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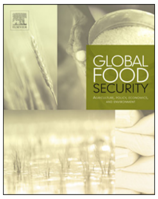

Science-based intensive agriculture: Sustainability, food security, and the role of technology

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1. Introduction

Sustainable agriculture describes crop management approaches that address the interdependent goals of increasing or at least maintaining yield while protecting the environment, conserving natural resources, and slowing climate change. Numerous authors have espoused limiting synthetic fertilizer and pesticides and promoting organic agriculture (Lechenet et al., 2014; Martinez-Alcantara et al., 2016; Muller at al. 2017), less meat consumption (West et al., 2014; Poore and Nemecek, 2018; Springmann et al., 2018), or combinations of these strategies as viable solutions to achieve those goals, thereby improving agricultural sustainability.

A closer look, however, reveals weaknesses in these strategies. Organic agriculture, for instance, has often been promoted as more sustainable than conventional agriculture. While organic production (i.e. without use of synthetic fertilizers and pesticides as used in conventional agriculture) may be an option for farmers or food companies to achieve greater profit for their products and offer consumers another choice, asking organic agriculture to feed a growing global population would come with significant tradeoffs.

Similarly, efforts to reduce global meat consumption may also have limited effectiveness. We argue that the goal should not be to drastically reduce animal agriculture but rather to continually improve it, given that animal agriculture provides economic viability to all types of farmers– especially to millions of smallholder farmers (SHFs)– and serves as a critical source of nutrition.

Often overlooked in sustainable agriculture discussions are the many contributions of sound science and innovation that can improve environmental performance of intensive agricultural systems and move them towards sustainability goals, food security, and improved farmer livelihoods. Technologies of modern agronomy, plant and animal breeding, and biotechnology have contributed to feeding the world, reducing negative environmental impacts, and mitigating climate change. The adoption patterns of these technologies highlight the role that market forces and risk management play in farmer decisions about which combination of crop and soil management practices to implement. The long-term trend of U.S. crop prices paid to farmers over the past 100 years has been a declining, inflation-adjusted real value (Sumner, 2009). After the run-up from 2008 to 2012, prices have fallen back into a downward trend (Fig. 1; Zulauf, 2016). Thus, any discussion of sustainability must consider these economic factors and how farmers would fare financially under recommended interventions.

The aims of this review are, therefore, to 1) develop a more complete understanding of the complexities of sustainable agriculture and sustainable intensification, and how this applies both to farmers and consumers in a time of climate change; 2) identify major challenges for intensive agricultural systems; and 3) offer ideas on an evidence-based path forward for greater sustainability of agriculture that builds on past

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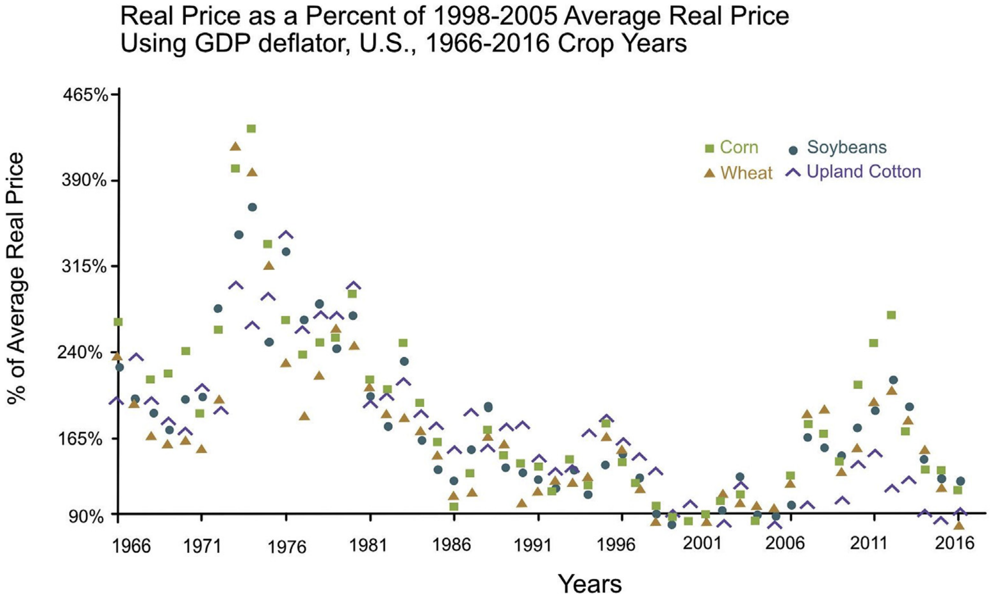

Fig. 1. Historical commodity price trend (recreated from Zulauf, 2016).

success, for which implementation is already underway and new technologies are being developed for the benefit of both farmers and consumers. While it is important to explore a variety of agricultural initiatives to improve sustainability, there is potential for real harm when these initiatives create a false sense of accomplishment and subsequent complacency, when certain technologies or systems are advocated or dismissed without examining the evidence, or when finite resources are directed to inconsequential efforts. We contend that the goal of achieving agricultural sustainability, regardless of the farming system, should be based on science and objective, risk-based decision-making.

2. The complexities of sustainable agriculture

For agricultural management and breeding approaches to be considered sustainable, they should have the potential to achieve four often-competing objectives. These objectives were previously developed through an extensive investigation and published in a review paper (Sayer and Cassman, 2013). The four objectives are:

1) Ensure production of an adequate food supply
2) Alleviate poverty
3) Achieve better health and nutrition for a growing population
4) Conserve natural resources

The objectives hold meaning for agricultural systems worldwide, regardless of geography or level of prosperity, and this broad relevance also aligns well with the Sustainable Development Goals established by the United Nations General Assembly in 2015 (United Nations Sustainable Development Programme, 2016). Yet this broad relevance also tends to create confounding paths forward in which progress on one objective may negatively impact another. An example is given by one of the scenarios in Frank et al. (2017) that results in a reduced rate of global warming – in this case by applying a uniform carbon price to agriculture and increasing soil carbon sequestration on agricultural land. As the authors note, however, that would also result in "undernourishment of 80–300 million people by 2050." While the scenario would help meet objective four – conserving natural resources - it would be devastating for the millions of people who would not achieve objectives one through three.

Another example of the difficulty in assessing sustainability approaches with confounding paths forward can be seen with organic agriculture. In evaluations where yields of organic production are found to be equal to conventional production (utilizing synthetic fertilizers and pesticides), the organic material supplying the nitrogen (N) has come from outside the immediate cropping system, and most often from other cropped areas (Kirchmann et al., 2008; Martinez-Alcantara et al., 2016). Thus, as Rosegrant et al. (2014) state, "Organic agriculture can make a substantial contribution to the global food supply only at the cost of expanding the global cropped area" because organic yields are substantially smaller than can be obtained with conventional management. An example of the unsustainability of this system is in Africa, where most smallholder farmers (SHFs) practice organic agriculture (though not by choice; many do not have access to inputs). Increased population density is driving continuous cultivation on tropical soils in countries with limited arable land (Jayne et al., 2014). With no access to agronomic inputs, like synthetic fertilizer, soil degradation and a low level of productivity mires farmers in poverty (Tittonell and Giller, 2013). These farming systems are not long-term sustainable, for either the environment or the farmers. Only a few African countries – Mali, Zambia, Ethiopia – are making consistent progress towards food security goals (van Ittersum et al., 2016). Some might argue that "organic", with its strict ban on the use of nearly all synthetic pesticides and herbicides - is based on ideology, and "mingling ideology and science compromises science, misleads the public, and hinders efforts to sustain agriculture" (McGuire, 2017).

Growth in emerging and recently emerged markets has led to some of the greatest constraints for meeting sustainability objectives, especially in Asia and Africa where a combination of population growth and a rapidly growing middle class has steadily pushed grain, oilseed, meat and dairy consumption to new highs. China has increased its consumption of animal products such that it now accounts for over half of the world's pork consumption and accounts for 62% of the world's soybean imports (USDA-ERS, 2017), with over 90 million metric tons (MMT) of soybeans imported in 2018, up from just over 50 MMT in 2011 (OECD-FAO, 2018). In India, which has the highest percentage of vegetarians in the world, growth in meat and fish consumption is projected to become among the highest in the world by 2027, and dairy consumption is forecast for 50% growth from an already high base through a combination of population growth and per capita increase in consumption. A different story is evolving in Sub-Saharan Africa (SSA), where per capita meat and fish consumption is forecast to decline due to rapid population growth, but *total* consumption is expected to increase by close to 30% by 2027 based on population growth alone (OECD-FAO, 2018).

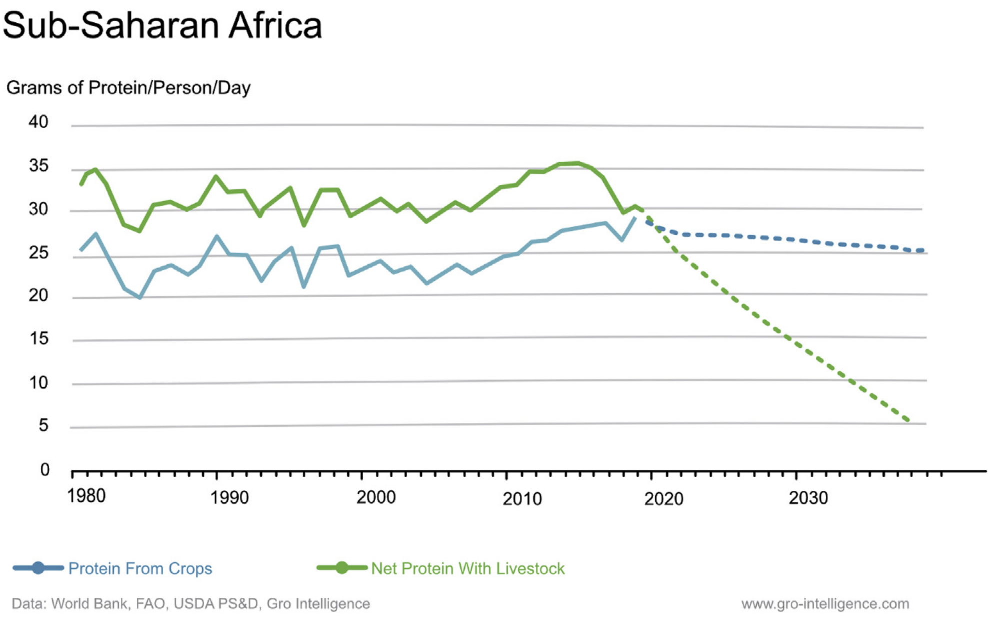

Fig. 2. Protein per person per day forecast in Sub-Saharan Africa (https://gro-intelligence.com/insights/which_countries_have_a_protein_shortage**).**

While curbing demand for animal food products has been offered as a key component of scenarios to reduce pressure on sustainability measures (Muller et al., 2017; Poore and Nemecek, 2018; Pretty et al., 2018; Springmann et al., 2018), the applicability of that recommendation should vary with economic conditions. While maintaining availability of a high quality and affordable protein source is important to health and nutrition regardless of low or high income country, moderating consumption of ruminant animal meat may make sense for high-income countries. For many in emerging markets, animal products represent a much-needed diversification of diet and improved nutrition (Randolph et al., 2007; White and Hall, 2017), and offer a greater means of economic viability through sale of livestock and poultry products (Mellor, 2017; Randolph et al., 2007). The situation in SSA, with the highest population growth of any region, is a case in point: current low levels of protein consumption and projections for even lower availability (Fig. 2; Gro-Intelligence.com, 2018) are not sustainable from a human health standpoint and the situation is not morally acceptable. Increased availability of protein from any source, and of vitamins and minerals available from a balanced diet that includes animal products, will be critical to the prosperity and health of over 2.5 billion Africans by 2050. And as Mellor (2017) states, for low and middle income countries, "the anti-livestock position is grossly misplaced." Furthermore, we note that even if animal agriculture were completely eliminated in the United States, the reduction in greenhouse gas (GHG) emissions would be minimal at only 2.6% (White and Hall, 2017).

Despite the complexity involved in trying to develop an approach capable of meeting all four objectives simultaneously, tremendous progress has been made toward sustainable agriculture in the past 30 years. There has been a long-term, upward trajectory in global yields of major food crops as farmers have adopted new technologies that improve productivity and in many cases also increase efficiencies in use of water and nutrients (CAST, 2019). Today's hybrid maize production in the U.S. Midwest is more resilient to stress (Atlin et al., 2017; Boyer et al., 2013; Gaffney et al., 2015); high yield environments are expanding in North America (Assefa et al., 2016); and record or near record U.S. maize and soybean yields have been achieved in almost every year since the 2012 drought (USDA-ERS, 2017). Based on work by Ciampitti and Vyn (2014) and Woli et al. (2016), we know that modern maize hybrids (since 1990) in North America have greater "physiological efficiency" in converting resources to economic yield. These hybrids utilize nutrients more efficiently and attain greater grain yield relative to the amount of N taken up from the soil (CAST, 2019). This conclusion is further supported by recent agronomic research with updated crop and soil management practices that optimize performance of modern hybrids (Assefa et al., 2016; Heggenstaller et al., 2018; Kitchen et al., 2017; Sawyer et al., 2006). Maize grain yield continues to climb as applied N rate has flattened since the 1980s (Fig. 3; Haegele et al., 2013). High-yielding cropping systems have another important benefit: Burney et al. (2009) estimate that from 1961 to 2005, up to 161 gigatons of carbon emissions have been "avoided" due to higher yields.

Improvements in irrigation technologies and management have afforded opportunities for increased irrigation efficiencies and overall water use efficiencies. Advances in irrigation technologies, including efficient low pressure center pivot irrigation and micro-irrigation; weather-based and soil moisture sensor-based irrigation scheduling; decision support tools integrating weather, soil and crop information; and improvements in overall crop water productivity (resulting from integrated crop management involving improved genetics, fertility management, integrated pest management and irrigation management), have resulted in higher crop water productivity (harvested yield per unit of water input). Hence, notable increases in crop yields are achievable without increasing water use (Wagner, 2012). Surveys of U.S. agriculture indicate a shift to more efficient irrigation systems over recent decades, contributing to reduced average per-water application rates per hectare across crops and regions (USDA-ERS, 2019).

When factoring in the nutritional needs and wellbeing of a growing and diverse population of farmers and consumers, meeting the fourth objective - conserving natural resources – is a formidable challenge. It includes a broad spectrum of soil health, water quality and conservation challenges including maintaining biodiversity of flora, fauna, and natural landscapes. The good news is that recent research and technological development are addressing these challenges; improved agricultural productivity through technological change is long-term positive for the environment (Mellor, 2017).

Managing agriculture for optimum productivity and sustainable land use is our best option for conserving natural resources and mitigating and adapting to climate change.

Progress is not limited to the U.S. As recently pointed out (Zaidi et al., 2019), the many exciting advances in new technologies for plant breeding, such as genome editing, are becoming increasingly accessible to the developing world. For smallholder farmers in developing

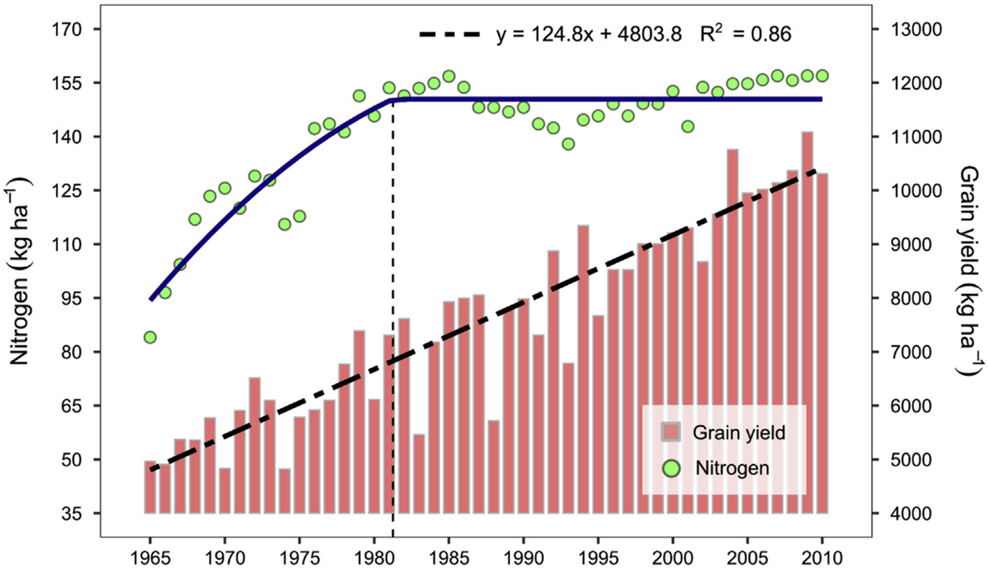

Fig. 3. Nitrogen use verses maize yields since 1965 (recreated from Haegele et al., 2013).

countries where agronomic inputs have been made available, significant improvement in productivity and prosperity are well documented. Examples include improved pearl millet seed systems and hybrids in India (Bantilan et al., 2003), and improved maize production in Ethiopia where a combination of improved maize genetics and other agronomic inputs (Abate et al., 2015) help lift an estimated 788,000 people out of poverty annually (Kassie et al., 2018). In China, an investment in agronomy and extension at the smallholder level has improved yields by over 10% and reduced excess nitrogen use by up to 18% within a 10-year period, contributing to both greater prosperity for approximately 20 million farmers and reduced nitrogen loss (Cui et al., 2018). Through a combination of improved seed, agronomic inputs, farmers' access to markets, and policies that encourage investment in agriculture, rapid progress has been demonstrated for a number of countries with highly varying economies (Abate et al., 2015; Cui et al., 2018; Fischer and Connor, 2018; Mellor, 2017). The challenge now is to extend these successes to those countries where yields have remained stubbornly low and the environmental footprint of agriculture is relatively large.

3. Identifying major challenges

Higher productivity in all regions of the world remains critical to meeting the objectives of agricultural sustainability, especially when considering the challenges embodied in objective four—conserving natural resources. However, agricultural intensification can also result in serious environmental damage when the underpinning technologies are immature or incorrectly used, such as by over-use of fertilizers and pesticides, or when regulations or market incentives are inadequate to protect the resource base. In Brazil, where crop rotations were limited and soybeans grown exclusively and extensive tillage used, soil organic matter (SOM) dropped dramatically, even with use of fertilizer (Wingeyer et al., 2015). Even in highly intensive management systems, there is opportunity for improved conservation of natural resources by continued innovation to improve resource use efficiencies which contributes to reducing or mitigating negative impacts. In the category of natural resource conservation, the greatest challenges are soil degradation, soil nutrient loss, weed and pest resistance, and aquifer depletion. Solving these environmental "mega-challenges" will ensure progress toward many other sustainable development goals.

Soil Degradation. Depletion of soil resources due to erosion has coincided with land-use changes from human activity, with dramatic changes occurring in the past 200 years (Lal, 2004; Sanderman et al. 2017a, 2017b). Soil degradation comes in many forms, from compaction and erosion to salinization and loss of soil organic carbon (SOC). Loss of SOC has the added effect of contributing to greenhouse gas (GHG) emissions, and both are most severe when native landscapes are converted to crop and pasture use. When it comes to preventing soil degradation, conventional, high input agricultural systems are generally recognized as more sustainable than low-yielding systems with low inputs, as they produce lower greenhouse gas emissions per unit of food produced (Balmford et al., 2018; Rosegrant et al., 2014), and contribute to land sparing, leaving more area for natural habitat and wildlife (Tilman et al., 2011). Studies in the U.S. Midwest, Brazil, and Australia have shown that managing a soil for high productivity also increases soil organic carbon (SOC) and promotes healthy soil microbial activity. These advances have a number of positive benefits including improved crop yields and overall soil health as well as greater moisture-holding capacity, which in turn reduces run-off and helps reduce nutrient loss (CAST, 2019; Clay et al., 2012; Clay et al., 2015; Poffenbarger et al., 2017; Sanderman et al., 2017a; Wingeyer et al., 2015).

By sequestering CO_2 in soil and reducing GHG emissions, farmers can help mitigate climate change, although experts are not in agreement as to the magnitude of potential impact. The effectiveness of increasing SOC and C sequestration depends on the availability of other nutrients to support the formation of microbial biomass that is resistant to degradation (Kirkby et al., 2016); this factor may lead to contradictory results. Minasny et al. (2017) state that an ambitious global strategy could offset 30% of global GHG while Schlesinger and Amundson (2019) argue a 5% offset is more realistic; still many agronomists and soil scientists believe SOC sequestration to be a realistic and valuable GHG mitigation tool (Frank et al., 2017; Fuss et al., 2016; Lal, 2004).

Nutrient Loss. Nitrogen (N) and phosphorous (P) are critical to plant growth and, after water, are often the most limiting factors for crop development and yield. While gains have been made in the fight to keep nutrients in place and available for crop production, the open soil system of agriculture continues to challenge maintenance of soil organic matter (SOM) and loss of environmentally sensitive nutrients (N and P). Loss of N from crop production systems is primarily via nitrate leaching to groundwater or with drainage systems to surface waters, or emission as nitrous oxide (a potent GHG) or N_2 (not a GHG), to the atmosphere. Loss of P from agricultural soils is via erosion of sediment-bound P or in the form of solubilized P in water run-off and drainage (CAST, 2019). Complexity of the cropping system, changes to watershed hydrology, and a vast geography with changing climatic and environmental conditions combine to make nutrient loss one of the more intractable environmental issues in production agriculture. The Mississippi River watershed, as an example, stretches from northern Montana in the west to New York in the east and drains among the most populated and industrialized regions of North America; with the major rivers of the watershed having been engineered for river traffic, flood control, recreation, and drainage, often creating a direct path to convey excess nutrient load of both N and P from a farmer's field to the Gulf of Mexico.

To combat nutrient loss, agronomists and land managers have developed an extensive array of Best Management Practices (BMPs) to enhance use efficiency and retain nutrients in soil, including intensive grid or management zone soil sampling to guide site-specific, variable rate P, K, and lime applications (Sawyer, 1994). Manure management has been improved by incorporating environmental P-Indexes into management plans with fertilizer applications (Lemunyon and Gilbert, 1993; Mallarino et al., 2002; USDA-NRCS, 1994). Leaf chlorophyll-sensing technology is being used to estimate N nutritional status as machinery moves through a crop field, thereby giving applicators greater knowledge of N-deficiency “on-the-fly”, allowing variable rate applications to ensure a more prescriptive rate of N is being applied and at the right time (Baral and Adhikari, 2015; Heggenstaller et al., 2018). Nitrification inhibitors applied with fertilizer, which have been in use for over 50 years, inhibit soil microorganisms (Nitrosomonas sp.) from oxidizing ammonia to nitrite, which thereby slows overall conversion to nitrate, and thus reduces nitrate leaching and loss and allows more N availability later in the season, when the crop needs it most. Cover crops, established after the primary, revenue-generating crop has been harvested, reduce erosion and thereby lower sediment-bound P loss, and at the same time take up nitrate, which reduces the amount of nitrate remaining in the soil.

Soil health and nutrient management are especially problematic when relying exclusively on manure, as is the case for much of organic production (Balmford et al., 2012; Pimentel et al., 2005; Tuomisto et al., 2012). Yet when used appropriately – through testing of nutrient levels in the manure and following best practices, manure in combination with synthetic fertilizer is a valuable source of fertility management and has many soil health benefits (Ozlu and Kumar, 2018). Management of livestock, livestock genetic potential, and containment of manure before application are key to maximizing efficiency of this resource (Oenema and Tamminga, 2006). In range and mixed cropping systems in many parts of the world, animal agriculture and manure management are critical components of nutrient cycling (Powell et al., 1996). FairOaks Farms provides an impressive example of how one of the largest dairies in the U.S. has implemented a wide variety of sustainable practices while maintaining profitability (Fairlife Dairy Farms, 2019).

Overall, we believe that focusing on solutions that are both profitable for the farmer and environmentally sound make the most sense. Initial adoption of new precision agriculture technology and practices are often expensive, especially in light of historical lower commodity prices, so progress may be slow even with clear benefits to consumers and the environment. Other practices, like grass waterways, edge-of-field vegetated filter strips, bioreactors, riparian buffers, or constructed wetlands (CAST, 2019) may require expensive engineering or removing land from production altogether, which in turn require financial resources. Numerous incentive programs for conservation practices exist at local, state, and federal levels in the U.S. (CAST, 2019), but limited funding often constraints impact, and farmers are understandably hesitant to undertake capital-intensive infrastructure projects on their own.

Pest and Weed Resistance. Weed, insect and plant pathogens resistant to management practices have been around as long as farmers have been trying to protect their crops from pests (Délye et al., 2013; Stout, 2013). Some believe these biotic agents may well be the greatest threat sustainable agriculture faces (Fischer and Connor, 2018). A number of especially problematic weeds, including members of the *Amaranthus* genus represent management challenges to farmers that did not exist 10 years ago (Hoffner et al., 2012; Weed Science Organization, 2019). Select insect species, especially in the Coleopteran and Lepidopteran families, are now among the most challenging insect species to manage due to changes in susceptibility to formerly highly effective control measures (Carrière et al., 2019; Siegwart et al., 2015). Recent focus has been on weeds that have developed resistance to the herbicide glyphosate and insects that have developed resistance to different forms of the *Bacillus thuringiensis* (Bt) protein included in transgenic maize, cotton, and soybeans. Increasingly, the effects of the global economy and changing weather conditions are enabling pests like *Diabrotica virgifera virgifera* (corn rootworm) and *Spodoptera frugiperda* (fall armyworm) to expand their geographical ranges from North and South America to Asia and Africa (Ciosi et al., 2008; Early et al., 2018).

Loss of a key control tactic, such as a highly effective herbicide or insecticide, can be devastating to crop yields (Délye et al., 2013; Ervin and Frisvold, 2016; Tabashnik and Carrière, 2017). Greater emphasis on Integrated pest management (IPM) for insect control, which combines tactics such as crop rotation, cultural practices, and insecticide programs that rotate different modes of action (MOAs), provide a template for sustainable pest control (Anderson et al., 2019). Management practices used to avoid or reduce build-up of weed and insect resistance to effective and environmentally benign pesticides extend durability in most cases; however, factors such as pest biology, effective dose of protein, and lack of a pesticide resistance management (IRM) plan all influence the years of product durability (Carrière et al., 2019). Pest susceptibility is arguably a common-pool resource available to all growers, thus the over use of management tactics whether in conventional or organic farming reduces the sustainability of our food production systems (Carrière et al., 2019).

In many ways, transgenic technology for pest control is in its infancy and best methods to deploy new products are still evolving (Carrière et al., 2019), and industry pipelines are full of new MOAs which will improve durability of all IRM strategies. New products coupled with sound IRM strategies are becoming more uniformly adopted as earlier failures to maintain durability are recognized as unsustainable (Anderson et al., 2019). Delays in regulatory approvals of these new MOAs in some countries remain one of the greatest barriers to effective resistance management (Carrière et al., 2019; ISAAA, 2019) despite the overwhelming consensus, supported by 1200 approvals in 28 countries over the past 20 years, that transgenic crops are as safe as the non-transgenic wild types (CropLife International, 2018; Gaffney et al., 2019). “The vast majority of studies demonstrate that the insecticidal proteins deployed today cause no unintended adverse effects” to valued non-target species (Romeis et al., 2019). It is thus fair to say that global regulatory authorities and policy-makers play an important role in efforts to develop and help implement sustainable agriculture.

Aquifer Depletion. Water drawn from many of the world's largest aquifers has supported major gains in crop and livestock production in semi-arid grasslands – including the Upper Ganges of India and Pakistan, the North China Plains, and the Central Plains and other regions of the U.S – but these aquifers are declining. Approximately 70% of groundwater withdrawals worldwide are used to support agricultural production and a similar withdrawal level is used for irrigation of crops in the U.S. (Tracy et al., 2019). The percentage of groundwater withdrawals used to support agriculture is even higher in arid and semi-arid areas, where the only consistent source of irrigation water is groundwater. Maintaining long-term sustainability of these aquifers may be the most difficult of the four agricultural sustainability challenges, since all or parts of many aquifers may be relatively closed systems for which recharge occurs over thousands of years and, once depleted, will not be of use to humans for several centuries (Steward et al., 2013).

The human factor as it affects sustainability creates difficult choices, since irrigated agriculture may be relatively more profitable and less risky than dryland farming, thus creating and supporting a higher level of service industries – seed and fertilizer suppliers, implement dealers, banking and insurance – and a higher tax base that provides for public services (Pfeiffer and Lyn, 2009). In low and middle income economies, substantial reduction in irrigated crop production may impact foreign reserves, food security, and political stability. Regardless of geography or economic situation, farmer productivity is often intertwined with the well-being of urban dwellers, which impacts the decisions of policymakers and politicians and emphasizes further the importance of productivity.

One option for slowing aquifer depletion and enhancing water availability for both urban and agricultural uses is water recycling. Israel leads the world in the impressive recycling of more than 85% of its wastewater to support its highly productive and profitable irrigated agriculture. By contrast, the U.S. recycles less than 10% of its wastewater. However, Israeli research has also shown that use of such recycled water does ultimately result in increased salinization of soils and proposes that long-term use of such recycled wastewater will require more highly-purified recycled water (Tal, 2016). Still, water recycling represents a growing business opportunity worldwide.

Breeding crops that need less water is another way to make water use for agriculture more sustainable. Maize breeding programs have created water efficient maize hybrids with increased yield under drought conditions, such as in the Texas high plains, but no yield penalty under good growing conditions (Adee et al., 2016; Gaffney et al., 2015; Hao et al., 2015). Reyes et al. (2015) demonstrated that grain yield of maize hybrids has been increasing consistently over the past 50 years, but total water extraction has remained stable.

4. A common-sense path forward

Investments in agricultural innovation by both the public and private sector in the basics of agronomy, plant breeding, biotechnology, and engineering have demonstrated the ability to deliver on the four objectives of agricultural sustainability while improving the livelihoods of farmers, lowering food prices and increasing choice for consumers. Expansion of agricultural innovation that unites intensive production with sustainability goals offers a pragmatic and science-based path forward that builds on the successes of the past. Although the path is proven, significant challenges remain. First, public and private spending on agricultural research must increase ito ensure that advances stay ahead of stressors, including climate change, soil degradation, and water resource limitations, and to reach those areas of the world where yields have the greatest potential for advance. China is currently leading the way in agricultural research spending (Boyer et al., 2013) and researchers there are filling scientific journals with important research. Second, changes in public policy need to be made at local, regional, national, and global levels to allow faster approval and implementation of new yield-boosting and resource-conserving technologies. In high income countries, policy decisions have often been driven by the desire to maintain viability of the family farm. Payments for fallowing cropland, commodity support prices, subsidized crop insurance, and the ethanol program were created and evolved with the best of intentions and often with broad political support. These efforts have helped maintain low food prices and have created a much-needed cushion against global food shortages and severe price swings. Farm policy should evolve further to support greater sustainability of farming systems. In low income countries, policy is urgently needed to create greater access to modern inputs and technology at the SHF level. Third, farmers, both those in large-scale production systems and smallholder systems, need to be adequately supported for the additional costs and risk they may bear in adopting innovations that improve off-farm ecosystem services. Finally, dialog amongst stakeholders is needed to communicate and understand that sustainable agriculture is a public good and therefore, the public needs to engage in developing and endorsing the technologies and policies that support it.

An over-arching need is a greater understanding of and trust in science. Modern, high input agriculture and the science that backs it are often under attack due to personal preferences, public perceptions, and ideology. Agricultural research should be based on science, not ideology and marketing (McGuire, 2017). The recent and highly publicized challenges to glyphosate herbicide are a case in point. Numerous comprehensive, scientific studies have demonstrated the safety of glyphosate (Andreotti et al., 2018), including those produced by national academies of science in a number of countries and the European Union (Tarazona et al., 2017). Any discussion about glyphosate should include the long and continual history of safe use by homeowners and farmers and the many advances in productivity and environmental benefits made possible by herbicide tolerant crops coupled with glyphosate herbicide. Excessively punitive jury awards and negative public perception can have a chilling effect on investment in agricultural research and any product or practice is in danger if the public narrative gets loud enough to drown out reason. A path forward must be found to ensure strong, effective, science-based regulation, or farmers will not have access to the full range of crop and soil management options to achieve a sustainable production system.

Some sustainability solutions may come with trade-offs that may mean greater costs for the farmer, an increased risk of lower yields and productivity, or the need to remove land from production altogether. With long-term trends of lower commodity prices, increasing input costs, and the pressure this creates to be more productive, can farmers stay in business while absorbing the costs of providing a public good? If farmers are providing a public good – carbon sequestration, healthier soils, improved water quality and water-resource utilization, climate change mitigation, and an abundant and high-quality food supply – should farmers bear the burden of paying the entire price? Innovative approaches to share the cost are already in place in some areas and could be expanded:

- USDA-Natural Resources Conservation Service Environment Quality Incentives Programs have encouraged adoption of efficient irrigation technologies and practices, as well as water quality protection practices. Examples include conversions of less efficient furrow irrigation and high pressure center pivot irrigation systems to more efficient low pressure center pivot irrigation and micro-irrigation systems; use of weather-based and sensor-based irrigation scheduling; and conservation activity plans/nutrient management plans (USDA-NRCS, 2019). Some local/regional groundwater conservation districts and natural resources conservation districts offer low interest loan assistance programs to encourage adoption of efficient irrigation systems and associated management practices.
- In the United States, Delaware farmers are paid up to $81/ha to seed a cover crop after harvest which helps hold nitrogen in place, reduces soil erosion, and builds SOM. Other states have similar programs at lower levels of remuneration and with caps on total area or funding.
- Payments for Ecosystems Services (PES) is another approach, already implemented broadly especially for forest conservation and water quality protection, and defined as "the exchange of value for land management practices intended to provide or ensure ecosystem services." (Salzman et al., 2018). In North American agriculture, the infrastructure is likely in place to keep transaction costs low and implementation reasonable, with both willing buyers and sellers of ecosystems services assembled. An example is an extensive effort in the US, spearheaded by the Noble Foundation, that seeks to organize a broad system of PES with a special emphasis on soil health (Noble Research Institute, 2018).

Payments for Ecosystems Services requires metrics to assign cost/benefits, demonstrate impact, and the ability to monitor participation.

Recent advances in remote sensing for monitoring land use, and advances in machine learning to identify participation in these programs will be important components in allowing broader implementation. Portable devices and test kits for in-field diagnostics are other areas where innovation will play an enabling role.

If aforementioned solutions for water quality and aquifer conservation, soil improvement, and GHG reduction represent insurmountable financial burdens for farmers, PES would seem a natural fit, provided that a true equivalency can be established between the cost of an effort to improve an ecosystem and the price the marketplace is willing to pay for that effort. The need for robust quantification of environmental benefits to justify such investments highlights the need for concomitant investment in “metric science” that develops reliable, low cost measurement capabilities.

Rice farmers in India and other Southern Asia countries would also be candidates for GHG, watershed and water quality PES efforts. Current rice yields in this region are low and stagnating (Gathala et al., 2014; Sharma et al., 2010), and millions of hectares of paddies are among the largest agricultural sources of methane and nitrous oxide emissions in the world (Tian et al., 2016; West et al., 2014). Technological innovations exist to improve the cropping system, but would incur cost at both the farm and extension services levels for implementation. A sound PES scheme for rice production would have positive implications for all four sustainability objectives while having immediate and measurable impact on the intractable problems identified in this paper.

Investment in agricultural research is more critical than ever because in addition to continual progress needed in Organization of Economic Cooperation and Development (OECD) countries, even more rapid progress will be needed in tropical regions with large populations of SHFs, who provide up to 85% of food needs for their countries (Rapsomanikis, 2014) but often struggle to maintain a living (Gaffney et al., 2019). Smallholder farmers also tend to dominate in low and middle income countries, and farms of less than 2 ha represent 12% of the world's agricultural land but a disproportionate share of land in SSA and South East Asia (Lowder et al., 2016). Farmers at this level are often highly resourceful and resilient but are stuck at a low level of subsistence, unable to attain greater prosperity regardless of access to inputs or markets, without access to improved education and off-farm income sources (Jayne et al., 2014). Successful transition from an agrarian-based society to industry and urbanization has almost always involved farm consolidation coupled with increased job creation in urban areas to utilize excess farm labor, and has been the model for nearly every country (van Ittersum et al., 2016). The process has always required a more modernized and productive agricultural sector to achieve the transition.

As advocated by Boyer et al. (2013), now is not the time to pull back on public spending for agricultural research that has been very results-oriented and has a high return on investment. Meeting the sustainability objectives identified by Sayer and Cassman (2013) and the United Nations Sustainable Development Goals (2016) will only be achieved with sound science, broader implementation of current technologies, and more deployment of new technologies in the near future. Partial solutions which may be based on ideology and have unintended consequences of destroying wealth, eliminating nutritional options, or creating a false sense of accomplishment, should be discouraged. As Mellor (2017) explains so well, “basic agricultural investment must be accompanied by technological improvement” for the transition to happen. Recognizing and exploiting the dynamic nature of technology development and efforts with regard to sustainability should focus not on just one aspect, but rather on performance of the entire complex system that represents today's agricultural enterprises.

Declaration of interest

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