Making science more effective for agriculture

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Abstract

The challenges facing global agriculture via population increase, climate change and dietary choices are unprecedented and urgent. In the context of declining public funding for research and development in agriculture (ag R&D), we highlight the historically high returns on such investments and outline an economic rationale to continue government involvement through support and policy ag R&D. Next, we illustrate the substantive agricultural impact of science and technology, and reveal cases where oversimplification, reductionism and lack of rigor compromise returns on investment. *Ex situ* conservation of genetic resources, organic agriculture, soil health and the water footprint illustrate issues that need attention because they feature flaws in important aspects of agricultural theory or practice with implications for policy and investment. We conclude with high-level propositions for improved allocation of ag R&D resources.

1. Introduction

Historically, technologies derived from ag R&D have increased agricultural productivity worldwide (Fischer et al., 2014; Fischer and Connor, 2018; Stewart and Lal, 2018). Investments in ag R&D have typically delivered benefit-cost ratios of at least 10:1 (Alston et al., 2009; Hurley et al., 2014). Significant increases in ag R&D investment and better use of these funds are required to meet the challenges of global agriculture: a growing demand for healthy, nutritious, affordable food; adequate farmers' income and welfare, and environmental protection in a context of scarcer land and water, and climate change (FAO, 2018; Fischer and Connor, 2018).

Despite a compelling case for more investment, we see less. In many countries, especially the high-income countries like the United States and Australia, public investment[a] in ag R&D has stagnated or is declining in real terms (Heisey and Fuglie, 2018; Pardey et al., 2013). Core investment for the Consultative Group for International Agricultural Research (CGIAR) has declined from US$ 382 M in 2014 to US$ 160 M in 2017 (CGIAR, 2015, 2017). At the same time, we and others question the effectiveness

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[a] We emphasize public investment that comprises about 50% of total world food and agricultural R&D—amounting to $69.3 billion (real 2009 PPP dollars) in 2011, and investment intensity of approximately 0.75% relative to AgGDP (Pardey et al., 2016). Despite its critical role in delivering new varieties of staple crops, we give less attention to private-sector research because it is less transparent, and hence less amenable to scrutiny, which is the objective of this paper.

and economic efficiency of ag R&D funding misallocated to fashionable research (Bernardo, 2016; Simmonds, 1991) with unlikely payoffs (Fereres et al., 2017; Fischer and Connor, 2018; Kirchmann and Bergström, 2008; Porter et al., 2018). Additional concerns are a shift towards bureaucratic industrial principles to organize scientific work; the opportunity cost of the scientists' time for applying and managing funds; reduced scope to pursue the unexpected because of contractual constrictions, incentive structures, and restricted exchange of information between scientists; and the erosion of scientific expertise in core disciplines including crop science and ecology (Boote and Sinclair, 2006; Bromham et al., 2016; Franzoni et al., 2011; Milojević et al., 2018; Osmond, 1995; Porter and Wollenweber, 2018).

Here we outline an economic rationale to continue government involvement through support and policy ag R&D. We illustrate the substantive agricultural impact of science and technology, and reveal cases where oversimplification, reductionism (sensu Kauffman, 2008) and lack of rigor compromise returns on investment. We conclude with high-level propositions for improved allocation of ag R&D resources.

2. Making science pay: The economic case for public agricultural R&D

In the absence of government intervention, the private market economy underinvests in certain types of ag R&D (Alston et al., 1995). Governments have reduced this market failure by creating intellectual property rights (IPRs) that reward and encourage private investment, supporting producer-controlled levy funding, providing public funding for privately performed ag R&D or conducting ag R&D in the public sector. Public funding requires policies to set research priorities (Alston et al., 1995) and to manage funds for ag R&D that complement private and producer-controlled investments.

Private firms invest in ag R&D where the products of research are "excludable" and protected by IPRs. This model currently dominates hybrid and GM crop breeding, agricultural machinery and pesticides (Fuglie, 2016).

Only governments invest in public-good research for which IPRs do not exist and individual investors cannot appropriate the benefits. Most science-based discovery research falls into this public good category. However, much ag R&D is an industry collective good whereby research beneficiaries are producers and consumers of a particular good (Gray, 2010). In this situation, commodity levies better align those who pay for ag R&D with those who benefit from it. To this end, governments in Australia, the UK, Canada and the United States developed frameworks to create ag R&D organizations that are funded by levies and controlled, at least partially, by producer representatives.

Collectively, these producer-controlled organizations invest several hundred million USD in ag R&D annually. The Australian Grains Research and Development Corporation is the largest of these organizations, with annual revenue of AU$200 M.[b] The producer board and advisory members, extensively involved in the decision-making, engage the scientific community, accumulate knowledge and social capital that enables the sector to identify and respond quickly to new opportunities for innovation.

Science policy can be improved. Failures of markets, governments and institutions have contributed to underfunding (CGIAR, 2015, 2017; Heisey and Fuglie, 2018; Pardey et al., 2013) and also misguided allocation of ag R&D resources, as outlined below. The remarkably high payoff from public investment in ag R&D (Alston et al., 2009; Hurley et al., 2014) is compelling evidence that the intervention has been suboptimal. No doubt, governments have occasionally failed to allocate research resources to the highest payoff areas or have invested in areas where the private sector would otherwise invest, crowding out private investment. Were it not for burdensome procedures that reduce the resources effectively available for research, the payoff could have been even higher.

Of course, it is a considerable challenge to get all of these policy aspects of agricultural science right given the time lag of decades between initiating research and observing its impacts, and the inherent uncertainty about the utility (Kauffman, 2008; Osmond, 1995) and adoption (Kuehne et al., 2017) of research products. These challenges are even greater for research that is less directly applicable, or for which the resulting knowledge is not embodied in inputs like seeds or simple management practices, including policy-oriented social science or research related to environmental externalities (Pannell et al., 2018).

3. The sciences supporting agriculture have been successful, but current research shortcomings must be addressed

Here we sample scientific and technological efforts to advance production, environmental and social outcomes, seeking to learn from both success and failure.

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[b] https://grdc.com.au/.

3.1 Improved varieties, better agronomic practices, and their synergy

Improved varieties, better agronomic practices, and their synergy have been the main drivers of yield and associated productivity gains in historic time scales (Evans, 1997; Fischer, 2009; Fischer et al., 2014; Sinclair and Rufty, 2012). In parallel, efficiencies in the use of key resources including water (Sadras and Lawson, 2013; Siddique et al., 1990), nitrogen (Barraclough et al., 2010; Giunta et al., 2007; Slafer et al., 1990; Wang et al., 2017) and phosphorus (Calderini et al., 1995; Wang et al., 2017) have increased. In Australia, the water use efficiency (grain yield per unit water use) of rainfed wheat more than doubled since the 1920s, from about 10 to 24 kg grain $\text{ha}^{-1}\,\text{mm}^{-1}$ (Sadras and Lawson, 2013). In the UK (Barraclough et al., 2010), Italy (Giunta et al., 2007), Argentina (Slafer et al., 1990) and China (Wang et al., 2017) the nitrogen utilization efficiency of wheat (grain yield per unit of crop nitrogen uptake) increased over several decades, albeit at the expense of grain protein concentration (Wang et al., 2017).

Transformative changes (Vermeulen et al., 2018) are rarely associated with single innovations, e.g., the Green Revolution has come partly from agronomic intensification, especially of nitrogenous fertilizer and irrigation which was enabled by the dwarfing of wheat and rice varieties, in turn made feasible by herbicides (Evans, 1997). Unrealistic claims of transformational technological breakthroughs (Nelson et al., 2007; South et al., 2019) have been promoted by research disciplines that are disconnected from each other and have limited contact to farmers. Focusing on the cumulative incremental gains offered by breeding and agronomy and working closely with farmers is a more reliable route to the desired progress, as illustrated for the production of wheat in Australia and maize in Ethiopia (Box 1).

Innovations from many fields have improved all four drivers of the rate of genetic gain of crop yield over the last decades (Langridge, 2018, 2019)

$$\textit{The rate of genetic gain} = \frac{\textit{Diversity} \times \textit{Populationsize} \times \textit{Heritability}}{\textit{Breeding cycle lenght}} \tag{1}$$

Wide crosses, mutation breeding and genetic engineering have enhanced *diversity*; over 2250 varieties of major crops have resulted from mutant screens (Ahloowalia et al., 2004), and many modern varieties carry important chromosome segments from wild relatives (Byrne et al., 2018). Mechanization of seeding and harvesting has allowed larger *population size;* statistical methods

BOX 1 Incremental transformation in productivity of wheat in Australia and maize in Ethiopia from system synergies

Water availability is the main constraint for dryland wheat in Australia (Fischer, 2009), but many farmers fall short of the water-limited yield potential (Hochman et al., 2012). Fig. B1A shows how wheat yields are lifted by the cumulative impact of management practices that improve the capture and storage of rainfall (stubble retention and weed control between crops), and increase the efficiency of water use (control of root diseases with crop rotation and earlier sowing). These management strategies require high-yielding semi-dwarf varieties that can be sown early but still flower at the optimum time (Kirkegaard and Hunt, 2011). Further gains are made through varieties with long coleoptiles (but short in stature) that enable deeper sowing in moist subsoil, and before the opening rains (Kirkegaard and Hunt, 2011). Each of these steps relies on access to cost-effective herbicides (Fischer and Connor, 2018; Hunt et al., 2013). These management and genetic solutions have limited impact when used in isolation but more than double the yield when combined (Kirkegaard et al., 2014; Kirkegaard and Hunt, 2011). Similarly, additive and synergistic effects from incremental adoption of simple, complementary practices can double maize yield in small-holder systems in Ethiopia (Fig. B1B).

Climate is the major cause of production risk in dryland farming (Ray et al., 2015). The spread of yield in the box plots of Fig. B1 illustrates the risk for wheat in Australia and maize in Ethiopia. In the Australian context, the downside risk is quantified as the yield (kg ha^{-1}) at an average price for wheat ($ kg^{-1}) that covers the cost of production ($ ha^{-1}); this is about 2000 kg ha^{-1} for no adaptation (red line in Fig. 1A) and increases to 2700 kg ha^{-1} with the combination of five technologies that return the highest yield. The no-adaptation is below the break-even yield of 2000 kg ha^{-1} almost 75% of the time. For a small holder in Ethiopia, a better measure of risk is the household energy requirement met by 1700 kg maize per ha per year (blue line in Fig. B1B). Combining weed control, legumes in rotation, stubble retention and fertilizer reduces the likelihood of not meeting the household's food-energy need to less than 10% (Fig. B1B).

Although the improved practices and varieties make growing the crop more expensive, this expense leads to higher profit in good seasons and decreases the chance of an economic loss. For resource poor farmers, even if they are convinced of the benefits from improved practices, the extra costs can be a major barrier to adoption. The late introduction of costly fertilizer input, as outlined in Fig. 1B, seeks to overcome this barrier.

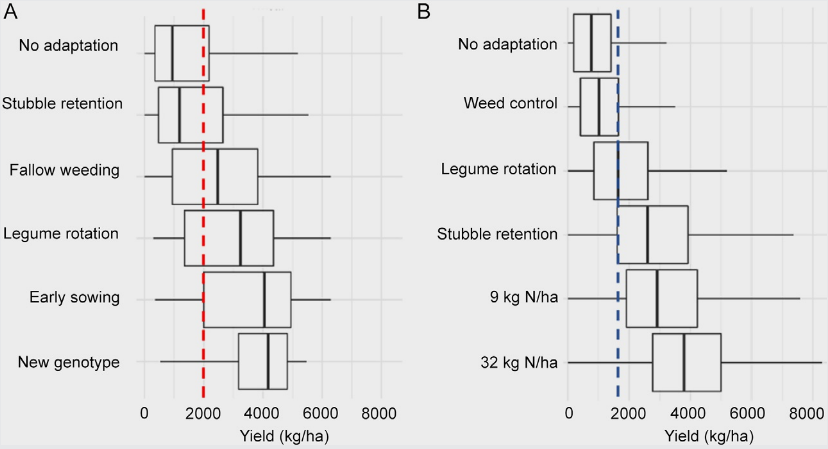

Fig. B1 Cumulative incremental adaptations to synergistically increase crop production in Australia and Ethiopia. (A) Frequency distribution of modeled wheat yield (box plot) and break-even yield for "No adaptation" strategy (red line) in northwest Victoria, Australia (370 mm annual average rainfall). (B) Frequency distribution of modeled maize yield (box plot) and the yield to meet the annual food-energy requirements of a typical 1-ha smallholder farm with five household members (blue line) in Ethiopia's Rift Valley (700–1200 mm annual average rainfall). In both cases, technologies are aggregated from top to bottom; for example, "legume rotation" in Australia includes "fallow weeding" and "stubble retention." For Ethiopia, technologies were aggregated in a stepping-stone approach from most affordable at the top to the most costly at the bottom. *From Panel (A): Kirkegaard, J.A., Hunt, J.R., 2011. Increasing productivity by matching farming system management and genotype in water-limited environments. J. Exp. Bot. 61, 4129-4143. Panel (B): Dimes, J., Rodriguez, D., Potgieter, A., 2015. Raising productivity of maize-based cropping systems in eastern and southern Africa: step-wise intensification options. In: Sadras, V.O., Calderini, D.F. (Eds.), Crop Physiology: Applications for Genetic Improvement and Agronomy. Academic Press, San Diego. pp. 93–110.*

accounting for spatial variation in field trials have improved estimates of *heritability;* and doubled haploidy, single seed descent and embryo rescue have shortened the *breeding cycle* (Langridge, 2018).

3.2 Biotechnology

Biotechnology (Langridge, 2019) has been particularly successful in crop protection (Dalal et al., 2017; ISAAA, 2017). Globally between 1996 and 2016, GM crops have expanded to almost 200 M ha p.a., returned a total benefit of about US$186 billion to more than 16 M farmers, and lowered the environmental impact of pesticides by 18% (ISAAA, 2017).

Biotechnology, however, has largely failed to improve yield potential (Fischer et al., 2014) and drought adaptation despite significant investment (Dalal et al., 2017; Nuccio et al., 2018). Reliable field work with maize (Nemali et al., 2015; Shi et al., 2015) and wheat (González et al., 2019) engineered for drought adaptation returned yield increases around 6%; this is modest given early expectations, the achievements in crop protection, and the opportunity costs of ag R&D investments (Dalal et al., 2017; ISAAA, 2017; Nuccio et al., 2018). Numerous claims of larger yield gains are commonly associated with lack of field tests or poorly designed field experiments (Nelson et al., 2007; South et al., 2019). Often transformed phenotypes are compared with wild-types lacking agronomic adaptation (Porter et al., 2018). A common explanation for this underperformance of biotechnology is that "yield is complex," but conventional breeding has improved yield steadily over decades, albeit at diminishing relative rates (Fischer et al., 2014). We suggest that explicit consideration of trade-offs, scales, context- and density-dependence in crop populations is required to capture the complexity of yield using molecular approaches and high-throughput trait phenotyping (Box 2).

Lagging theory and over-emphasis on data also compromise our ability to capture the complexity of crop yield and crop adaptation to abiotic stresses. Over-simplistic theory assuming a unidirectional arrow from genotype to crop phenotype is part of the problem; more nuanced and testable theories of the phenotype need attention (Félix, 2016; Noble, 2012; Piersma and van Gils, 2011; West-Eberhard, 2003). Two entrenched metaphors are particularly unhelpful—that genes "control" development, and that genomes embody "programs" for development (Félix, 2016; Noble, 2012). A unified theory of phenotypic development and evolution emphasizes that "the individual's genotype can never be said to control development. Development depends at every step on the pre-existent structure of the phenotype, a structure that is complexly determined by a long history of both genomic and environmental influences" (West-Eberhard, 2003). This perspective is more broadly captured in the concept of downward causation (Flack, 2017; Noble, 2012).

"Omics" technologies have led to large, cryptic datasets on genes, their expression (transcriptomics) and products (proteomics, metabolomics), but they have essentially failed to resolve key agronomic traits (Langridge, 2018; Porter et al., 2018). These "omics" efforts have been largely driven

BOX 2 Overlooking trade-offs, scaling, context- and density-dependence undermine research in crop yield improvement

Breeders have successfully used *direct* selection for yield over much of the past century, but the rates of genetic gain (Eq. 1) are declining for maize, rice and wheat—the crops that collectively account for ~50% of global food calories (Fischer et al., 2014). *Indirect* approaches (Sadras and Richards, 2014) using molecular tools (Nuccio et al., 2018; Vinocur and Altman, 2005) and high-throughput trait phenotyping (Fahlgren et al., 2015) seek to lift the rate of genetic gain. We argue that overlooking core biological and agronomic principles undermines these indirect approaches.

Overlooking trade-offs leads to overoptimistic projections (e.g., for biotechnology (Nelson et al., 2007) or for agriculture that "mimics nature" (Denison, 2012)), while slowing actual progress**,** because improvements in one trait often come at the expense of other traits (Denison, 2012). Natural selection among crop wild ancestors is unlikely to have missed simple, trade-off-free improvements in individual-plant fitness (Denison, 2012). Trade-offs linked to plant partitioning of resources (e.g., carbon partitioning to seed versus root) have discouraging implications for the potential yield of long-stemmed, deep-water rice or perennial grains. For example, peak-year grain yield of perennial wheatgrass is one-third that of annual wheat (Culman et al., 2013). Some allocation trade-offs are more severe than expected from metabolic costs alone, as seen with some defensive toxins (Kakes, 1989). Other trade-offs make the simultaneous optimisation of defense against biotrophic versus necrotrophic pathogens (Spoel et al., 2007) or root uptake of water versus phosphorus (Ho et al., 2004) more challenging. Constitutive expression of genes that increase yield in some environments will often decrease yield in others, a problem that has plagued biotechnological attempts to improve drought adaptation (Nelson et al., 2007). On the other hand, trade-offs between fitness in past environments and today's agricultural goals can represent unexploited opportunities (Anten and Vermeulen, 2016; Denison, 2012), as has been observed by the general reduction in stature, tillering, leaf size and leaf angle in modern high-yielding wheat cultivars (Denison, 2012).

Overlooking biological context makes many controlled-environment studies agronomically irrelevant. Plants have evolved to use proxy sources of information (e.g., photoperiod to predict temperature). Therefore, experiments where correlations between environmental variables have been unrealistically altered (Annunziata et al., 2017; Krizek, 2004), are often agronomically irrelevant. For example, diurnal profiles of carbon and nitrogen metabolites of plants grown with a step-change in radiation do not match those for plants grown with both regular (day-night sinusoidal cycle) and irregular (due to clouds) fluctuations in radiation (Annunziata et al., 2017).

Continued

BOX 2 Overlooking trade-offs, scaling, context- and density-dependence undermine research in crop yield improvement—cont'd

*Overlooking scaling issues is a source of experimental shortcomings***.** In the context of crop genetic improvement, a trait "scales up if it remains agronomically relevant at higher levels, and eventually at the population level where yield is defined" (Sadras and Richards, 2014). Hence, the mixed record of achievement in biotechnology (Dalal et al., 2017; ISAAA, 2017; Nuccio et al., 2018) can be seen from a scaling perspective. Higher-level interactions are less likely to undermine biochemical defenses against pests and herbicides. By contrast, yield potential (Fischer et al., 2014) and drought adaptation (Brugiere et al., 2017; Habben et al., 2014; Lafitte et al., 2018; Shi et al., 2015) involve elaborate processes at all levels of organization over a wide range of temporal scales. Simple genetic changes may alter the timing of crop water use, but the effects on yield will depend on weather, soil water holding capacity, plant population density, etc.

Density-dependence (Donald, 1963; Harper, 1977) is a primary reason for yield not to scale from individual plant to crop stand (Fischer and Rebetzke, 2018; Pedró et al., 2012; Sadras and Richards, 2014). Crop yield, defined as mass of produce per unit land and time (Evans, 1993), depends on plant-plant interactions mediated by competition for resources between genetically identical neighbors, and non-resource cues and signals such as spectral composition of light and plant volatiles (Donald, 1963; López Pereira et al., 2017; Pierik et al., 2014). Furthermore, when the source of variation is competitive ability, single-plant and whole-crop yield are *negatively* related (Denison, 2015). In chickpea, Fst genome scan showed a mismatch between the top genomic regions under selection for yield in border rows under relaxed competition and yield in inner rows under full competition (Lake et al., 2016). Such an observation reinforces the bias in yield arising from small plots and edge effects recognized in agriculture (Fischer and Rebetzke, 2018; Kravchenko et al., 2017) but overlooked in plant biology (South et al., 2019).

Asking questions about trade-offs and scaling, and using context- and density-dependence as a compass can improve our experimental settings and avoid expensive distractions. Potted plants in a glasshouse could be useful to screen for herbicide tolerance, but less useful for traits that depend on stand properties and plant-plant interactions, including tillering (Casal et al., 1986), photosynthesis (Jarvis and McNaughton, 1986; Pettigrew et al., 1989), responses to drought (Turner, 2018), nitrogen uptake and partitioning (Gastal et al., 2015), and yield (Denison, 2012; Fischer and Rebetzke, 2018; Lake et al., 2016; López Pereira et al., 2017; Sadras and Richards, 2014).

by technology (Edwards et al., 2013) and the promise of patentable products and processes (Nuccio et al., 2018), rather than based on clear hypotheses. The difficulty in relating such data to crop performance has prompted renewed investments in high-throughput trait phenotyping (Araus and Cairns, 2014; Fahlgren et al., 2015; Furbank and Tester, 2011; Langridge, 2019). Similarly to the early "omics," this phenotyping effort is technology driven (Fahlgren et al., 2015) and is generating large datasets that are not necessarily relevant to agronomic traits in breeding populations. Big data (and related technologies) is the next promise but hypothesis-based research is essential for effective design of experiments and therefore for the biological and agronomic relevance of data (Box 2).

A more robust biotechnological approach with modest but commercially valuable improvement of yield under drought is emerging (Habben et al., 2014; Lafitte et al., 2018). It relies on explicit utility criteria: the construct had to provide a repeatable yield benefit in most environments, across multiple genetic backgrounds, have no negative side effects, be dominant and easy to introgress, and meet regulatory and public expectations; in addition for hybrids, it has to be functional in a hemizygous state. This approach is hypotheses- rather than data-driven, accounts for evolutionary constraints, trade-offs, context and scaling by being based on phenotyping of both yield and physiologically meaningful secondary traits such as the anthesis-silking interval and canopy senescence. The approach is comprehensive as it tests multiple transgene events in multiple genetic backgrounds of agronomically adapted phenotypes, and is field-based targeting intentionally managed environments with careful consideration of agronomic context (Habben et al., 2014; Lafitte et al., 2018). This approach innovatively reverses the direction of the biotechnology "pipeline from lab to field" (Nuccio et al., 2018).

3.3 *Ex situ* conservation of genetic resources

Ex situ conservation of genetic resources is a cornerstone of crop improvement for global food security by the CGIAR. This well-functioning system was based on trust and a clear understanding of the benefits to food crop production in developing countries. During the past 20 years, *ex situ* conservation has been marginalized by political developments including a campaign against alleged biopiracy, the Convention on Biological Diversity, and the International Treaty for Plant Genetic Resources for Food and Agriculture (Andersen, 2008; Wood and Lenné, 2011). Furthermore, the science-based approach to *in situ* conservation on-farm (Brown, 1999) has been ignored, superseded by an agenda which assumes implausible rates of beneficial *in situ* evolution (de Boef et al., 2013). An unnecessary polarity has been created to justify funding to *in situ* conservation with no evidence of scientific value, and funds vital for science have been redirected to expensive distractions. Twenty years ago, the need for an integrated system for conserving genetic resources for crop breeding was highlighted (Wood and Lenne, 1997). By closely linking targeted, structured, science-based *in situ* conservation with *ex situ* genotyping and phenotyping, we would identify the most valuable resources to be conserved for the future.

3.4 Organic agriculture, soil health and the water footprint

Organic agriculture, soil health and the water footprint are value-laden terms (Kirchmann and Bergström, 2008; Sojka et al., 2003) and illustrate further issues that need attention because they feature flaws in important aspects of agricultural theory or practice with implications for policy and investment in ag R&D.

3.4.1 Meta-analyses of organic crop yields mislead by disregarding system boundaries

A common opinion is that organic agriculture (OA) is superior to conventional agriculture (CA) because it uses only natural means and methods (Kirchmann and Bergström, 2008). Meta-analyses comparing yields of organically and conventionally grown crops have shown that organic yields are reduced by 25% on average (de Ponti et al., 2012; Seufert et al., 2012) although more recent estimates indicate that yield gaps apparently approach insignificance when OA is intensified (FAO, 2017; Ponisio et al., 2015). Analysis of national Swedish statistics on yield of OA crops relative to CA crops reveal an average reduction of 35% (Fig. 1A).

We argue that meta-analysis of crop-by-crop yield comparisons does not represent crop productivity under large scale implementation of OA because: (a) export of nutrients from CA to OA is ignored; (b) extrapolating organic yield data from plot- to farm-scale underestimates on-farm pressure by weeds, pests and diseases; (c) more frequent cropping of legumes for nitrogen fixation in OA, and (d) less non-legume crops reduces total system food production. Omitting these constraints leads to an overestimation of productivity of organic agriculture (Connor, 2008, 2013, 2018).

Productivity of OA is dependent on nutrient transfer from CA that would not be available to large-scale OA. Nutrient availability is fundamental for crop yield. To date, exclusion of mineral fertilizers in OA has been possible by import of

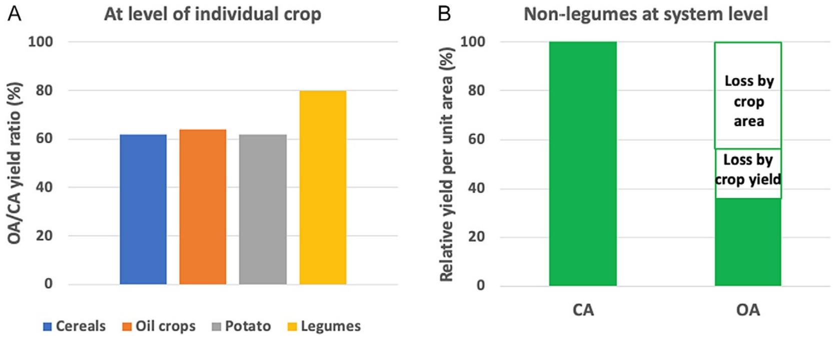

Fig. 1 Comparisons of productivity of organic (OA) and conventional (CA) systems in Sweden. (A) Mean estimates of individual crop yield ratios (OA/CA). (B) Relative productivity of non-legumes in OA versus CA. *Source: National Statistics of Sweden (SCB, 2018a,b,c).*

certified nutrient sources originating from CA including animal manures, organic fertilizers, feedstuff and straw that accounted for 23% of N, 53% of P and 73% of K applied on 63 organic farms in France (Nowak et al., 2013). Similarly, nutrient balances of organic farms revealed common usage of animal manure, meat- and bone-meal, feedstuff and straw imported from CA (Kirchmann and Bergström, 2008).

OA as the major system at large scale would be exposed to greater biological stress. Timely and effective mechanical weed control is as a major challenge for OA (Kravchenko et al., 2017). Furthermore, if OA becomes dominant, benefits of weed, pest and disease control by surrounding conventional agriculture will disappear; for example a landscape dominated by Bt crops also protects non-Bt crops (Hutchison et al., 2010). Greater biological pressure and sole reliance on mechanical and biological methods will make weed and pest control less efficient so organic yields will suffer greater losses (Fig. 1A).

Substituting nitrogen fertilizer by legumes significantly restricts food supply. To provide nitrogen to organic crops requires more frequent growth of legumes that in turn reduces the proportion of non-legume crops relative to CA. National statistics from Sweden reveal a reduction of 44% that has greater impact on overall production of non-legume crops in OA than does, in this case, the smaller yield (35%) of individual crops (Fig. 1A).

Relative productivity of non-legume crops is lower in OA. Combining the impact of reduced area with smaller individual crop yield provides an estimate of the relative productivity of non-legumes in Swedish OA at 36% of CA (Fig. 1B). At large-scale organic farming, manure purchased from CA to OA would become very limited, which would further decrease the productivity of OA.

Organic agriculture means extensification with lower yields to be compensated by expansion of arable land (Muller et al., 2017; Searchinger et al., 2018). Organic agriculture means "growing less food per acre leaving less land for nature" (Borlaug and Dowswell, 1994). Proponents commit a serious error when concluding that transformation to large-scale organic agriculture could provide global food security (Connor, 2018).

3.4.2 Soil health is a simplistic perspective lacking agronomic context

Soil health has been defined as "the capacity of the soil to function as a vital living ecosystem to sustain plants, animals, and humans" (NRCS, 2018). This viewpoint is influential, and advocates that redesign of agricultural systems to meet goals of global food security, sustainable intensification and food nutritional quality should have a key, or even primary, focus on soil microbes (Rillig et al., 2018; Rodriguez and Sanders, 2015). We suggest that this simplistic perspective centered on soil microbes risks being an expensive distraction because it largely disregards agronomic principles and techniques (Ryan and Graham, 2018; Ryan et al., 2019). Little debate occurs despite the mismatch between findings on the importance of targeted management of soil microbes between the agronomic literature and claims coming from journals devoted to soil microbiology, ecology, and plant science.

As an example, there are divergent viewpoints on the need for farmers to enhance arbuscular mycorrhizal fungi in farming systems (Ryan and Graham, 2018; Rillig et al., 2019, 2019). Several factors contribute to the failure of the vast research effort on arbuscular mycorrhizal fungi to support a need to manipulate these fungi in the majority of agricultural systems, including the poor relevance of potted-plants in glasshouse experiments to field conditions (Box 2), and lack of agronomic context (Ryan and Graham, 2018; Ryan et al., 2019). Owing to similar constraints, the soil health literature is overly optimistic. Moreover, complex experiments and new molecular techniques now reveal increasingly complex (and fascinating) information about soil microbes. Such studies are often published in high-impact non-agronomic journals, with relevance to agricultural systems lost in detail. To achieve better on-farm impact for ag R&D investments, the assumptions of "soil health" need critical revision, and the focus should shift to specific questions in a farming systems context, such as the well-known but poorly understood effects of certain crop sequences (Karlen et al., 1994), using rigorous agronomic research methods (Ryan et al., 2019).

3.4.3 The ecological water footprint of most rainfed crops is close to zero

Canopy photosynthesis is coupled with transpiration, which in turn depends on climatic factors, particularly air dryness quantified as vapor pressure deficit (*VPD)* (Monteith, 1993). Evapotranspiration (*ET*) comprising both transpiration and soil evaporation is thus a passive process driven by energy and *VPD*, and limited by the water available in soil, implying that both crops and natural vegetation use more water where *VPD* is greater. Consequently, water use efficiency or water productivity, defined as the ratio between yield and evapotranspiration, decreases with increasing *VPD* (Monteith, 1993).

The water footprint (*WF,* L of water per kg of produce) has been recently presented as an indicator for the water used in the production of food and services (Hoekstra and Mekonnen, 2012), but is flawed for two reasons (Fereres et al., 2017): (a) the "*Green WF*" of a crop, supplied by stored soil water, such as rainfed crops, may actually be less than the water consumption of adjacent native vegetation so there is no actual "footprint" of human action; (b) the total water consumption of a crop ("*Green WF" +* "*Blue WF*" from stored water resources) is computed as the maximum potential crop *ET*, which is often significantly higher than actual seasonal crop *ET* (*ETa*) (Fereres and Soriano, 2007).

To respond to the legitimate concerns of society on the use of scarce water resources, an "*Ecological water footprint*" (*WF**) is defined that captures the default water consumption of natural vegetation *ET*,* and is therefore ecologically and economically more robust:

$$WF^* = (ETa - ET^*)/yield \tag{2}$$

The numerator makes explicit the putative footprint as the increase in seasonal water consumption *ETa* relative to the water use of the native vegetation *ET*,* calculated as reference evapotranspiration *ETo* for periods when water is available in the soil, and equal to *rainfall* during dry periods (*rainfall* < *ETo*). The *WF** for most rainfed agriculture is therefore negligible, zero or negative because *ET* is limited by rainfall, in both the natural and the agricultural ecosystems as shown for rainfed wheat in Northern Spain (Table 1).

In irrigated systems *ETa* depends on irrigation supply. The maximum *WF** can be calculated as the ratio of crop water requirement (Villalobos et al., 2016) and yield:

$$\text{Maximum WF}^* = (\text{ETa} - \text{ET}^*)/\text{yield} \tag{3}$$

Table 1 Average and standard deviation of *WF* and *WF** in Valladolid (41.6523° N, 4.7245° W, 600 m asl) and Burgos (42.3440° N, 3.6969° W, 800 m asl) in the Northern Plateau of Castilla-Leon (Spain) from 2006–07 to 2012–13 cropping season.

	$WF = ETa/yield\ (L\,kg^{-1})$		$WF^* = (ETa - ET^*)/yield\ (L\,kg^{-1})$	
Location	**Average**	**SD**	**Average**	**SD**
Valladolid	998	494	0	0
Burgos	1090	242	13	35

Wheat yield was 2759 ± 842 kg ha^{-1} in Valladolid and 3804 ± 411 kg ha^{-1} in Burgos, and seasonal rainfall was 253 ± 96 mm and 417 ± 110 mm, respectively.

Data sources: Spanish Ministry of Agriculture, Fisheries and Food (www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/) and Meteorological Office (www.aemet.es).

where *ET** can be calculated as the difference between in-crop rainfall and extractable soil water at sowing. Therefore *WF** will be smaller in soils with high water holding capacity or when a large fraction of *ET* can be met by rainfall. Deficit irrigation will also contribute to reducing *WF** of irrigated crops.

The simple, one-dimensional indicator *WF* is a perverse assessment of agricultural water productivity but is a strong competitor in the scientific ecosystem of ideas. Being simple it attracts researchers that generate an increasing number of papers and then citations which give "objective" scientific support to the idea. Despite a positive, albeit small ecological water footprint *WF**, irrigated agriculture is bound to be essential to global food security; judicious governance for translating science of water management into action cannot be overemphasized (Stewart and Lal, 2018). A change in public perception on irrigation is required as public opinion informs research funding.

4. More rigorous allocation of ag R&D Resources to meet the challenges of global agriculture

We advance three high-level propositions to increase the impact of ag R&D investment, and to capture the synergy between curiosity and utility (Alston et al., 1995; Osmond, 1995)—the dual motivation of scientific research in agriculture.

4.1 *Multiple perspectives* in research would reduce the likelihood of misconstructed science and improve the return on ag R&D investment. In 1786, Auguste Broussonet, the secretary of the Société Royale d'Agriculture in Paris, urged for multiple perspectives (Jones, 2016), and the list of research styles including multi-, inter- and trans-disciplinarity continues to grow (Bammer, 2013). But our record of achievement is mixed, for example, when we focus on single resources such as water or energy (Bleischwitz et al., 2018). We suggest that promoting scientific breadth would help; student training with the T-skills framework (Kropff and Kalwij, 2008) provides both disciplinary depth (the vertical line of the T), and the broader context (the horizontal line). Modeling could be useful for cross-disciplinary training (Berge and Kropff, 1995). Demographics of scientific careers and academic reward systems need attention, including the escalating proportion of temporary scientists (Milojević et al., 2018), some questionable financial incentives linked to publications in high-end journals (Franzoni et al., 2011) and the lower funding success of interdisciplinary proposals (Bromham et al., 2016). Fostering Merton's norms (Merton, 1942) of communality, universality, and personal disinterestedness could help by relaxing the tension between competition and co-operation that obstructs multiple perspectives (Porter and Wollenweber, 2018).

4.2 *Explicit pathways to agronomic applications and reality checks* would increase the likelihood of real-world impact. Consideration of trade-offs and synergies, biological and agronomic context (Box 1 and 2) and system boundaries (Section 3.4.1) are important. Research proposals must articulate how outputs from ag R&D would enhance economic, environmental and social outcomes. Early engagement with practitioners including farmers, agronomists and breeders would provide reality checks. The realities of risks associated with climate and markets, policy change, labor supply, logistics, ease of implementation, personal circumstances, motivation and many other factors influence the interest and capacity of growers to adopt innovations (Kuehne et al., 2017). Science that proceeds without connection to that context, no matter its quality, is less likely to lead to significant impact.

4.3 *Rigor in claims of utility* is important for both funding bodies and scientific journals. It could be improved by an expanded definition of "peer" to assess not only the quality of science, but also the claims of relevance. Significant investments in laboratory research seek, for example, to improve crop tolerance to salinity and drought (Vinocur and Altman, 2005) with little consideration of trade-offs, scaling, context- and density-dependence (Box 2). Like-minded peers that review this kind of research contribute to a loop whereby claims of agronomic relevance, despite being poorly justified, reinforce misguided investment.

Analogous to the rigor in the protocol for drug development,[c] claims of agronomic utility must be supported by comprehensive, agronomically sound field experiments where new phenotypes or practices are tested in a sensible sample of target environments (Andrade et al., 2019; González et al., 2019; Habben et al., 2014; Lafitte et al., 2018). We advocate for funding bodies (and journals) to augment their evaluation panels, where necessary, with people who can effectively judge claims of utility. To do so would have a double benefit. It would select proposals with better chances of practical success, and if seen as a dichotomous process, it would free up funds for other scientists across all levels of biological organization to ask questions that are more penetrating of the materials that interest them—for deepening understanding at every level remains essential (Passioura, 2020).

5. Conclusion

There is no silver bullet in agricultural research. Agricultural innovation (Dimes et al., 2015; Evans, 1997; Fischer, 2009; Kirkegaard and Hunt, 2011) emerges from new combinations of existing technologies (Kauffman, 2008, 2016). Funding bodies should scrutinize carefully new "bandwagons" (Bernardo, 2016; Simmonds, 1991). Donors and investors who are reluctant to support "more of the same" unintentionally favor spurious claims of breakthroughs that need to be challenged. Excessive emphasis on data clouds the issues, while testable hypotheses remain paramount for robust and relevant science.

Given the above analysis of the current interplay between science and agriculture, the situation is not static—the targets of agricultural R&D evolve. A likely future direction for research in agriculture and food will be to ask as much about the efficiency of demand issues as the past has been concerned with food supply. Environmental resilience is expected to remain central, and the interface between agriculture, human nutrition, diet and obesity is increasingly important (FAO, 2018). Irrespective of the targets, investments in agricultural science and technology must be used more effectively, and declining public investment reversed. All actors must preserve the same high, evidence-based standards that has led to the success stories discussed in this paper—but also be prepared to move out of their intellectual comfort zones (Passioura, 2020).

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[c] The US Food & Drug Administration outlines drug development from lab to animal models, and the three phases of clinical trials https://www.fda.gov/ForPatients/Approvals/Drugs/default.htm.

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