manure nutrients that prioritizes recycling between livestock systems and cropping systems (Spiegal et al., 2020). As proposed, manureshed management expands collaboration of a plethora of actors to coordinate the transformation and transfer of manure resources across multiple scales, appropriating practices and technologies to ensure that manure nutrients are available in the quantity, form, and timing required of crop production systems (Bryant et al., 2021; Dell et al., 2022; Meinen et al., 2022). Essential to the reintroduction of circularity is the inclusion of actors who can operate across the complex set of industries, regulations, relationships, and transactions demanded of modern agriculture (Fig. 4; Meredith et al., 2022).

4.2 Fertilizer innovations

Innovations in the production and recovery of fertilizer nutrients are central to any vision for transforming modern nutrient cycles. Many systemic challenges of fertilizer management in conventional and alternative production systems, including those reliant on organic, manure-derived nutrients, have been long-identified but never fully addressed (Kirchmann & Bergstrom, 2001; Poudel et al., 2002). There is undoubtedly a need for

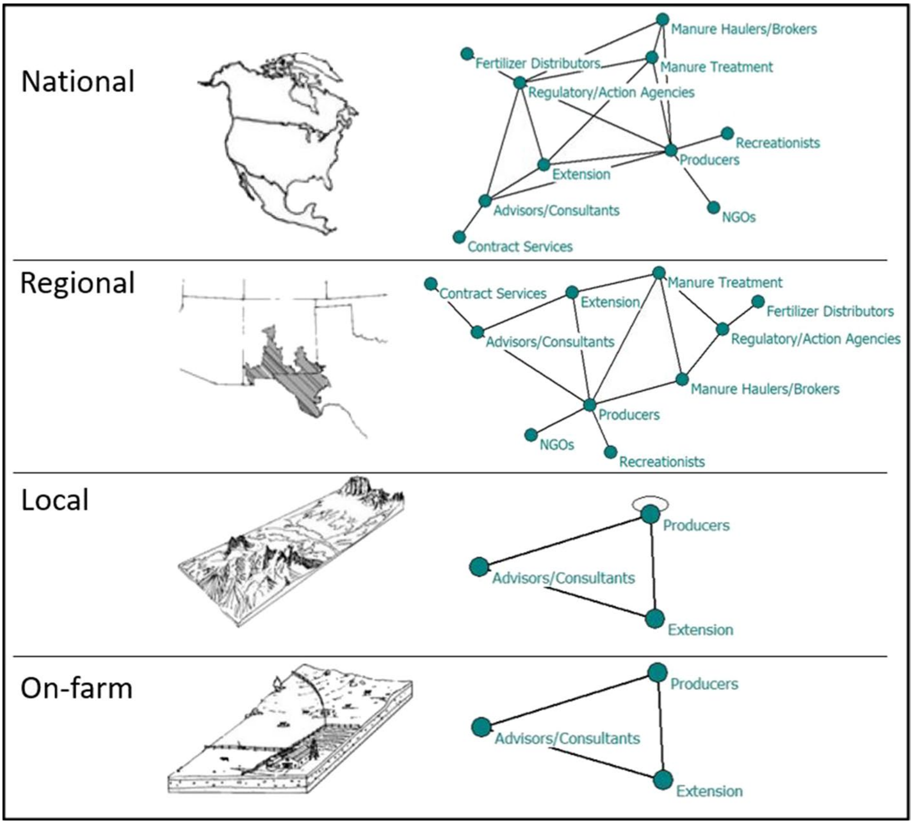

Fig. 4 Actor networks required to recover nutrients in animal manure for use in crop production at farm, local, regional, and national scales (adapted from Meredith et al., 2022)

change, either through adoption of cropping systems that can themselves take advantage of biological nutrient cycling or through the development of new technologies and strategies that lessen environmental footprints and improve nutrient use efficiency.

Biological N fixation serves as the source of most of the earth's reactive N, and integrating legumes into cropping systems has long been a staple of sustainable cropping systems. More recently, molecular techniques have been used to improve biological N fixation efficiency, as well as introducing biological N fixation into non-leguminous crops (Eskin et al., 2014; Goyal et al., 2021). Pimentel was a strong proponent of expanding legume-based crop rotations in modern production systems (Pimentel et al., 2005), but he also cautioned of trade-offs associated with genetic engineering (Paoletti & Pimentel, 1996; Pimentel, 2001; Pimentel & Ali, 1998). Today, a wide array of biofertilizers and biostimulants are available, principally to promote the fixation of atmospheric N but also to increase plant availability of insoluble P forms (Soumare et al., 2020). While the legitimacy of biological amendments warrants healthy skepticism (O'Callaghan et al., 2022; Owen et al., 2015), there is reason for optimism in their potential to harness natural microbiological processes to improve agricultural nutrient cycling (Busby et al., 2017).

The Haber–Bosch process serves as the foundation of modern commercial N fertilizer production, converting inert elemental N from the atmosphere into ammonia. Pimentel was an early and ardent critic of agriculture's dependence upon this energy-intensive process (Pimentel et al., 1973, 2005). Despite major gains in energy use efficiency, commercial ammonia production is estimated to account for 1% of human energy consumption, accounting for most of the energy use across all fertilizer production and significant greenhouse gas emissions (Menegat et al., 2022; Seyedehhoma et al., 2021). Major investment in the development of ammonia production alternatives promise to reduce net energy consumption (blue ammonia) or eliminate it (green ammonia), as well as promoting on-farm (aka, "point of use") fertilizer production, mitigating emissions associated with retail transportation networks (Driver et al., 2019; Ornes, 2021).

Despite his embrace of older systems and approaches to agricultural management (Kleinman et al., 1995; Pimentel et al., 1973), as well as his caution of overselling the potential for technology to solve agriculture's grand challenges (Pimentel et al., 1993), Pimentel was a proponent of change in many forms, including in agricultural technology and practice (Pimentel et al., 1982). The production of P fertilizers, derived primarily from the acidulation of mined rock phosphate, has come under intense scrutiny over the past decade following the recurrence of concerns over its long-term scarcity (Cordell & White, 2011; Jarvie et al., 2015). A myriad of processes have emerged in recent years to recover P from waste streams and conversion into forms better suited for agricultural production (e.g., mine tailings, industrial by-products, post-harvest wastes; Cieślik & Konieczka, 2017; Mayer et al., 2016; Tarayre et al., 2016). However, many of these post-recovery products fail to offer the quality (nutrient density, stoichiometry, purity) standard in commercial fertilizers and required of modern crop production, pointing to the continued need for technologic development. Even so, the primary limitation to adoption of these technologies continues to be comparatively high cost (Law & Pagilla, 2019; Molinos-Senante et al., 2011; Nättorp et al., 2017) despite major investment by governments that have facilitated progress, as well as important case studies on how to introduce P recovery processes to create circular agricultural economies (De Boer et al., 2018; Phos4You, 2022).

4.3 On-farm management

In addition to the need for systemic transformations beyond the farm gate, the establishment of efficient nutrient cycles begins and ends with on-farm management. The nutrient imbalances manifest at regional scales reflect enterprise management decisions (e.g., Reimer et al, 2020) and imbalances at farm and field scales resulting from systemic factors (e.g., Leytem et al., 2021). Across his career, Pimentel routinely employed case studies to elucidate the potential for significant change in management practices used on farms (e.g., Pimentel et al., 1993). As earlier mentioned, Pimentel advocated for diversified cropping systems that include legumes and help to lower fertilizer N inputs, thereby improving farm-gate nutrient balances (e.g., Pimentel et al., 2005). Notably, Pimentel et al. (1987) identified no till as a key to soil conservation, a practice that is widely advocated to improve soil organic matter, rainfall infiltration, and other important properties influencing nutrient cycling but not without site-specific constraints and trade-offs (Haddaway et al., 2017; Kleinman et al., 2022a; Ogle et al., 2019).

A myriad of management practices either directly, or indirectly, improve nutrient use efficiency on farms (Rotz et al., 2005). Implementation of agronomic and animal production practices aimed at improving on-farm nutrient management is complicated; adjustments to on-farm management have ripple effects that are acutely felt by agricultural producers, affecting both adoption and outcomes of adoption (Liu et al., 2018; Prokopy et al., 2008; Smith et al., 2018). In animal agriculture, the array of management decisions begins with decisions influenced by veterinarians, nutritionists, and others focused on animal health and productivity (Harrison et al., 2012), involves clear trade-offs (Beukes et al., 2019), includes investments in expensive infrastructure, such as barns and manure handling/storage systems (Kleinman et al., 2019), and can occur under highly regulated conditions that limit options (Kaye-Blake et al., 2019). In crop production, concepts such as the “4 Rs” of nutrient stewardship (Johnston & Bruulsema, 2014) seek to educate producers on options, often provided as prescriptive menus (https://nutrientstewardship.org/4rs). Not surprisingly, many conventional management practices remain firmly rooted in farming systems long after preferred alternatives for soil conservation and nutrient use efficiency have been developed.

Many on-farm nutrient management improvements can be tied to new technologies and data-based decision support tools that collectively fall under the umbrella of agricultural precision management (Monteiro et al., 2021). The proliferation of precision management technologies, favoring producers in wealthier economies, is as difficult to track as is the advance of the information technologies and computing systems that often underpin them. Again, Pimentel offered healthy skepticism toward viewing technology as a panacea, and he was aware of trade-offs (Pimentel et al., 1982). However, the application of precision management to on-farm fertilizer decisions offers clear opportunities to include multiple factors, including nutrient use efficiency and environmental outcomes (Sapkota et al., 2013; Hedley, 2015). Indeed, precision management has naturally entered the realm of agricultural conservation, now termed “precision conservation” (Delgado et al., 2017).

Table 1 Benefits, costs, concerns, sources and solutions related to global nutrient distribution

Nutrient redistribution
Benefits—Human prosperity (addresses the unequal distribution of nutrients across the globe that is needed for food, fuel, fiber and forage production)
Costs—Environmental (surface water eutrophication, global warming potential, drinking water pollution, disruption of ecosystem stoichiometry)
Concerns—Social (inequitable distribution of fertilizer nutrients)
Sources of fertilizer nutrients
N—principally by Haber–Bosch process, biological fixation, green and animal manures
P—principally by mining geologic P and recycling animal manure
A partial list of needed solutions
Technology—Green and Blue ammonia production
Technology—Best crop farming practices (4 "Rs" of nutrient application- Right rate, Right form, Right Placement, Right timing; Cropping systems to improve nutrient use efficiency, biological N fixation)
Technology—Best livestock farming practices (ap)
Technology—Nutrient capture from waste streams (animal and human)
Technology—Efficient fertilizers that are balanced to meet crop demand
System—Integration of crop and livestock farming (manureshed management)

5 Conclusions

History has repeated time and time again the knowledge that conservation of soil and water resources is the foundation of the sustainability of human civilizations. Pimentel's focus on systematic evaluation of modern agricultural systems and related concerns of energy, water, and soil conservation is the type of scientific and societal thinking needed to address the seemingly incongruent issues—increased agricultural production to feed, clothe, and fuel and growing population and mitigation of adverse ecological and economic impacts of off-farm N and P loss. Pimentel's willingness not to settle for status quo, to offer controversial alternatives, and to confront uncomfortable topics should be celebrated and critically evaluated. As humankind struggles to make necessary progress in balancing increased agricultural production and mitigating and correcting adverse ecological and economic impacts (Table 1), David Pimentel's legacy and contributions provide valuable insight to agriculture's wicked nutrient challenge.

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Data availability Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

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