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Review: Closing nutrient cycles for animal production – Current and future agroecological and socio-economic issues

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ABSTRACT

We face an urgent and complex challenge to produce large amounts of healthful animal and plant foods for an estimated 10 billion people by 2050 while maintaining essential ecosystem services. To compound this challenge, we must do so while not further degrading our environment and conserving essential nutrients such as copper, magnesium, phosphorus, selenium, and zinc that are in short supply for fertilization. Much good research has been done, but to meet this challenge, we need to greatly increase on-farm and watershed-scale research including on-farm evaluations and demonstrations of the putative best combinations of stewardship techniques over multiple years in real-world settings, which are backed by data on nutrient inputs, soil, air, and water chemistry (fluxes) and water discharge. We also need to work with farmers, specialists, and generalists in highly creative interdisciplinary teams that resist forming silos and that use combinations of techniques linked to agroecology and industrial ecology in combination with state-of-the-art engineering. Some of these research and demonstration farms need to be in catchments prone to pollution of aquatic and terrestrial ecosystems with nitrogen, phosphorus, and other nutrients. Some promising approaches include mixed crop-livestock systems, although these alone may not be productive enough without updating to meet the dietary needs of an estimated 10 billion people by 2050. Other approaches could be state-of-the-art multi-trophic production systems, which include several species of plants integrated into production with vertebrates (e.g., ruminants, pigs, poultry), invertebrates (e.g., insects, earthworms) and fish, shrimp, or crayfish to utilize wasted feed and excreta, and recycle nutrients back to the animals (via plants or invertebrates) in the systems. To cut costs and increase desirable outputs, we must recycle nutrients much better within our food production systems and produce both animal and plant foods more efficiently as nutrients cycle through systems.

Implications

Over the next 10–30 years, major policy changes will likely occur in food systems of developed nations, as consumers, industry, and policymakers become more aware of the challenges and changes needed for sustainable food systems. Agricultural systems will have to conserve and better recycle nutrients, use external inputs more sparingly, and reduce pollution of air, water, and land. Fertilizers that are upcycled from waste streams will have to become more common. More complex systems may produce multiple species of animals, including combinations of terrestrial and aquatic animals, and diverse species of crops that better recycle nutrients. Regenerative agricultural practices will need to expand rapidly to improve soil health and fertility, and improve efficiency of nutrient use in order to meet the grand challenges of feeding an estimated 10 billion people by mid-century in a sustainable manner.

Introduction

We make a case in this review for the need to transform conventional animal and plant food production, but this is impossible unless we first transform how we see ourselves, our relationship with one another and the environments we inhabit. This thinking was fundamental in cultures when most people were involved in food production and had a strong connection to the land. Over a hundred years ago, American professor F.H. King wrote ‘Farmers

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of Forty Centuries – Organic Farming in China, Korea, and Japan'. In the introduction, he states: "Again, the great movement of cargoes of feeding stuffs and mineral fertilizers to Western Europe and to the eastern United States began less than a century ago and has never been possible as a means of maintaining soil fertility in China, Korea or Japan, nor can it be continued indefinitely in either Europe or America. These importations are for the time making tolerable the waste of plant food materials through our modern systems of sewage disposal and other faulty practices; but the Mongolian races have held all such wastes, both urban and rural, and many others which we ignore, sacred to agriculture, applying them to their fields."

While nature has introduced great biodiversity into ecosystems, modern farming systems are adamant on simplifying production to single species of crops or animals in separate production systems (Watson et al., 2019). Simplified systems may be productive in the short run, but they make it difficult for farming systems to recycle nutrients and be sustainable in the long-run. In the long-run, simplified systems go against the five principles for sustainable food and agriculture: (1) improving efficiency in the use of resources; (2) conserving, protecting, and enhancing natural ecosystems; (3) protecting and improving rural livelihoods, equity, and social well-being; (4) enhancing the resilience of people, communities, and ecosystems; and (5) promoting good governance of both natural and human systems (FAO, 2019). Raising awareness of 'traditional' wisdom among consumers, producers, scientists and policymakers would help to restore production systems that value biodiversity and promote self-sustainability through raising multiple crops in rotations that integrate multiple species of livestock, and in some cases in combination with aquaculture (e.g., rice-duck-fish farming in Southeast Asia).

Many people now question meat and dairy production and consumption in a world of nearly eight billion people with growing awareness of widespread human and environmental health problems (Frazao, 1996; Steffen et al., 2015; Alexander et al., 2016; Fanzo et al., 2020). We now use over a third of the Earth's land surface and over 75% of the world's freshwater supply for crop and livestock production (IPBES, 2019). Intensive forms of livestock production have been and will continue to be challenged over concerns for animal welfare (Manteca et al., 2008; Provenza et al., 2019), for adding to antibiotic and antifungal resistance (Spellberg et al., 2016; Hoelzer et al., 2017; Fisher et al., 2018), and for transmission of disease such as coronaviruses (Jacobs et al., 2020) to people (Graham et al., 2008). While these concerns will probably also influence future livestock management, for this review, we identify and describe approaches that could help close nitrogen (**N**), phosphorus (**P**), and other nutrient cycles for intensive and semi-intensive livestock production systems of high-producing species as well as related challenges and trends for the next two to three decades. The need for changes to reduce reactive N pollution alone is clearly urgent (Uwizeye et al., 2020).

In the distant past, carbon (**C**), N, P and other nutrients were coupled and considered to be recycled better in agroecosystems because integration of crop and livestock production was common and manure was a primary source of nutrients for crops (Watson et al., 2019). However, there was some pollution of N and P (and C loss) into air and aquatic systems with these mixed farming systems, especially when managed improperly (e.g., ammonia emissions from excreta, soil erosion from tillage or excessive livestock stocking rates, and/or inappropriate type of livestock for particular landscapes; Wang et al., 2017). However, livestock numbers were generally lower in the first half of the 20th Century and earlier so it is difficult to determine, without more research, how much difference mixed farming systems could make now with more livestock. A recent study by Noll et al. (2020) suggests that mixed organic production systems have similar losses of reactive N species (ammonia, nitrate, and nitrous oxide) per unit of N as conventional systems, except organic beef production, which lost more per unit N or per unit product. Moreover, there have been very few multi-year water quality studies comparing mixed crop-livestock farming with non-mixed farming on the same soil and landscape to determine if N and/or P lost from mixed farming systems are lower than for non-mixed systems (Faust et al., 2017). Yet, there is some evidence that mixed crop and livestock production that manages all resources for more coupling of C, N, and P is better for soil health and nutrient cycling especially if perennial pasture with a diverse mixture of plant species is rotated with arable annual crops (especially using no-till cropping and including cover crops), and only moderate removal of vegetation by livestock is allowed. Lin et al. (2016) found that an organic mixed farming system in southern Germany with an intensive N cycle between soil, plant and animal components had accumulation of soil organic N, the highest N-use efficiency and the lowest N surplus compared to two arable cropping systems. Assmann et al. (2017) observed that long-term integrated crop-livestock systems in southern Brazil enabled more constant and efficient nutrient cycling because animal, pasture, and crop residues release nutrients at different rates. The authors found that the greatest rates of total P and K release were from pasture and dung residues under light grazing intensities. They also found that about 25 kg P/ha and about 155 kg K/ha were cycled in an integrated soybean-beef cattle system, which they considered desirable for the mineral-deficient clayey Oxisol soil. Denardin et al. (2020) observed that rice yields were higher with a rice-cattle integrated system with winter grazing of annual ryegrass and no-tillage rice production compared to conventional rice monocropping with tillage and winter fallow. Franzluebbers (2018 and 2019) found that cornfields with minimum tillage, multi-species cover crops, and animal manure amendment had greater soil biological activity, greater soil health and soil microbial biomass carbon, and greater N mineralization; thus they needed less synthetic nitrogen fertilizer. This evidence suggests that air and aquatic systems could have less N pollutants if livestock and crop production are integrated into systems with less mineral fertilizer use and in a manner that includes cover crops and perennial vegetation (with legumes) rotated with arable crops, which are grown with minimal tillage. These combined practices build up organic matter and various types of organic carbon in soil. With increasing simplification and intensification of farming systems, nutrient cycles have become uncoupled in many farming systems across the globe.

Although mixed or integrated crop and livestock production has potential to improve nutrient use efficiency while reducing negative externalities of farming systems (Kronberg and Ryschawy, 2019), it is not a panacea for completely closing nutrient cycles and improving soil health (Liebig et al., 2017). Problems such as soil compaction, uneven distribution of nutrients from excreta, and poor synchronization of nutrient availability with crop needs can occur. However, manure is often not managed ideally on farms that produce only livestock because it is typically considered more of a costly problem than a valuable resource and is usually moved only short distances to farmlands. Moreover, the flow of nutrients in manure from animal-only farms tends to be one-way with nutrients in manure not returning in animal feeds as there is little if any nutrient cycling between animal- and crop-only farms (Nowak et al., 2015).

Any form of farming can be managed poorly; however, farms that produce only arable crops often apply excess mineral fertilizers (unless precision fertilization is used) rather than manure—which can be applied precisely too— (Moshia et al., 2014; 2015) and may not time fertilizer application well with crop needs. In addition**,** N fertilizer may be applied in a manner that leads to N loss to volatilization or movement on fields from runoff, not grow ideal mixtures of cover crops, which can take up excess nutrients — such as nitrate— not used by arable crops (Thapa et al., 2018), till the fields frequently, and not use wide vegetated buffer strips between cropland and wetland to prevent water contamination from excess nutrients (Zhang et al., 2010). Consequently, soil and soil microbes are frequently disturbed, which harms soil health and generates significant air, aquatic, and terrestrial pollution associated with various forms of N and P fertilizer that require fossil fuels and associated emissions of carbon dioxide, nitrogen oxides, and other compounds to produce and transport. In contrast, no-till crop production and light or well-managed moderate grazing of cover crops by animals can push vegetation down near the ground to decompose while the livestock excrete many nutrients back to the soil (Haynes and Williams, 1993). Both these processes improve soil health and fertility thus reducing or eliminating the need for mineral fertilizers, and provides a return on investment for cover crops by feeding animals, which help farmers justify growing them (Roesch-McNally et al., 2017; LaCanne and Lundgren, 2018). Besides improving soil fertility with the abovementioned processes, symbiosis between crop roots and mycorrhizal fungi early in the growing season can allow for development of an extensive hyphal network in the soil that can provide nutrients including water to the crop such that mineral fertilizer is not needed and if used, it can prevent the low-cost (to the farmer) symbiosis with fungi from developing early in the growing season by reducing plant input for symbiosis (Grant et al., 2005). In regard to the animals in this type of system, small herbivores such as Muscovy ducks, geese and rabbits should be considered for grazing cover crops, and not just cattle or small ruminants, because small herbivores can compete much better with chickens and pigs for efficient meat production (Dickerson, 1978).

As social pressure regarding animal welfare and sustainability mount, it is possible that over the next 10–30 years, a greater proportion of citizens will want animals raised with more space and environmental variety, and with freedom of diet selection without use of antibiotics except for healthcare (Vigors et al., 2021). Improving human health will also be a high priority for several reasons including reducing healthcare costs. Many people will probably continue to eat meat, eggs and dairy products, which is scientifically justifiable because these foods contain a wide variety of nutrients (e.g., vitamin B_{12}, taurine, carnosine, cysteamine, creatine, anserine, various fatty acids and other bioactive peptides with potential health effects; Raiten et al., 2020; van Vliet et al., 2020) that are unlikely to be found in plant-based meat and dairy substitutes (Vanga and Raghavan, 2018; van Vliet et al., 2020). For instance, beef alone contains an expected >40 000 unique compounds (FoodDB, 2020) and we are likely only scratching the surface with our understanding of the complexity of the 'food matrix' and its influence on human health (Barabási et al., 2020; van Vliet et al., 2020). Moreover, studies show the agroecological importance of integrating livestock with forage and arable crop production (with less tillage) for improving soils, nutrient cycling, and agricultural sustainability (Kronberg and Ryschawy, 2019; Moraes et al., 2019; Lemaire et al., 2019; Denardin et al., 2020). Incentivizing such practices through community-based initiatives, and institutional and governmental support, is an important strategy to produce more products per unit land, thereby enhancing food security (Sulc and Tracy, 2007; Mbow et al., 2019).

In this review, we address the great challenge of trying to close nutrient cycles for intensive and semi-intensive livestock production with special focus on N and P. The challenge of improving soil health is an important part of this (Lehman et al., 2015; Meena et al. 2017). We take an integrative approach to intensive and semi-intensive meat, egg, and dairy production, and attempt to add ideas to the literature that expand the discussion beyond excellent papers by Withers et al. (2015a and 2015b)—who proposed a five-point framework to improve stewardship of phosphorus and other scarce nutrients and many excellent 'green' ideas—and Dumont et al. (2012 and 2020), who argued for using agroecology and industrial ecology to reduce environmental impacts of animal production and adding diversity to animal production systems. An integrative approach is also needed to assess risks and benefits from various livestock policies to help minimize unintended consequences. For example, while the compound 3-nitrooxypropanol can lower enteric methane emissions from cattle, it can also increase urea-N levels in animals (Melgar et al., 2020), which could lead to more urea excretion and more ammonia and/or nitrous oxide emissions from soil or manure (Mosier et al., 1998; Powell et al., 2011; Powell and Wattiaux, 2011; Duval et al., 2016). Furthermore, feeding more grain to young beef cattle with genetic potential for fast growth can increase their growth rate, reduce the amount of methane they produce before slaughter (compared to grass-fed cattle) and perhaps increase the net profit from producing them (if grain is inexpensive). However, feeding more grain may also increase the amount of N and P applied in fertilizers to grow more grain and some of this N and P may be lost from the land and pollute air and water. These two examples illustrate the need to carefully consider trade-offs.

Lovelock (2015 and 2019) warned us earlier while Bradshaw et al. (2021) recently reinforced the notion that future environmental conditions on Earth will be much worse than most people currently believe. Bradshaw et al. (2021) argued that the scale of the threats to life on Earth is so great that it is difficult to grasp—even for experts—and that our political and economic systems are not prepared to handle the predicted disasters. Therefore, extraordinary responsibility is placed on scientists to communicate these urgencies candidly and accurately to all non-scientists including those in government, business, and the general public. Hagens (2020) has similar concerns and argues that we are not prepared financially (too much debt) and are far too dependent on fossil fuels to satisfy our huge and growing appetite for energy given the grand challenges we will have to address to maintain the projected eight to eleven billion people on our planet. Hagens (2020) argues that 7.7 billion people are acting like a superorganism that is unable to alter its behavior for its own long-term well-being. Others have argued that the primary limitations on significantly reducing N and P pollution from livestock production are not the science and engineering, but rather the nature of human beings, the ethos of our societies, and their politics, policies, and economics (Berry, 1977; Gordon et al., 2017; Lovelock, 2015 and 2019). Therefore, we also discuss these aspects relative to how we might improve animal production systems to make them less polluting and more effective in their use of N, P, and other nutrients.

Intensive animal production systems – Modifying existing systems, adding new systems and learning from natural systems

Intensive and semi-intensive animal production systems can take many forms, including those used much less now than in the past. We can gain valuable knowledge from studying sustainable organic systems such as those used long ago and for thousands of years in China, Korea, and Japan (King, 1911) and from evaluating much more recent regenerative systems that are not capital intensive, but have multiple animal species raised in synergistic ways on pastures for part of the year. Examples in the US include Polyface Farm in Virginia, which raises cattle, pigs, turkey, rabbits, and chickens for meat and eggs (Salatin, 2011); Brown's Ranch in North Dakota, which raises similar types of livestock and grows arable and cover crops (Brown, 2018); and Apricot Lane Farms in California, which also raise many species of livestock integrated with production of more than 200 varieties of fruits and vegetables (Apricot Lane Farms, 2020). Other examples include Asian systems that integrate rice, duck, azolla, and fish in Japan (Furuno, 2002). For example, Cheng-fang et al. (2008) found that, compared to rice alone, the presence of ducks and fish decreased N losses via ammonia volatilization, nitrous oxide emissions, leaching of nitrate and total N (55.0, 52.6 and 51.4 kg N lost/ha for rice only, rice-fish and rice-duck, respectively). There are similar examples of this type of integration using rabbit and fish or duck and fish in India and Thailand (Mahadevaswamy and Venkataraman, 1988). An integrated rabbit, fish, and rice system in Rwanda is an example where Nile tilapia (*Oreochromis niloticus*) recovered 19–38% of N and 17–34% of P of the total N and P inputs in the pond water, after which the pond effluent was used to irrigate rice produced without inorganic fertilizers (Taboro, 2011). Integrated rice-animal farming can also help to remove health threats to local communities, such as the consumption of mosquito larvae by fish in rice fields, which reduces incidence of malaria in local farming communities (Lacey and Lacey, 1990).

In comparison to current conventional agriculture that relies on mineral fertilizers, an important feature in the non-capital-intensive system described above is potential improvement by the use of manure and animal-plant integration. However, given the complexity of interactions in regard to manure (Rotz, 2004), exacting management of each system is critical. Alternatively, some new capital-intensive production systems use sophisticated equipment, such as robotics, to reduce human labor. One example is Ynsect's mealworm production combined with aquaculture shrimp or fish production (Ynsect, 2020), which uses mealworms as shrimp and fish feed. A critical aspect of these production systems is synergy among two or more animal species such that there is potential for increased recycling of N and P as well as other nutrients within the production system. This does not imply that all production systems must have synergy among two or more animal species to recycle N, P and other nutrients well (nor does it guarantee that nutrients will be recycled). A beef cattle farm where all the forage and feeds consumed by animals are grown on the farm and the manure recycled back to the farmland may recycle nutrients well and be relatively sustainable. Garnier et al. (2016) found that French organic crop farmers using long and diversified crop rotations with alfalfa as the starter crop of the rotation followed by a cereal and a grain legume reduced N losses in surface water by half, and were as efficient as non-organic conventional farmers in regard to N yield, but had 21% less N protein exported with their organic rotations and 26% lower soil N inputs (with exogenous inputs only 11% of total soil N inputs). When the organic crop farmers could sell their alfalfa to dairy farmers and obtain manure, the mixed system was improved, and despite the lower cereal yield of the organic systems, the farmers' incomes were not reduced because their expenses were much lower (no mineral fertilizer or pesticides purchased).

However, given the relatively low meat production efficiency of beef cattle—including cradle-to-producer gate life cycle energy use, feed-to-food caloric flux, and protein and calorie retention of beef cattle compared to poultry, including herbivorous geese, rabbits, pigs, and some fish (Dickerson, 1978; Pelletier et al., 2011; Shepon et al., 2016; Fry et al., 2018)—the nutrients are probably not producing as much meat per hectare of land as they could if they were increasingly recycled through poultry, fish, or pigs. This is especially important for nutrients such as P that appear to have a limited supply (Withers et al., 2015b). However, we are not aware of any calculations of food production efficiency that take into consideration the very important ecological services that a diverse mixture of animals can provide in mixed crop-livestock systems following agroecological principles. These include nutrient fertilization with excreta, weed and pest control, and stomping cover crop material closer to the soil surface where a variety of invertebrate and microbial species can move the C, N, P and other nutrients into the soil. This more comprehensive ecological understanding of food production efficiency, which encompasses the vital roles that animals can play in improving agricultural sustainability, is unfortunately lacking but badly needed. Moreover, we need to heed the wisdom of Wendell Berry's words in his classic book *The Unsettling of America – Culture and Agriculture.* 'The exploiter is a specialist, an expert; the nurturer is not. The standard of the exploiter is efficiency; the standard of the nurturer is care. The exploiter's goal is money, profit; the nurturer's is health – his land's health, his own, his family's, his community's, his country's. Whereas the exploiter asks of a piece of land only how much and how quickly it can be made to produce, the nurturer asks a question that is much more complex and difficult: What is its carrying capacity? (That is: How much can be taken from it without diminishing it? What can it produce dependably for an indefinite time?)' We argue that for agriculture to be more sustainable and less polluting, farmers and ranchers must balance efficiency and profit with care and operate as 'efficient nurturers'.

While N fertilizer production is probably more reliable than P fertilizer production due to the Haber-Bosch process, industries use large amounts of natural gas and some coal to produce N fertilizer, resulting in large emissions of carbon dioxide, nitrous oxides and other pollutants. Thus, recycling nutrients is preferable irrespective of scarcity. While we are likely to eventually produce green ammonia N using solar or wind energy as well as bio-based P fertilizer (Eckelkamp, 2020), this N and P could still be mismanaged in a manner that pollutes, air, and water. This is also true with poorly applied manure or poor grazing management that allows for poor distribution of livestock across fields so regardless of the form of N and P, they need to be applied following up-to-date guidelines (e.g., injected with minimal disturbance to pasture or no-till crop field) and not in excess for plant needs (Maguire et al., 2011). Also, due to problematic potential occurrence of heavy metals, antibiotics and resistance genes in manure, which can be transferred to soil (Guo et al., 2018), integrated crop-livestock systems must be developed in a holistic or comprehensive manner that carefully evaluates and manages all aspects of complex agroecological farming systems such that no parts of the systems greatly harm other parts. A good example of this is the Brown Ranch in the northcentral US which uses very few external inputs, lets their livestock do much of the work via grazing much of the year (including cold winters), and appears to have good soil health and profitability (Brown, 2018; LaCanne and Lundgren, 2018; Fenster et al., 2021).

Common intensive, single-species, animal production systems and simple cropping systems, such as continuous maize or a maize-soybean rotation, tends to suffer from poor recycling of N, P, and other valuable nutrients as well as water pollution (Jarvie et al., 2015). Several practices can help reduce loss of N, P, and other nutrients, including precision agriculture technology (variable rate applications of mineral fertilizers to crops), engineered nanoparticles as fertilizers, reduced tillage, stimulating soil biota to enhance nutrient cycling, nitrification inhibitors, altering type and timing of fertilization, timing of forage cutting, altering type of pen surface material, reducing stocking rates and N and P levels in feed, as well as other technologies and approaches. However, they also need to be economically feasible for conventional non-integrated producers who are often marginally profitable. Consumers may need to accept policies that support the internalization of environmental costs (and thus pay higher prices for some foods), which have traditionally been externalized (Tegtmeier and Duffy, 2004) and tolerated or ignored. Moreover, consumers must understand that, while the "true cost" of food does not appear directly on their grocery bill, they are paying for these externalized costs in other ways (Pretty et al., 2001). For example, costs incurred by water delivery companies for cleaning water supplies including removal of nitrate and eutrophication management are passed onto their customers. Tolerating or ignoring environmental costs is becoming more difficult to do with the amount of food produced nowadays and the urgency to achieve more sustainable production systems (Bradshaw et al. 2021).

Ecological and economic concerns over widespread fertilizer use have prompted the development of sensing technologies to measure and monitor N and P throughout agricultural fields. Procedures to determine macronutrients within soils that have previously been limited for use in lab environments have been adapted for in-field, portable sensing applications. Non-destructive methods, such as near-infrared spectroscopy (**NIRS**), can be used for in-field evaluation of multiple macronutrients (Sinfield et al., 2010), along with other physical soil characteristics. Large databases of soil spectra are continuously being developed (Rossel et al., 2016) and further support the widespread use and adoption of visible and near-infrared spectroscopy sensing technologies, which can be deployed from ground or aerial vehicles. *In situ* soil sensors have long been used, but are becoming smaller, more energy efficient, more accurate, and come at lower cost, which is leading to potentially transformative approaches for on-farm soil testing at high spatiotemporal scales (Rossel and Bouma, 2016). More recent work has explored the development of biosensors for ion-specific detection and measurement of macronutrients in particular forms, for example, nitrites (Siontorou and Georgopoulos, 2016). These sensor systems ultimately generate high-resolution maps of N, P, and other macronutrients, which can be used to generate prescription maps for variable rate application or used in modeling crop nutrient productivity. Soil nutrient sensing, in its variety of forms, is becoming more accessible and can be adopted as a low-cost approach to better understand nutrient distribution, cycling, and uptake on-farm.

Other approaches to improve nutrient recycling for intensive animal production include (1) collaborative manure distribution among farms to farmland where manure is needed (Spiegal et al., 2020), and (2) modifying confinement- and barn-based production systems with technologies to remove nutrients such as P and trace minerals from excreta with approaches such as the MAPHEX (Manure Phosphorus Extraction) System (Church et al., 2018; 2020) or other P and N removal technologies, such as air scrubbers (Melse and Ognik, 2005; Melse et al., 2006; Yilmazel and Demirer, 2013; Yerushalmi et al., 2013; Szögi et al., 2015; De Vies and Melse, 2017; Georgiou et al., 2019; Montalvo et al., 2020; Bhambri and Karn, 2020), that make it more feasible to remove and recycle N, P and trace minerals for fertilizing arable crop fields and pastures. Using this new technology with existing forms of intensive animal production might make meat, dairy products, and eggs from confinement-based systems more expensive, but it may also reduce costs to improve environmental health that have been externalized for intensive animal production (Naylor et al., 2005). There are global companies that are advancing combinations of pollution-control technologies that could increase the cost of some functions while decreasing others.

As societies in some countries demand that animals be given more freedom of movement with less crowded conditions, expensive confinement systems such as those currently used to produce pigs may no longer be as economically viable. Moreover, if societies demand dairy cows to have a longer life than the abnormally short life many currently have (3–4 years in countries with high-producing dairy cows; De Vries and Marcondes, 2020), intensive dairy operations will have to adjust to survive. Therefore, we expect to see much greater development and use of combinations of confinement and pasture systems to meet demands of the public in the future. For example, animals may be confined closer together during winter, but given access to pasture and crop fields (crop residue from arable crops and/or cover crops) during or after the growing season. The pastures should ideally be mixtures of grasses and legumes that are not fertilized with N or P, and given the serious predicament we are in, we need to consider more innovative systems that, to the best of our knowledge, have not been thoroughly evaluated. We discuss aspects of conceptual and alternative systems below using integrated multi-trophic aquaculture as a model to reduce N and P lost from a food production system. For example, Wei et al. (2017) used a red alga seaweed (abalone feed) to remove dissolved N and P from water in Yantian Bay, China where fish are farm-raised, and determined how much seaweed would be needed to remove excess N and P generated from farmed fish production. Along with systems mentioned above, insects and/or fish could be produced in multi-trophic production systems with poultry, pigs and/or cattle, and their excreta used to either produce insect larvae or earthworms that are used as feed for both terrestrial and aquatic animals, which reduces the need for fishmeal or feeds produced with fertilizers and fossil fuels, while the residue from the invertebrate production is carefully returned to crop fields and pastures (Fig. 1). For example, the black soldier fly (*Hermetia illucens*) can grow well in dairy cow, pig, or chicken manure and remove 60–70% of P and 30–55% of N from these manures (van Huis, 2013; Zhou et al., 2013). The goal of these systems would be to reduce or eliminate the use of N and P fertilizers.

To further diversify, the aquaculture portion of the system could be made into an integrated multi-trophic system with fish, and extractive shellfish and seaweed that function as bio-remediators to utilize uneaten feed intended for the fish and/or fish excreta. A major advantage for sustainable intensification of such a system is that less efficient feed converters, such as cattle (Dickerson, 1978), can be combined with more efficient converters, such as poultry and/or fish and shellfish (Pelletier et al., 2011; Shepon et al., 2016; Fry et al., 2018), to improve overall production efficiency of the entire animal production system and recycle N, P and other nutrients through multiple animal species. For example, cattle, poultry, fish, shrimp, and insects may be produced more efficiently in an integrated system with insects and worms grown on composted mixtures of cattle manure, with poultry, fish, and/or shrimp consuming insect larvae, worms and plant-based feeds from crop residues. Although cattle do not convert grain into meat as efficiently as do chickens, nor are cattle as efficient at converting forage into meat as efficiently as rabbits (Dickerson, 1978), their manure may be very useful to improve soil health and fertility, and help grow some types of insect larvae and earthworms as bio-remediators and producers of high protein feeds (Hussein et al., 2017; Parolini et al., 2020). Insects such as mealworms and fly larvae can be used as nutritional feed for pigs, poultry, and fish, and have high content of digestible protein with high levels of essential amino acids as well as lipids, minerals, and vitamins (De Marco et al., 2015; Marono et al., 2017; Iaconisi et al., 2018). Integrated animal production systems may be worrisome in respect to disease transfer or somewhat distasteful to some people because they involve the use of animal excreta to grow insect larvae, earthworms or plants or bio-remediators such as sea cucumbers (Stenton-Dozey et al., 2020). While more research on multi-trophic animal production is certainly needed, as is the case for multi-trophic aquaculture systems (Rosa et al., 2020), several studies show insect larvae can significantly reduce pathogen content of manure (Erickson et al., 2004; Awasthi et al., 2020). Nonetheless, more research is needed on aspects of producing insects from manure in ways that make them safe as a feed source in all respects including hygienically (van der Fels-Klerx et al., 2018).

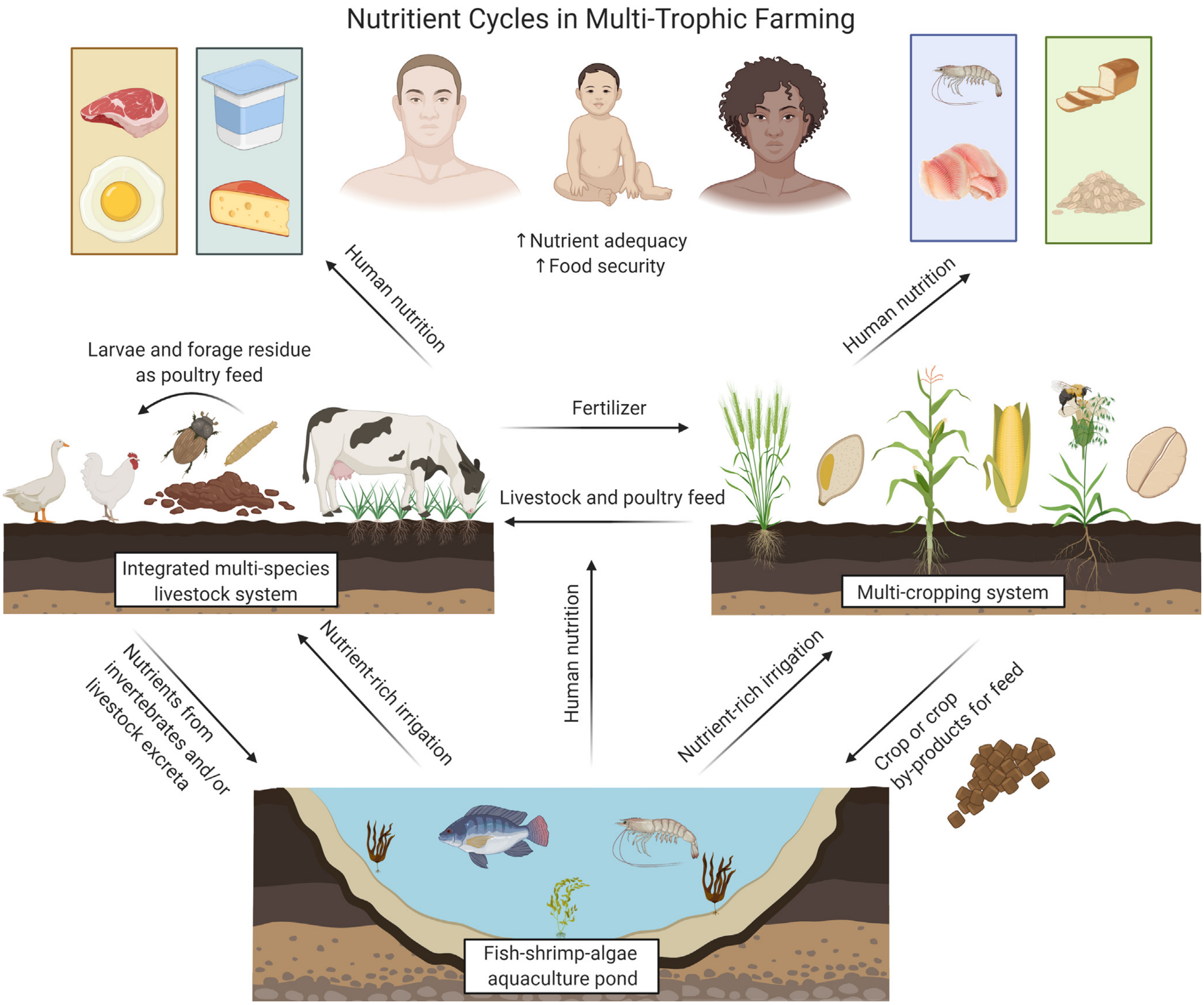

Fig. 1. A conceptual model for potentially linking terrestrial and aquatic animal production with plant production in integrated agricultural production systems.

We also need to develop N and P use efficiency ratios and do flow analysis for various types of food provisioning systems (Bai et al., 2016; Rothwell et al., 2020) so we can compare them easier and manage them better. For example, a flow analysis for P in a Northern Ireland food system found that P contained in livestock manure slurries, which were returned to farmland, exceeded crop and grass P requirements by 20% and were the largest contributor to annual excess soil P accumulation. We need the ratios and flow analyses for various crop-only systems, animal-only and mixed crop-livestock systems to inform management decisions.

Human behavior – A critical aspect for improving intensive animal production

Many people have argued that we will have to produce more animal-based foods with growing human populations and increasing demand and consumption of these foods. However, we lack evidence to comfortably believe that this is possible given the amount of environmental damage that has already occurred producing animal-based foods. With our current forms of intensive and semi-intensive animal production, we may be unable to increase production without crossing planetary boundaries, which are critical to maintaining resilient Earth systems, and consumers (especially in high-income countries) may reduce consumption of animal-based food in an attempt to improve environmental health (Leip et al., 2015; Steffen et al., 2015; Desmit et al., 2018). The same can be said for arable crop production, which has a very long history of environmental degradation (Montgomery, 2007; Sanderman et al., 2017). By nature, humans discount damages to our environment for short-term gains in productivity and wealth, and we lack evidence that we can greatly increase production of animal-based foods if this relies primarily on grain and soybean production, which we struggle to produce sustainably on a large-scale (Montgomery, 2007). Also, we are still trying to understand how people conceptualize policies and governance underpinning them, in order to introduce policy changes that are more effective (Fischer et al., 2011).

We recognize that (1) people are often not good at implementing conservation practices with a sustained effort over a long period to achieve desired results, although this is often necessary for success (Flaten et al., 2019), (2) changing our food production systems is made more complicated by not encouraging more local solutions to solve agricultural and water problems (Richter, 2014), and (3) more progress toward sustainability will be made by giving farmers flexibility to choose the approaches that work best for each farmer and each farm's situation, and that incentivize least-cost control practices to pollution-reduction strategies that use mixes of incentives and regulatory constraints like true cap-and-trade permit trading with economic incentives tied to environmental outcomes (Shortle, 2017). In order for change to occur, farmers need to conclude that regenerative agricultural practices can generate more income and greatly decrease their impact on the environment and there is some evidence to support this (Brown, 2018; LaCanne and Lundgren, 2018). While the importance of protecting the environment has long been recognized and substantial expenditures have been made on policies to reduce negative environmental effects of agricultural production, inefficiencies of current policy approaches that limit achieving environmental improvements are well-known. These inefficiencies are tied to the economic, social, cultural, political, and natural complexity of environmental problems, and will require engaging social and biophysical expertise to develop solutions that work ecologically, economically, socially, and politically (Shortle, 2017; Pretty et al., 2020). Lastly, research and development can help only if farmers have effective incentives to develop and adopt farming practices that improve environmental and human health (Dumont et al., 2020). To make production of animal-based foods more efficient and less polluting, societies in most countries will probably become convinced that they need to make it more difficult and expensive to degrade soils, air, water, plant, and animal communities. For example, grain-fed cattle may be as profitable to produce as grain-fed chickens when maize is cheap and environmental degradation associated with maize production are externalized, but if maize is more costly to produce and expensive to buy when grown with much less environmental degradation, then animals such as chickens, which utilize maize more efficiently than cattle, could become more profitable and more desirable to produce compared to grain-fed cattle. Therefore, more people could come to understand that requiring arable crops to be produced with much less environmental degradation is an essential step to improve the sustainability of animal production.

With a combination of significant changes, we may be able to sustainably produce enough nutritious and healthful food for 9–10 billion people by 2050, but only if we are willing to better understand human nature and better understand adaptive capacity of people (Mortreux and Barnett, 2017), and work to make the scientific approach to solving problems better understood and accepted. To assist with these changes, animal scientists need to understand and appreciate research by other scientists (and vice versa) including evolutionary biologists, primatologists, anthropologists, and psychologists who have all worked to help us understand human behavior (Wolpert, 2006). While doing so we need to keep the following worrisome comment by Francis Bacon in mind – "Man prefers to believe what he prefers to be true".

Deception is a universal feature of life within and among species, though self-deception may only occur with people (Trivers, 2010). Trivers' research suggests that the human unconscious mind hides true information from the conscious mind, which helps us understand how people can ignore or downplay environmental damage to focus on immediate success. Research by scientists who study primate and human behavior helps us understand many aspects of human behavior including intragroup cooperation and apparent irrational aspects of cooperative behavior and violation of norms of economic decision-making by foregoing maximization of individual benefit (Kappeler and Silk, 2017). These important considerations, which are relevant to feeding billions of people without destroying Earth's support systems, can help us understand the challenge of getting some groups of people to eat more fish, herbivorous ducks, geese, and rabbits when their prestige, wealth, reproductive success, and group cooperation are connected to beef, pork and chicken production and/or consumption.

More animal scientists need to focus on sustainable animal production and work more cooperatively with scientists and managers such as soil scientists, agronomists, biogeochemists, hydrologists, economists, engineers, human nutrition scientists, plant ecologists, rural sociologists, technology transfer/public relations specialists, and policy developers (Finley and Fukagawa, 2019). However, this is difficult to do because specialists have been rewarded for independent modes of research and/or development. Thus, they think their focus is more important than that of other specialists (Walker, 2019) and this problem is probably connected with self-deception. Oster et al. (2018) provide a relevant example of this in the European Union regarding an awkward definition of manure that, at least a few years ago, was limiting potential for generating chemical fertilizer from excess manure. So, we need leaders who, like Steve Jobs and Elon Musk, insist that their teams do not create silos or divisions that lead to an 'us versus them mentality and impede communication', which is a natural tendency within people. Instead, people need to be encouraged to see the 'bigger picture' and work for the success of the larger group.

Conclusion

We face significant pollution and environmental degradation problems associated with the intensive production of food-producing animals, and we are not currently dealing with these problems effectively. Some argue that sustainable farming is not practical or even possible in some places even with traditional extensive animal production and we may have to accept degraded waterbodies in some farming areas (Doody et al., 2016). While some eutrophic aquatic ecosystems may be difficult and take a long time to clean-up, drastically changing the type of animals produced may be the remedy in some challenging locations. For example, one complex system might include some extensive and some intensive production—a few cattle grazing a pasture with a mixture of plant species, with insect larvae and/or earthworms grown in cattle manure (perhaps mixed with wasted hay and straw), and chickens eating some vegetation along with insect larvae and worms, plus trout in aquaculture tanks eating larvae and worms with shellfish utilizing feed missed by the trout, and trout excreta with outflow from the tanks that are precisely put back into pasture soils (Fig. 1). Alternatively, the aquaculture system might be a recirculating system (Bergman et al., 2020).

We need to open our minds to new ideas and expand our knowledge and collaboration to improve our understanding of what we need to change in order to produce animal-based foods with fewer negative impacts on the environment. We need on-farm type research and farms that can serve as demonstration sites and ideally whole watersheds (catchments) where the putative best combinations of techniques are used and evaluated for multiple years in real-world settings (Frei et al., 2020). These need to be used aggressively to educate consumers and farmers (and industrial producers) so that they know what is possible and how it can be achieved. Some of these farms/production sites need to be in catchments that are the most challenging to prevent pollution of aquatic and terrestrial ecosystems with N, P and other nutrients. Reluctant farmers/producers and consumers will be more likely to support change when they hear about and see realistic examples of what is possible.

Ethics approval

Not applicable.

Data and model availability statement

Not applicable.

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Scott Kronberg wrote the initial draft of the manuscript and **Fred Provenza**, **Stephan van Vliet** and **Sierra Young** made important improvements to it.

Declaration of interests

All authors consume omnivorous diets.

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