Making science useful to agriculture

Adelaide, 26-29 November 2018

University of Adelaide

North Terrace Campus

Horace Lamb Room 422

Foreword

The challenges for global agriculture in the next two decades are[1]: (1) for all at all times, abundant, affordable, healthy and nutritious food; (2) for farmers, comfortable stable incomes, in line with the rest of society, from sustainable farming with less drudgery; (3) for the non-farm environment, absence of encroachment and of contamination by farming; (4) for the rural communities, viable support and attractive landscapes; and (5) for the world, maintenance of non-agricultural biodiversity.

Meeting these challenges requires focused investment of scarce R&D resources, and managing the tension between formal economic evaluation of alternative investments and fostering ingenuity, serendipity and scientific entrepreneurship[2]. An implicit assumption in the assembly of R&D portfolios is that the underlying science is sound.

This workshop will discuss the investment of limited resources to R&D in agriculture, illustrate instances where reductionism, oversimplification or plain lack of rigour compromise the outcome of these investments, and highlight cases where genuine multidisciplinary research reduces the risk of misconstructed science.

Victor Sadras

Adelaide, November 2018

1 Fischer, R. A. & Connor, D. J. Issues for cropping and agricultural science in the next 20 years. Field Crops Res. 222, 121–142 (2018).

2 Alston, J. M., Norton, G. W. & Pardey, P. G. Science under scarcity: principles and practice for agricultural research evaluation and priority setting. (Cornell University Press, 1995).

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Pedro Aphalo, Ford Denison, Peter Langridge and Victor Sadras conceived and developed this project.

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Monday 26 November. Investing in R&D

Chairs morning, Kathy Ophel-Keller; afternoon, Stephen Loss

0800-0900		Registration
0900-0910	Victor Sadras	Welcome
0910-0940	Primal Silva	OECD Co-operative Research Programme: Biological Resource Management for Sustainable Agriculture Systems
0940-1030	Victor Sadras	Reductionism, over-simplification and plain lack of rigour can misguide R&D investment
1030-1110	Julian Alston	Science under scarcity: principles and practice for agricultural research evaluation and priority setting
1110-1130	Coffee	
1130-1210	Stephen Loss Francis Ogbonnaya	Investing in R&D to create enduring profitability for farmers
1210-1240	Alan Mayfield Malcom Buckby	The role of the South Australian Grains Industry Trust (SAGIT) in agricultural research
1240-1310	Peter Appleford	A primary industries research investment framework for the allocation of state government revenue
1310-1400	Lunch	
1400-1440	Richard Gray	Decision making in producer controlled research organizations
1440-1520	Bill Long	Farmer perspective
1520-1540	Coffee	
1540-1700	Discussion	
1800-2000	Welcome drinks	Wined Bar, National Wine Centre of Australia

1) What is the state-of-the-art in the methods of funding allocation to R&D in agriculture? What makes successful research and what leads to waste and failure?
2) Comparison of different models and scales; state, national, international.
3) How to manage the trade-off between socially and economically sound investment requiring priority setting, and encouraging scientific entrepreneurship, creativity, serendipity and innovation?
4) IP issues in public/private research, help or hindrance.
5) How to manage the trade-off between collaboration and competition?
6) Peer-review of research funding proposals, pros and cons. How can it be improved?

Tuesday 27 November. Failure and success in crop improvement

Chairs morning, Tony Fischer; afternoon, Renee Lafitte

0900-0940	Peter Langridge	State-of-the-art in genetic resources
0940-1020	Pedro Aphalo	The importance of context in plant biology
1020-1100	Ford Denison	Evolutionary trade-offs as constraints and opportunities
1100-1140	Coffee break	
1140-1220	Jill Lenne	Scientifically sound conservation of genetic resources for crop breeding
1220-1300	Renee Lafitte	Searching for transgenes that improve yield: promise and reality
1300-1400	Lunch	
1400-1440	Tony Fischer	Expensive distractions in pre-breeding research: can we do it better?
1440-1520	Martin Kropff	Intensive maize and wheat breeding efforts at CIMMYT
1520-1540	Coffee	
1540-1700	Discussion	

1) Misconceptions in scientific research impacting the return of R&D investment; focus in breeding.
2) Critical comparison of “Gene-first” and “phenotype-first” models. Can we improve return from R&D investment with a more nuanced definition of phenotype?
3) Progress in plant breeding. state-of-the-art in quantifying genetic and environmental components of phenotypic variance. The role of models.
4) Avoiding expensive distractions in pre-breeding research and plant breeding – can we identify them?
5) Private plant breeding and global monopolies

Wednesday 28 November. Failure and success in agronomy

Chairs morning: Tim Reeves; afternoon: David Connor

0900-0940	Holger Kirchmann	Why organic agriculture is not the way forward
0940-1020	Megan Ryan	How to increase impact for agriculture from research on the soil biota?
1020-1100	Ines Minguez	Simple indicators, society concerns, and scientific rigour: the example of the water footprint
1100-1120	Coffee break	
1120-1200	Peter Hayman	Making climate science useful to agriculture
1200-1240	John Passioura	Translational research? Which way?
1240-1330	Lunch	
1330-1410	John Kirkegaard	Incremental transformation: science and agriculture learning together
1410-1450	John Porter	Identifying model improvement through yield and resources use efficiency identities
1450-1530	Daniel Rodriguez	Agricultural systems research to tackle complex problems in agriculture
1530-1600	Coffee	
1600-1700	Discussion	
1900-2230	Dinner	Majestic Roof Garden Hotel; 55 Frome Street, Adelaide

1) Misconceptions in scientific research impacting the return of R&D investment; focus in agronomy.
2) Critical comparison of production systems with emphasis on water and nutrients.
3) Avoiding expensive distractions in agronomy – can we identify them?
4) Genuine multidisciplinary research to avoid misconstructed science.
5) Peer-review and the role of journals setting agendas.
6) University drivers (ARC drivers, university rankings, overseas student recruitment, high-cits, H-indexes etc) on staff focus.

Thursday 29 November. Integrating discussion

0900-1200	Final discussion	Chair: John Passioura
1200-1215	Close	Primal Silva
1215-1330	Lunch	

Outcomes from final discussion

- CRP perspective
- Survey of participants
- Main findings of workshop: initial summary
- Consolidated set of papers for proceedings
- Single, multi-author paper

Reductionism, over-simplification and plain lack of rigour can misguide R&D investment

Victor Sadras

South Australian Research and Development Institute

Closing the gap between food demand and supply requires focused investment of limited R&D resources, hence the need for formal economic evaluation of alternative investments and priority-setting procedures (Alston et al., 1995). This in turn requires solving the tension between the fact that we cannot "manage the discovery of the unknown" (Osmond, 1995), hence the inherent risk in R&D investment, and the need to avoid, in Tony Fischer's terms, "expensive distractions" in agricultural research (see Fischer's paper in this proceedings). The problems of food security and agricultural sustainability are here and now, and tools to help us to narrow our focus and improve chances of successful investment are crucial. Transforming cereals to fix nitrogen is a biologically fascinating proposition, but it could be argued it is an expensive distraction in a pressing context of food security.

The increasing carrying capacity of agriculture over historical time scales is the best evidence of robust and relevant progress in its subsidiary sciences (Connor, 2008; Sinclair and Rufty, 2012). However, there is room for improvement; reductionism (sensu Kauffman 2016), over-simplification and occasional lack of rigour can misguide allocation of R&D effort, and compromise returns on investment especially when scales, trade-offs and larger contexts are ignored. A few examples dealing with organic agriculture, water management, biotechnology and conservation of genetic resources illustrate this point.

Seufert et al. (2012) compared yield of organic and conventional production systems and concluded that "under certain conditions - that is, with good management practices, particular crop types and growing conditions - organic systems can thus nearly match conventional yields, whereas under others it at present cannot. To establish organic agriculture as an important tool in sustainable food production, the factors limiting organic yields need to be more fully understood, alongside assessments of the many social, environmental and economic benefits of organic farming systems." This paper published in Nature attracted over 660 citations – a measure of its influence - and promotes the investment in research to identify the causes of yield gaps in organic agriculture to improve global food production. The conclusion of this study is however, misleading because it fails to account for the supply of organic nutrients required to replace inorganic fertilizers, and hence confuses yield of individual crops with that of production systems (Connor, 2013; Kirchmann et al., 2016). Predicting field-scale organic yields from small plots is also risky (Kravchencko et al., 2017). This illustrates the issues from over-simplification related to scales, in this case using the research plot or even field, rather than the farming system, as the biophysically and economically relevant unit for comparison. Similar scale issues abound in pest management. For example, a single transgenic plant releasing aphid alarm pheromone repels aphids, but aphid numbers were not reduced when an entire field did so (Bruce et al., 2015). On the other hand, a landscape dominated by Bt crops may also protect non-Bt crops (Hutchison et al., 2010).

The importance of water for agriculture and society at large cannot be understated. The water footprint has been defined as "a measure of humanity's appropriation of fresh water in volumes of water consumed and/or polluted" (http://waterfootprint.org/en/water-footprint/what-is-water-footprint/.). This taps on a legitimate society's concern with the use of natural resources. Depending on its source and fate, the water footprint defines blue, green and grey water. However, the concept of water footprint and these water categories are a gross oversimplification, and its application to food production is largely meaningless as highlighted by Fereres et al. (2017). Nonetheless, the simplicity of the concept makes it appealing, and funding research allocated to this perspective is at the very least, a distraction.

Biotechnology has transformed cropping systems worldwide. Before transgenic Bt crops, the Australian cotton industry was poised between two unsustainable states (Downes et al., 2016; Fitt, 1994). One of them was the economically unsustainable option of limiting insecticide applications to control Lepidoptera pests, with costly implications for yield and profit. The other was the precarious reliance on broad-spectrum organophosphates, carbamates, and pyrethroids, as well as endosulfan where crops were typically sprayed 12–16 times per season. Early Bt-cotton and following upgrades dramatically reduced the dependence on insecticides and shifted the industry into a more sustainable trajectory, despite the emergence of new challenges. In 2009, Bt maize was sown on more than 22.2 M ha in the US, accounting for 63% of the national crop and returning an estimated cumulative benefit over 14 years of US$3.2 billion for maize growers in Illinois, Minnesota, and Wisconsin, and US$3.6 billion for Iowa and Nebraska (Hutchison et al., 2010). Early transgenic soybean featuring glyphosate resistance and associated agronomic innovations, chiefly no-till, have re-shaped the agricultural landscape of South America (Cerdeira et al., 2011; Marinho et al., 2014; Viglizzo et al., 2011). Brazil and Argentina became world leaders in production and export of soybean products. The cotton, maize and soybean examples are relevant because biotechnological innovations with widespread agronomic impact largely relate to crop protection (Dunwell, 2011; Halford, 2012; Mannion and Morse, 2012). Relative to crop protection, biotechnological approaches have under-delivered in improving yield potential and drought adaptation despite significant commitment of resources (Passioura, 2006). A common explanation for this underperformance has been that yield is a complex trait. However, this argument is incomplete for at least two reasons. First, direct selection for yield, has and continues to deliver significant improvements in crop yield (Fischer et al., 2014). Second, under-preformance of biotechnology to improve yield also relates to an over-simplified view of the phenotype (Félix, 2016; Piersma and van Gils, 2011; West-Eberhard, 2003, 2005), trade-offs (Denison, 2012), and scaling across levels of organisation (Sadras and Richards, 2014). Reductionist and over-simplistic views are not universal (Reynolds and Tuberosa, 2008) but remain influential in biotechnology (Pickett, 2016; Vinocur and Altman, 2005).

Ex situ conservation of genetic resources for the use of plant breeders is the proven cornerstone of crop improvement for global food security. Yet in the past 20 years, increasing funding has been allocated away from *ex situ* conservation to *in situ* conservation of wild species and on-farm conservation of landraces on the expectation that such populations will evolve useful traits with environmental change (Wood and Lenné, 2011). Where population monitoring occurs, it is based on assessment of overall genetic diversity. Functional diversity (identifying resistances to diseases and pests and tolerance of abiotic stresses) is rarely assessed. To date, there is no evidence of successful identification of useful traits. This is not unexpected since evolutionary changes may not be observed for 100 years or more (Frankel et al., 1995). In fact, Harper (1990) noted that the occurrence of resistance genes in wild relatives of crops is evidence of powerful long past selective forces. The lack of success in demonstrating a major value for *in situ* conservation for food security signals the need for a radical rethink on the most resource and cost effective way to conserve valuable genetic resources. *In situ* conservation in the absence of appropriate research is an expensive distraction in the context of food security.

In this context, this workshop will discuss the investment of limited resources to R&D in agriculture, illustrate instances where reductionism, oversimplification or plain lack of rigour compromise the outcome of these investments, and highlight cases where genuine multidisciplinary research reduces the risk of misconstructed science.

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Science under scarcity: principles and practice for agricultural research evaluation and priority setting

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Among the messages in "Science under Scarcity" is the idea that we cannot formally evaluate everything in sight, and should not aspire to do so, but it is desirable nevertheless to inculcate an "economic way of thinking" into research management processes. For example, in the Conclusion to the book:

> *Perhaps the major benefit from a process of research program review, evaluation, and priority setting is that the participants gain a clearer view of what they are trying to achieve—and how best to get there. Scientists and policymakers will make better decisions as they develop an economic way of thinking about research investment choices*. (p. 512)

This economic way of thinking entails combining an understanding about the fundamental determinants of the payoffs to particular research investments with the logic of choice as it applies to allocating scarce research resources among alternative project investments in a context of considerable uncertainty.

In this presentation, I plan to discuss the logic of (economic) choice as it applies to evaluating investments in R&D and setting priorities, the critical determinants of the payoffs and thus priorities, short-cut methods to be applied when a full benefit-cost analysis is not appropriate, and the issues that arise in contemplating investments where the benefits are less easy to measure (or even envision measuring)—e.g., as discussed in the context of policy-oriented environmental research by Pannell et al. (2018).

In some senses this will be a synopsis of lessons to be learned from "Science under Scarcity" and some more-recent sources, including Alston et al. (2009), and the Council for Rural Research and Development Corporations (2014) among others. These lessons will include some consideration of the challenges in ex ante analysis, of having meaningful estimates of (a) the gains per unit (e.g, per hectare) if the research is successful and adopted, (b) the number of adopting units, and (c) the timing (research, development, and adoption lags).

I also envision commenting on the role of formal evaluation and priority-setting processes and their limitations, and the risk of stifling curiosity, serendipity, and other good things that are part of creative processes of discovery and knowledge creation, some of which is discussed in Alston and Pardey (1996, especially pp. 318–324 and pp. 338–342). Another place for the useful application of an economic way of thinking is in the design of the institutional arrangements for research funding, resource allocation, and management.

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Investing in R&D to create enduring profitability for farmers

Stephen Loss and Francis Ogbonnaya

Grains Research and Development Corporation, Australia

The Grains Research & Development Corporation (GRDC) is a statutory body established in 1992 under the Primary Industries Research and Development Act (1989) of the Australian parliament. Under this act various research and development corporations were created with funding from commodity based levies and government contributions to invest in scientific research that drives agricultural innovation and creates knowledge, products and services that enhance efficiencies.

Over the past 25 years farmer funded levies from 25 grain crops plus government contributions have been successfully invested by GRDC to benefit the grains industry. Over the past 15 years, the gross value of grains production in Australia has grown from $5.1 to $18.2 billion, and GRDC currently invests around $200 million p.a. in roughly 900 research, development and extension (RD&E) projects. Unfortunately, state governments have reduced funding to agricultural agencies over a similar period of time, and GRDC is now the primary investor in the Australian grains industry.

Governance

GRDC is governed by a Board of Directors and Managing Director appointed by the Minister of Agriculture and Water Resources. Issues constraining farm businesses and opportunities to grow the industry through RD&E are guided by Northern, Southern and Western Regional Panels consisting of farmers, advisers, agribusiness and researchers. These panels identify and monitor regional issues, interact with stakeholders to keep them informed of GRDC strategic direction, and assist staff in monitoring the effectiveness of the investment portfolio. Each regional panel is further augmented by a number of Regional Cropping Solution Networks or Grower Solutions Groups. The panels and network groups operate with a high degree of altruism and passion for the industry, and their participation in RD&E process fosters quality innovations and more rapid adoption.

2018-2023 Investment Strategy

Traditionally, GRDC has focused on boosting crop productivity through investments in genetic improvement, crop protection, agronomy, farming systems and natural resource management, which have made significant contributions to the growth of the industry. As part of a new five-year strategic plan (2018-2023), GRDC has redefined its purpose:

To invest in RD&E to create enduring profitability for Australian grain growers.

This purpose feeds into five key objectives:

1) improve productivity and yield stability;

2) maintain and improve price;

3) optimise input costs;

4) reduce post-farm gate price, and

5) manage risk to maximise profit and minimize losses.

These, in turn, feed into 30 Key Investment Targets which prioritise the most important constraints or opportunities for investment. The new GRDC purpose signals a change in focus on a number of fronts.

Invest - The Corporation has recently undergone a major renewal and expansion under a “hub and spoke model”, opening new offices in Perth, Adelaide, and Toowoomba. About 50% of staff now based outside of Canberra, thereby providing greater engagement with the industry in the regions. The number of staff managing investments has increased, and they take a more active role in the direction of each project, regularly monitoring progress and new opportunities with researchers throughout the year. In this regard GRDC has moved away from being a ‘set and forget funder’ to an ‘investor and partner’. New RD&E proposals are developed and justified based on a business case and its likely return on its investment on behalf of Australian grain growers. Consequently, GRDC have employed a team of economists to help in the analysis and development of business cases.

Create - In the past GRDC called for project proposals from researchers and R&D organisations, but as the funding pool grew this became unmanageable given the sheer number of applications, even when priority areas were specified. Many discipline-based researchers are constrained in their approaches to issues and fail to consider alternatives e.g. pre-breeding organisations tend to advocate genetic solutions to low protein in wheat. GRDC is now placing greater emphasis on analyzing each core constraint or opportunity with input from stakeholders and technical experts, and weighing up a range of potential solutions and RD&E investments. Outputs from investments tend to be more prescriptive, and are either procured via an open tender to ensure value for money, or via a direct negotiation where one organisation has unique facilities, knowledge and skills. This enables GRDC to procure in a number of RD&E investments to address an issue, employing creative approaches while fostering collaboration and national coordination.

For many years GRDC and researchers paid close attention to how RD&E projects were going to provide impact for growers. However, this approach was probably over-emphasised, and many short-term and low-return development and extension projects were conducted where impact could be easily demonstrated. In some cases, innovative growers were more advanced in their thinking and practices than researchers. Interestingly, grains industry stakeholders have recently provided clear feedback to GRDC that they welcome more investment in high-risk and high-return ideas with potential to provide large boosts to profit and transform grain businesses. This points to the creative element required in identifying innovative scientific ideas and translating them into practical benefits for farmers. At the end of the day, a balanced portfolio of investments is required.

For many years GRDC has had alliances with CIMMYT, ICARDA and ICRISAT, and has recently entered into a large Herbicide Innovation Partnership with Bayer. GRDC is keen to learn from leading private and public organizations, and will help establish international collaboration where this creates value for Australian growers.

Profitability - The shift of focus towards profitability is noteworthy. Business skills are important in running a profitable farm, and many grain growers could benefit from improving their business management. Farm business advisers have a key role to play in this area and GRDC can help foster this type of training and advice. While yield is a big driver of profit for unsubsidized Australian grain growers, we should not ignore the major influence of commodity price and production costs. And risk is always a major consideration for Australian growers who are susceptible to seasonal variations in rainfall and temperature, and fluctuations in grain prices.

Over the past few decades many growers have moved away from livestock production largely because of low meat and wool prices, towards continuous cropping which has increased their level of inputs and risk. GRDC has always emphasized optimising input costs to maximise profits, and it is now more open to investments that maintain and improve grain price through novel products, functionality, and processing, and other innovations that may reduce post-farm gate costs through more efficient logistics and handling, where a benefit is returned to the producer.

Enduring - The word ‘enduring’ in the new GRDC purpose statement picks up on the risk element, and also indicates a need for economic, environmental and social sustainability. Despite the expansion of large corporate farms in Australia, most of our farms are still family-based businesses managed within rural communities. The social needs of families are important and family farms have adapted to operate in remote areas where populations have declined significantly over the past century, particularly in WA and SA.

While Australia’s grain production has a ‘clean and green’ image and its impact on natural resources appears to minor, environmental sustainability is becoming increasingly important, especially as social values are driven by growing urban populations on the coast. Recent public misperceptions over the safety glyphosate is one pertinent example. The grains industry needs to be able to quantify its impact on the environment and justify its ‘clean and green’ image. Where impacts are significant, they must be mitigated. GRDC has an important role in the production of evidence-based data to inform policy in these areas. Many of these issues are cross-sectoral, and GRDC explores and co-invests with other industries where there are synergies e.g. with meat, wool, and cotton.

Australian grain growers - Finally, the new purpose clearly identifies GRDC’s major stake holder – growers. This is not to say that government is not important, as they contribute around $70 million p.a. The GRDC strategy is to make growers more profitable for the benefit of the industry, which should in turn keep governments satisfied. This aligns with the government’s policy of improving net farm-gate returns for the primary industries. While not all growers will benefit from every investment, the GRDC aims to deliver impact to all growers commensurate with the levies they contribute.

Genetic Enhancement

GRDC investments in pre-breeding are focused on the effectiveness of the breeding programs in achieving maximum genetic improvement, a function of improving the rate of genetic gain (amount of increase in performance achieved per unit of time through artificial selection), which is a universal measure of breeding progress. Consequently, investments are tailored to impact on the major planks of that framework including:

- adequate genetic variation
- enabling higher selection intensity
- improving accuracy if selection
- accelerating the breeding cycle

This ensures that maximum value is delivered to Australian grain growers through the rapid delivery of improved varieties. GRDC's R&D targets for investment in this area are tailored towards high priority issues identified by growers (aligned to the 30 Key Investment Targets), as well opportunities including market drivers which inform and contribute to breeding program outcomes. Engagement with breeding entities as co-investors ensures a path to market, but GRDC does and will not subsidise core breeding activities or create market failure.

Crop Protection, Agronomy and Natural Resource Management

Investments in agronomy, crop protection and natural resource management take the best adapted genotypes and explore management practices to exploit their genetic potential. These disciplines also play an important role in informing pre-breeders of the major constraints to profits from each crop in each sub-region and quantifying the value of specific traits to overcome limitations. Farming systems research integrates all other research areas and helps farmers determine the most effective way of producing crops (and other commodities) given the natural resources, labour, machinery and infrastructure, economic drivers and attitude to risk, while informing them of their long-term impact on the environment.

Collaboration, Creativity and Intellectual Property

Being the dominant investor in the Australian grains RD&E landscape, GRDC has a role in coordinating activities that foster collaboration, scientific entrepreneurship and creativity, while minimizing duplication and waste. To this end, GRDC recently instigated national forums for GRDC researchers in the each of the areas of agronomy, farming systems, nutrition and soils. These areas of investment are often regionally specific and researchers are sometimes unaware of similar work in other regions. The first of these forums in 2018 were highly successful in better coordinating R&D. GRDC also has role in fostering international collaborations with private and public organizations.

Where valuable intellectual property is developed through GRDC supported R&D, GRDC works to ensure that this is protected and parties that contribute to its creation and development reap a fair financial reward from its commercialisation. In this regard GRDC has co-invested in the establishment of breeding companies and commercial products and services, and consequently, receives a small proportion of its funds from royalties and other income streams. GRDC's primary aim is to ensure innovations are rapidly brought to the market and are widely adopted to benefit grain growers. A variety of commercial arrangements can help achieve this. Occasionally, GRDC is criticised for using grower levies and government funds to develop and commercialise a product or service, and that growers are then forced to pay a second time to access these. However, without investment from GRDC these innovations may not reach the market and any income coming back to GRDC is re-invested in further R&D.

Extension and Communication

Without adoption, scientific innovation is virtually pointless. Over the past three to four decades, governments have retreated from funding farm advisers and the gap has largely been filled by private and retail agronomists. Local farming system grower groups have also developed an important avenue for promoting practice change. For example, the formation of state based No-Till groups was particularly instrumental in the adoption of conservation agriculture, especially reduced tillage.

GRDC and partners have an important role in facilitating the extension and communication of R&D outcomes to promote practice change on farms. As farmers have less and less time to attend field days, workshops and discussion groups, and limited capacity to digest the myriad of technical publications produced by various organisations, GRDC is increasingly targeting advisers for their extension and communications. By informing and influencing one adviser, this could lead to practice change for 30 or 40 growers. GRDC will continue to stay in close touch with growers through its regional panels, and Regional Cropping Solution Networks or Grower Solutions Groups. While GRDC does not provide funding for core activities of farming systems groups, we work in close partnership through validation, extension and communication projects to drive practice change.

More Information

Website: https://grdc.com.au/

The role of the South Australian Grains Industry Trust (SAGIT) in agricultural research

Malcolm Buckby & Allan Mayfield

South Australian Grains Industry Trust

Structure and role of SAGIT

The South Australian Grains Industry Trust (SAGIT) is a SA based agricultural research funding organization that was established in 1991 as a Charitable Trust from levies paid by grain growers in South Australia to the Commonwealth government. No other such state organization exists in Australia, the national equivalent is the Grains Research and Development Corporation.

The Trust operates with a Board of five Trustees, one a Ministerial representative, Andrew Barr, and four grower representatives, Max Young (Chair), Michael Treloar, Bryan Smith and Edward Langley, who meet a minimum of four times per year. The term of office for a Trustee is three years and a maximum of three consecutive terms can be served.

The management of the Trust is undertaken by the Project Manager, Malcolm Buckby. A Scientific Officer, Dr Allan Mayfield, advises the Trustees on project applications and reviews progress of the research projects.

Funding for research is from a 30 cent per tonne levy on grain sold by South Australia growers. This levy is received by the Department of Primary Industries and Regions through an Act of the South Australian Parliament – Primary Industry Funding Schemes Act 1998 - *Primary Industry Funding Scheme (Grain Industry Research and Development Fund)* Regulations 2013. On average $1.7m is received annually which is allocated to research within South Australia.

Operation

In late November an open call is made for research applications (closing on the first Friday in February). SAGIT does not set any priorities and applicants determine the issue(s) they wish to investigate.

There are several types of applications: Research, Capital, Travel, Out of Session (for issues that arise between the annual calls) and Grower Group (a maximum of $3,000 to assist grower groups to pay for the cost of speakers at workshops and field days).

The Trustees meet in March to decide which projects are to be funded, based on assessment criteria (including relevance to the grains industry, scientific merit, innovation, probability of success and value for money). The funding available is based on the levy income from the previous harvest, with a possible additional allocation from reserves. Funding is set aside for the full duration of the project thereby ensuring that should a drought occur, and levy funds diminish in a particular year, the project is not affected. A Funding Agreement contract is then sent to the successful applicants for signing. Payments are made twice per year, on 1 July and 1 January.

Each year the project supervisor must provide a Progress Report (due at the start of February) and, upon completion of the project, provide a Final Report.

Projects funded by SAGIT

Typically, SAGIT funds between 20 and 30 new projects each year. There are also 20 to 30 on-going projects each year.

Project areas range from pre-breeding, to crop agronomy and crop protection to publications and to visiting speakers for grower group workshops. In a relatively new research area, this year there were three projects approved to study the impact of pesticides on soil microbial functions. The geographic spread of projects is from Streaky Bay on the Far West Coast to Millicent in the South East. This research also covers most broadacre crops as well as some pastures, with an emphasis on those crops grown over greatest area (wheat and barley) or of highest value (lentils).

Projects are mostly with research institutions, such as universities, SARDI and CSIRO, but some are also with other organisations, such as agronomists and grower groups.

Several projects are collaborative with GRDC, but most are stand alone. Researchers have used SARDI funding to tests concepts at early stages of development. A good example of this is development of the SARDI root disease testing service, PREDICTA® B.

SAGIT has a strong interest in increasing the research capacity within the state. In recent years it has funded two internships per year – one based in SARDI (and jointly funded with GRDC) and the other with the Hart Fieldsite Group in the Mid North.

SAGIT also supports projects to encourage secondary students to choose agricultural science as a career, through interaction with agricultural science school teachers and also by promoting agriculture at career expos.

Project monitoring and communications

As well as assessing Progress and Final Reports, projects are monitored by making site visits. Most projects are visited by the SAGIT Manager and Scientific Officer, and usually with one trustee, during the year – this is typically in August or September. These visits are to learn more about the project details, review project progress and maintain good communications between project staff and SAGIT.

AgCommunicators promote current SAGIT projects and results of research. A journalist from AgCommunicators travels with us when doing project visits to record videos with the project staff and write articles summarising projects – these videos are available on the SAGIT website. AgCommunicators also summarise SAGIT project Final Reports and upload these onto the website. This website also contains other current project information as well as application forms for funding, press releases and contact details of the trustees and management staff.

SAGIT also convenes a communication forum in July each year for current and interested project participants. This forum is used to highlight current SAGIT research, especially by young researchers, and also to reinforce messages about maintaining a high standard of research applications and reports. As part of this coaching in applying for SAGIT funding, the Scientific Officer is available to review draft applications at any stage and any time up to project application. This has improved the clarity of research applications making the job easier for the trustees.

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For further details, including project reports - www.sagit.com.au

A primary industries research investment framework for the allocation of state government revenue

Peter Appleford

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State Government's in Australia have research institutes responsible for delivering agricultural research on behalf of the state. Over the recent decades there has been an overall reduction in the funding for these institutes. This has necessitated the development of research investment frameworks that ensure efficient allocation of state resources to high priority areas that align with government policy.

The South Australian Research and Development Institute (SARDI), the research division of Primary Industries and Regions South Australia (PIRSA) is the South Australian State Government's principal primary industries research institute. Its vision is to deliver applied science that grows South Australia's primary industries, food and wine.

SARDI undertakes applied science that helps increase the productivity, sustainability and adaptability of the state's primary industries, food and wine enterprises, creates opportunities for market growth, addresses barriers to growth and provides applied solutions. SARDI has established a strong reputation for its technical excellence and undertakes significant and important research at a national level. SARDI is greatly valued by both industry and government agencies and accordingly receives strong support from funding bodies.

SARDI operates on the research continuum and bridges the gap between university research and industry implementation. This is a critical space on the research and development continuum where research results can be turned into public value through commercialisation and industry uptake. SARDI conducts high quality applied research for the grains/cropping, wine, horticulture, fishing and aquaculture, livestock (including wool), poultry, pig and food sectors.

A key challenge for SARDI is to ensure that SARDI research investment is driven by State Government policy priorities so it provides value for money to South Australia. This requires an objective Research Investment Framework to ensure the SARDI ongoing research investment decisions are in areas where:

1. It has a distinct advantage, that is there is the role of the South Australian Government and SARDI is best placed to provide the necessary research,
2. There is a direct contribution or added value to state economic growth and future research capability, that is the investment will add value.

Any research investment framework should be applied with rigour on investment decisions, from project to corporate scales, and should include a portfolio balancing tool. This will provide for risk-return (and other) tradeoffs and alignment with strategic goals and other priorities can provide a clear basis for transparent decision making and reporting, considering the option value of new capabilities as well as closure of existing capabilities.

The SARDI Research Investment Framework has the following elements.

1. *An assessment against key investment criteria*

This process is to identify long term changes (5 years) in the level of state government investment across the sectors. The options are start, maintain, increase, decrease and stop investment.

The criteria used in the SARDI investment framework are:

- government policy
- sector growth
- industry funding
- South Australia's has a comparative advantage
- maintenance of capability to support legislative decision making
- succession planning requirements for core science capability.

2. *A Portfolio Balancing/Investment Decision Process*

A process where high-level changes in the investment portfolio can be made in a transparent manner. The portfolio balancing/allocation decision process:

- Determines the investment available for commitment
- Proposes transparent mechanism for the allocation of investment across the SARDI programs/sub-programs
- Provides decisions on split of investment across science programs and sub-programs for the next three to five years
- Provides decisions on investment into new programs (if any) and how those programs will be funded and fit into the overall R,D&E program
- Provides for decisions on long term funding direction for the programs/sub-programs.

Based on the assessment against the investment criteria, an assessment against the sector policy priorities and the outcomes of an investment conference, the future allocations to current programs/sub-programs and any new opportunities are determined.

3. *Project Assessment Process*

Once the funds available within each research program/sub-program are identified it is important to ensure that the projects developed within those investment areas are consistent with policy. The project assessment process:

- Provides a transparent mechanism for selection of projects for investment
- Determines if the project aligns with policy
- Determines if the project is realistic and deliverable
- Determines if the outputs/outcomes of the research can be translated into impact.

To achieve this a four step process has been developed to assess projects.

Step 1 –alignment with the PIRSA Corporate Plan, SARDI Strategic Plan and or sector plans. If yes progress to Step 2, if no reject.

Step 2 –SARDI capability/infrastructure supports delivery of the project. Funding is likely to be available internally or externally. If yes progress to Step 3, if no reject.

Step 3 –research outputs/outcomes can be translated into impact. An acceptable return on investment to South Australia and the industry sector is expected. If yes progress to Step 4, if no reject.

Step 4 – a live project available to seek funding from unallocated SARDI investment pool (cash or in-kind) or external sources.

4. Research outcomes/return on investment

Monitoring and evaluation of research investment is an important component of any investment framework.

It is important that research portfolio performance is assessed against the relevant performance indicators. State, departmental those targets. This includes determining the return on investment from the research investment.

The role of producer controlled research organizations in making science useful to agriculture

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Producer controlled research organizations are prominent in the agricultural innovation systems of several countries, most notably in Australia, Canada, and United States. In each of these jurisdictions, government regulation allows the establishment of marketing orders to levy the sale agricultural commodities with the proceeds being used to fund industry directed research and development. These research funds are typically administered by an organization reporting to a producer board of directors. Given the sustainability and apparent success many of these Producer Controlled Research Organizations (PCROs) in facilitating agricultural innovation, these organizations very much belong in a discussion of *Making Science Useful to Agriculture*.

The goal of the research reported in this paper is to develop a better understanding of how these organizations contribute to effective innovation systems. The paper begins with a theoretical exploration of the role that PCROs can play in addressing market failures and externalities associated with research, intellectual property and extension. This is followed by an overview of the legal framework used to create PCROs, their activities and their performance. I then more closely examine the internal decision-making processes of grain based PCROs located in Australia, Canada and United States. The paper concludes with a discussion of the role the PCROs play in maintaining the social capital that facilitates agricultural innovation.

Very broadly speaking, science based agricultural innovation involves investment to undertake research to create knowledge that is eventually used to develop new products that are adopted by producers. For at least 150 years, governments have recognized that markets often fail to provide adequate incentives for purely privately funded systems agricultural innovation.

The lack of enforceable intellectual property rights (IPRs), market power, and asymmetric information, have been identified as important impediments to agricultural innovation. Without the protection of IPRs, most knowledge is as public good, which by definition is both non-rival and non-excludable. When IPRs are limited or non-existent, this reduces the private incentive to invest, causing a partial or complete market failure. When the lack of private incentive is addressed through strong IPRs, the non-rivalrous nature of the knowledge creates other forms of market failure related to toll goods and market power. Specifically, firms owning protected knowledge will charge a price above marginal cost and often restrict knowledge access by competitors. Finally, the producer adoption of most new products is a costly or/and a time consuming process, ultimately requiring an expectation that the purported benefits of the technology will be realized. Public testing and knowledge dissemination have often been used to address the market failure in this critical phase of the adoption.

Although governments have often addressed the market failures related to agricultural innovation through publicly funded research, development and extension (RD&E) activities, some policies also recognize that some of these public goods are best governed and funded by those in the industries that are most directly effected. Typically the benefits from research accrue most directly to those who are either consumers or producers of the commodity or sector where the research takes place. Alston et al (1995) also elegantly make the point, that unlike income tax, a sales tax on product has the same proportional incidence on producer and consumer surplus as the returns from a unit cost reducing innovation. Thus levy funded research results in a minimal transfer of resources from those funding the research to those who benefit from the research. Producer controlled organization can also serve as a trusted broker in testing and providing information about new technologies. From an institutional economics perspective PCROs are well-incentivized to address the market failures associated with agricultural research and adoption (Picciotto, 1995).

In Australia, several PCROs, established under the *PRIMARY INDUSTRIES RESEARCH AND DEVELOPMENT ACT* 1989, play a central role in agricultural research, development and extension. The Grains Research and Development Corporation, the largest PCRO with a budget close to $ 200M AUD, is funded by a 1% levy on the sale of 27 grains matched with a 0.5% contribution for the Commonwealth Government (Gray et al 2017). The GRDC board of directors (BOD) is made up of producer nominated, government appointed directors. Several mandated cost/benefit studies have found high rate of return on investment activities. In Canada, the Canadian Wheat Board established the Western Grain Research Fund in 1981. Later in the same decade many provinces introduced legislation to facilitate the development of PCROs, with just over 50 in existence today. Perhaps the most successful is Saskatchewan Pulse Growers whose efforts created globally competitive lentil and pea industries. In the United States, State or Federal Marketing orders can be used to create state- or national-level commissions with the authority to Research, Development and Marketing activities. The US Soybean Board is the largest US PCRO with budget exceeding $100M USD per year. Several State Wheat Commissions have been dominant in wheat breeding.

As a means to better understand the decision-making processes of PCROs, Hossieni (2017) conducted a series of interviews with the managers and directors of fourteen PCROs across Australia, the United States and Canada. During these interviews, it became clear that with the exception of the GRDC, the BODs are involved in both oversight and management decisions.

The lack of separation in task assignment sharply contrasts with most of the theories and empirical studies focusing on the governance structure of non-profit and for-profit organizations (Brown and Guo 2010; Fama and Jensen 1983; Miller-Millesen 2003). To explore this anomaly we modelled the incentives of the manager and the BOD as agents of the PCRO with differing motivations to exert effort. The directors of the PCROs, as farmers are agricultural sector beneficiaries, can be positively affected through altruism and learning in the process of decision-making. The manager exerts effort in return for financial compensation including a base salary and a bonus. The bonus can be based on a performance measure of PCRO output or, alternatively the observed expertise and effort of the manager.

The theoretical analysis shows that a separation of BOD oversight and management is optimal when output of the PCRO can be measured accurately. However, the very long research lags and the lack of a market valuation of the non-profit research portfolio generally precludes any timely measurement of output for the PCRO, thus output is poorly suited to incentivize the manager (Sappington, 1991).

When output measures are precluded shared decision-making is more likely to be the norm. In these situations, the directors will participate shared decision-making in order to directly contribute to and incentivize managerial effort. Therefore, it seems that there is a rationale behind the choice of shared decision-making in these organizations. In fact, the unusual task assignment of PCROs helps these producer-led entities to accomplish their mission in provision of industry good. The results of the study also show that board members' altruism and knowledge levels are important contributions to the success of PCROs. This implies that resources spent on increasing knowledge stock through recruitment, training, and retention could pay long-term dividends to the PCROs.

The GRDC, which is an order of magnitude larger than most of the PCROs we studied, has a greater separation between oversight and decision-making roles. However, the GRDC has also devoted resources to ensure producer input and expertise in their research decision-making and have supported local producer research groups through the Grower Group Alliance and Cropportunity Networks (Gray et al 2017).

More research is required to understand how producer involvement supports effective agricultural innovation systems. To this end, some of my more recent work looks a greater range of producer organizations involved over time in agricultural RD&E. In Saskatchewan, the ability and agility to create new organizations to engage, public, private and producer resources foster innovation very well developed. For instance, the development and rapid adoption of zero tillage was supported by newly purposely formed Saskatchewan Soil Conservation Association, which grew to over 3,000 members at its peak, and the Indian Head Agricultural Research Foundation, which facilitated field scale testing and demonstration of the technology. Four years ago, when soybeans were still less than 0.2% of the cropped area, the Saskatchewan Pulse Growers, helped create a Soybean Cropportunity group made up of all the relevant public, private and producer stakeholders, with goal of identifying and addressing any impediments to soybean adoption. Given these and other examples, I'm convinced that collectively the province has developed the *social capital* to foster and support agricultural innovation. With the goal of replicating this success my current research is analyzing the role that events, key individuals, organizations and public policies have played in the development of the innovation related social capital.

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State-of-the-art in genetic resources

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The breeders' equation sets out the four major factors that influence the rate of genetic gain achieved in a breeding program. Breeders will seek opportunities in all four areas to improve the success of their programs and over the past hundred years, they have adopted many innovations from a wide range of research fields.

$$The\ rate\ of\ genetic\ gain = \frac{Diversity\ \times\ Population\ size\ \times\ Heritability}{Breeding\ cycle}$$

Some clear examples include the introduction of mechanisation in seeding and small plot harvesting that has allowed large increases in scale and population sizes, new statistical methods and the use of computing leading to big improvements in heritability through spatial correction of field trials, and tissue culture methods, such as doubled haploidy and embryo rescue, that have reduced the breeding cycle. Enhancing the diversity available in a breeding program has also expanded through new technologies. These include the use of wide crosses, mutation breeding and genetic engineering. Over the last 70 years over 2250 varieties for most of our 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; Feuillet et al., 2008). However, perhaps the most impressive and controversial example of enhancing diversity has come through genetic modification (GM). This technology has been banned or blocked in many countries and regions but has, nevertheless, expanded to cover almost 200 million hectares in the 22 years since the first commercial were grown (ISAAA, 2018). The time to uptake of this technology was also very rapid since it was only around 15 years from the first GM plant to the first major commercial crop. GM was launched with considerable hype around its potential to change almost all aspects of crop breeding and many of the promises have not been realised despite large investments. It is certainly true that the poor acceptance of the technology by some countries and the complex regulatory framework have proved major impediments to delivery of outcomes (Smyth, 2017), but it is also likely that many of the targets would never have been feasible with a single gene approach which has been the basis for GM crops. A component of this problem has related to evaluation of genes and GM lines. For simple traits, the phenotyping has been relatively cheap and easy; the plants are resistant to the herbicide or not. For complex traits, the phenotype is often more subtle and extensive field evaluation is needed. For GM lines, this is difficult and costly due to the regulatory requirements and is not feasible for many researchers, particularly in the public sector. An example of this problem can be seen through the attempt to engineer drought tolerance in crops. Despite a large effort, and large investment, progress has been limited. Only two GM crops engineered for enhanced drought tolerance are in commercial production (maize and soybean) and the yield benefit is maize is only around 6% under drought (Nemali et al., 2015). This is lower than hoped for from the technology but is around the same as achieved through other approaches, such as physiological breeding for canopy temperature suppression and carbon isotope discrimination (Reynolds and Langridge, 2016).

Despite these issues, there are still several major research programs targeting complex traits that will involve multiple transgenes. These include programs on enhancing photosynthetic rates (Betti et al 2016; Long et al 2015), converting C3 to C4 photosynthesis (Von Caemmerer et al., 2012; IRRI, 2018) and transferring N fixation to non-legumes (Mus et al., 2016). These will all have a long delivery timeframe and there ultimate value may lie primarily in enhancing our understanding of the genetic control of key growth and developmental pathways. They also offer important training programs and help maintain interest, excitement and investment in basic plant science.

Assessing the impact and relative value of technologies is difficult. On the surface, GM technologies would rank at the very top of modern technologies given the speed and extent of adoption (close to saturation in the top 5 countries) and the large economic impact. The estimated economic gains are US$186.1 billion and there have been major environmental benefits; 670 million tonnes reduced pesticides and reduced CO_2 emissions of 27 billion Kg in 2016 alone (ISAAA, 2018). Overall, a good outcome particularly given the regulatory constraints. However, this outcome falls far short of expectations and promises. The new technologies of gene editing may provide a non-GM path for deploying our knowledge of genes and their function but it is still not clear how or if this technology will be regulated (Araki and Ishii, 2015).

The investment in GM crops was built on the concept of expanding genetic diversity available in breeding programs through accessing genes from any source. For some crops, such as cotton, canola, maize and soybean, GM varieties now dominate and a large proportion of breeding investment is based on GM lines. This has reinforced the commercialisation of plant breeding with a concomitant decline in public sector activity. Therefore, in some regions, where GM lines are not available to farmers, there is limited access modern varieties. However, for some crops, such as wheat and barley, there are no commercial GM lines available and there is no expectation that this will change over the next decade.

The underlying technology for GM crops was molecular genetics; the isolation and characterisation of genes. This technology has now moved well beyond GM crops and found many other paths for delivery to crop improvement. These include the use of molecular markers to track traits in breeding programs; a technology that is now deployed with great success in most major crops. The technological advances have also taken us from the analysis of single genes to a consideration of the entire genetic make-up of a plant. This expansion was seen as a potential path to explore the control of complex traits that had proven recalcitrant to the single gene approach. The rise of the ‘omics’ technologies led to a shift in the approach to tackle complex genetic problems with many groups hoping that the generation of large datasets on genes, their expression (transcriptomics) and products (proteomics and metabolomics) would somehow resolve the complexities of environmental and pathogen responses. Large datasets of variable quality and value have been generated and many provide valuable resources, but they have largely failed to resolve the control of key traits. The drive to generate the various ‘omics’ databases was largely technological advances, it was possible and therefore done, rather than based on clear hypotheses. Although the resources are now proving useful for many researchers, the difficulty in relating the data to plant performance has prompted renewed efforts in characterisation for germplasm or phenotyping (Araus et al., 2014; Fahlgren et al., 2015). This has also been largely technology driven and risks falling into the same trap as happened with the ‘omics’ technologies; namely, generation of large and confusing datasets that are hard to use and not necessarily relevant to the assessment and screening of the targeted traits.

Returning to the breeder's equation, there is clear evidence that the advances in genetic characterisation, genotyping, has led to major changes in breeding methodologies. The evidence lies in the broad adoption of molecular markers, which have improved all four parameters in the equation. More recently, the use of genomic selection as a tool to manage large populations and reduce the breeding cycle time has shown positive results. However, this does come with the potential penalty of reducing the genetic diversity available in a breeding program since novel alleles and diverse germplasm can reduce the predictive power of the selection models.

The advances in genotyping and phenotyping have revitalised interest in the utilisation of genetic resources and several large research programs have sought to characterise accession in genebanks as a route to improve use. There are around 7 million accessions in about 1750 genebanks around the world but only a few percent of the accessions have been used and it is estimated that only around 10% of the natural diversity has been captured in elite germplasm of our major crops (Feuillet et al., 2008). Plans have been initiated to genotype entire genebanks (McCouch et al., 2013; Divseek, 2018) and some programs have attempted to provide both genotypic and phenotypic information on accessions (Seeds, 2018). The researchers undertaking this work have been motivated by several examples where major yield gains have resulted from introgression of wild germplasm into breeding programs (examples include Robigus wheat in the UK and Fathom barley in Australia). However, this has usually been a matter of chance rather than the result of a systematic screen. An exception is provided by simply inherited traits where a clear phenotyping assay is available, such as for many disease resistance loci.

This leads back to the same problem that was faced in attempts to improve multigenic traits through physiological breeding and GM. Genotypic information provides data on redundancy and diversity in gene banks, it does not provide information on functionality. Therefore, we are faced with the problem of assessing unadapted germplasm for adaptive traits. The Focussed Identification of Germplasm Strategy (FIGS) (Sanders et al., 2013) uses a knowledge of the environment where accessions were collected to prioritise lines for evaluation. This has been successful for some traits and can reduce the scale of screening needed, but his approach has been difficult to implement for complex traits. The second problem relates to the technical difficulties in introgressing chromosome segments from land race or wild germplasm into elite cultivars. This can take many years of hard work due to low recombination rates and the associated problem of linkage drag. Therefore, a large investment of time and effort is needed to evaluate just a small number of accessions. Finally, the problem of multigene traits appears yet again. Unless the effects of the genes are additive, which is unlikely for most yield related traits, it is impractical to transfer a large number of genes from an unadapted line to an elite cultivar. The population sizes needed to manage even a small number of genes makes the costs of this approach prohibitive.

Where does this leave us? We know that diversity is a major factor influencing genetic gain and we can see specific examples where genomic regions from wild germplasm has led to large yield jumps. We also know that the diversity in modern breeding programs has narrowed and that several new technologies may exacerbate this problem. We have access to huge variability in genebanks but we are struggling to find ways to use this variation effectively. Our strength in deploying variation has been largely through managing single genes and easily assessed traits, such as many disease resistances, and we have done this through accessing wild germplasm or inducing new variation with mutagenesis and GM. This work must continue and will be helped with the new tools for allele mining with advances in genotyping and phenotyping. However, we also need to find new ways of bring multiple genes into our breeding programs and there are some encouraging new trends in this area with the possibility of re-domestication (Lemmon et al., 2018; Zsogon et al., 2018).

Over the past few decades, research into genetic resources has been dominated by the field of molecular genetics. As with most areas of science, molecular genetics has led us down several blind alleys, but it has also led to some major triumphs. Scientific, economic, social and political factors have played a role and, while many groups have looked askance at the flow of research funding to molecular genetics, this area of research does now underpin most areas of biological research and has found broad application.

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The importance of context in plant biology

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The idea that how and where we grow plants affects the results from physiological experiments is well established. Differences between controlled environment experiments and field experiments are the norm rather than the exception. Differences among species, ecotypes, cultivars and even accessions are well documented. Consequently, even if there are similitudes at the genetic and metabolic level among species, ecotypes, cultivars and accessions, regulation must differ for the very clear differences at higher levels of organization to emerge.

The main challenge for understanding how regulation works at the genomic and metabolic levels is in dealing with complexity, in particular the very complex interactions. Is the problem tractable? And under which conditions? My view is that this is an intractable problem, unless we confine research to some specific context of interest. Simply trying to untangle signalling interactions would require so many different experimental conditions and genotypes/mutants as to make such studies impossible in practice. On the other hand, we can, I think identify the main players in the regulation under restricted conditions. This, simply means, that studies about signalling and regulation must be done in the right context. The context under which we hope to make use of this understanding.

Even under a realistic context, complexity creeps in from many directions. For crop yield, there is no doubt when it should be measured, and that in most cases one measurement is all what is needed. For photosynthesis we quickly run into the problem that we cannot easily quantify it over the whole growing season and neither it is necessarily the main limitation to yield, and so correlations with yield tend to fail. If we go down to genes, even if we quantify the whole transcriptome, decisions such as when to sample or what part of the plant to sample will drastically affect the "snapshots" we get.

Results from our attempts to untangle the interactions behind the perception of *solar* ultraviolet and blue radiation by the photoreceptors cryptocrhomes and UVR8 are a good example of how context can affect the regulation of gene expression and lead to "surprises" compared to earlier studies under unnatural light conditions. 1) In sunlight the "ultraviolet-B photoreceptor" UVR8 functions as the main ultraviolet-A photoreceptor. 2) Mutants lacking photoreceptors for either family, grow almost normally in full sunlight, only the genotype lacking both types of photoreceptors die if exposed to sunlight containing ultraviolet radiation. 3) There is an interaction in how these photoreceptors control gene expression, which could be expected, but surprisingly there seem to be different patterns of interaction affecting different genes. The main, and still unresolved question, is what is the role of the perception of radiation by these photoreceptors? What cues are perceived and what information is acquired?

Evolutionary trade-offs as constraints and opportunities

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Understanding past evolutionary tradeoffs can benefit crop improvement in two different ways: by identifying or quantifying constraints and by suggesting opportunities. Past natural selection was constrained by various tradeoffs, some of which still limit our ability to improve crops today. Some constraints are well understood, if sometimes ignored. Making more seeds leaves fewer resources for each seed, although this constraint may be obscured by differences in resource supply among plants (Spaeth & Sinclair 1984; Roff & Fairbairn 2007). Similar tradeoffs occur between perenniality and yield (González-Paleo et al. 2016) and among various components of water-use efficiency (Condon et al. 2004).

When the tradeoffs a crop faces today are similar to what its wild ancestors experienced, it will often be difficult to improve on adaptations that evolved over millions years. Simple genetic modifications, such as deletions or increases in expression of key genes, will usually duplicate a phenotype that arose repeatedly in the past, only to be rejected by natural selection (Denison et al. 2003). In such cases, tradeoffs in wild populations (Silvertown & Dodd 1996) may be a useful quantitative guide to what is feasible.

Radical innovations not tested by past natural selection may be more promising than simpler modifications. Some combination of gene transfer from unrelated species and redesign of key pathways could perhaps lead to significant improvements (Kebeish et al. 2007). Also, some tradeoffs may apply to only a subset of possible genotypes. For example, many bacteria, plants, and red algae show a strong tradeoff between the activity and the CO2-specificity of rubisco, but some cyanobacteria have greater activity than expected for their specificity (Tcherkez et al. 2006).

Some tradeoffs are poorly understood. Consider the fitness tradeoffs in plants making cyanide for defense against pests (Stanford et al. 1960). When cyanide is not needed for defense, its fitness costs to plants can greatly exceed its metabolic costs (Kakes 1989), but the severity of this tradeoff will depend on mechanisms that are still being explored (Kooyers et al. 2018). The most-fundamental tradeoffs, such as those based on conservation of matter and energy, will apply to every possible genotype, not just those already tested by natural selection.

Fortunately, even some options rejected by natural selection may be useful in agriculture and fairly easy to implement (Denison 2015). Evolutionary tradeoffs do not always imply agronomic tradeoffs (Condon et al. 2004). Natural selection improved individual-plant fitness in past natural environments, whereas crop yields depend on the performance of a plant community under modern agricultural conditions. Tradeoffs between past and present conditions may represent relatively easy opportunities to improve crop performance, simply by reversing some effects of past natural selection. For example, increases in atmospheric CO2 may have moved the optimum rubisco phenotype along the activity-versus-specificity tradeoff line, although the potential improvement is small (Zhu et al. 2004).

Individual-versus-community tradeoffs may offer greater opportunities to improve crop performance (Donald 1968; Reynolds et al. 1994; Denison et al. 2003; Anten & Vermeulen 2016). For example, shorter plants with more-vertical leaves are less competitive in mixed communities, yet higher-yielding in monoculture. This tradeoff apparently inspired the development of IR8 rice (Jennings 1964) and it was confirmed by Jennings & de Jesus (1968) the same year that individual-versus-community tradeoffs were proposed as a major hypothesis by Donald (1968). Since then, increases in leaf angle and decreases in tassel size and grain protein, all of which would decrease individual-plant fitness in mixed communities, have plausibly contributed to yield increases in maize over 60 years, apparently as side-effects of selection for yield (Duvick & Cassman 1999).

Would deliberate selection based on individual-versus-community tradeoffs have resulted in faster progress? A recent experiment found more improvement selecting for yield than for target traits (Yuan et al. 2011). However, the trait targets were apparently not based on Donald's (1968) tradeoff hypothesis. Plants selected for yield were shorter than those selected based on a (taller) height target, so the yield difference is actually consistent with Donald's hypothesis. In this specific case, greater attention to Donald's hypothesis and subsequent discussions (Denison et al. 2003; Anten & Vermeulen 2016) might have helped. In general, however, do we understand individual-versus-community tradeoffs well enough to use them effectively in plant breeding?

A plant-breeding or biotechnology program that pays attention to evolutionary tradeoffs should make faster progress. However, some tradeoffs are probably unrecognized and most are poorly quantified. An alternative approach, therefore, might be to select for community-level performance earlier in a breeding program. This would require much more land, relative to early selection based on individual plants, but advances in automation and remote sensing could reduce labor requirements.

Consider "drought tolerance." Tardieu (2012) has argued convincingly that traits enhancing performance under some drought scenarios will degrade performance or increase risks under others. Measuring yields of large number of genotypes under multiple drought scenarios would be very expensive, but aerial infrared thermometry can quickly estimate canopy temperature from hundreds or thousands of field plots. Lower temperatures indicate higher transpiration rates, which can be positively correlated with yield (Reynolds et al. 1999) if water is not limiting.

When water supply is limited, however, traits that favor community performance over individual competitiveness might be more beneficial. For example, two recent maize varieties apparently achieve "drought tolerance" by using less water early in the season, so that soil is actually wetter during the critical silking period, relative to soil under a check variety (Cooper et al. 2014; Nemali et al. 2015). Conserving water over shorter time periods could also be useful. The ratio of photosynthesis to transpiration is much greater on cool mornings than hot afternoons (Kumar et al. 1999). Using less water in the afternoon could therefore pay large photosynthetic dividends in the mornings. Natural selection would have rejected such water-sparing tradeoffs, because water conserved by one plant would be used by its prodigal neighbors.

Both natural selection and plant breeders have neglected the effect of this year's genotype on plant growth in the same soil in subsequent years. Crop effects on pathogens, mutualists, or persistent root channels are some possible mechanisms (Schlatter et al. 2017; Johnson et al. 1992; Rasse & Smucker 1998). Growing a large number of genotypes, followed by a genetically uniform test crop, could reveal such effects. Plots would need to be large enough for effects to persist in the face of some homogenization by field operations, so remote-sensing approaches (Peng & Gitelson 2012) would be useful.

To summarize, some tradeoffs that constrained past natural selection are equally limiting today. Ignoring such tradeoffs could lead to substantial wasted effort. On the other hand, some options that past natural selection has "left on the table" may represent "low-hanging fruit", opportunities to significantly increase crop-community performance, simply by reversing past selection for individual-plant competitiveness. This could involve either selection for specific traits or human-imposed group selection at earlier stages in the breeding process.

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Scientifically sound conservation of genetic resources for crop breeding

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Introduction

About 250 years ago, formal systems of conservation of plants began, first in tropical botanic gardens for plantation crops, and then in developed countries to store safely and then to provide raw materials for crop breeding. More than 50 years ago, the institutes of the Consultative Group for International Agricultural Research (CGIAR) began targeted collecting of their mandate crops to feed into active breeding programmes focussed on developing countries. The conservation of genetic resources by developing countries – always a major source of genetic resources – is fairly recent. The paper will look at recent developments in the *ex situ* conservation of genetic resources for crop breeding and yet more recent development of *in situ* conservation of crop wild relatives and on-farm conservation of crop landraces. Although the focus is on the importance of scientifically sound conservation, it is the politics surrounding conservation that has driven the global agenda in the past 30 years especially for *ex situ* conservation. Science has been marginalised and as a result suffered from lack of funding.

Ex situ conservation

Scientifically sound conservation for crop breeding

Over more than 50 years, excellent, large, well-managed collections have directly serviced global crop breeding in a number of developed countries and nine international agricultural research centres of the CGIAR located in developing countries. In the CGIAR alone, more than 600,000 accessions of major food crops, sourced worldwide, are safely stored, partly characterised (genotyped, phenotyped and sequenced) and documented for features of value to crop breeders, available worldwide and duplicated in other safe genebanks for security (Wood and Lenné, 2011).

The CGIAR institutes were very active in seed collecting over decades for conservation for current and future use. For most years between1972 and 1998 accessions to CGIAR genebanks exceeded 10,000 seed samples: the number peaked in 1977 at 32,000 samples. In the past 20 years, acquisition of new accessions has been sporadic, largely dependent on short-term project funding from donors such as the Bill and Melinda Gates Foundation. For example, in the past 10 years, the IRRI genebank acquired 15,921 accessions; most were from national genebanks with unique accessions threatened by lack of funding, only 926 accessions were directly collected (Sackville-Hamilton, pers. comm.).

Ex situ conservation of genetic resources for the use by crop breeders is the proven cornerstone of crop improvement for global food security (Everson and Gollin, 2003). Until the 1990’s, free and willing acquisition and exchange of genetic resources was based on trust and a clear understanding of the benefits to food crop production in developing countries.

Biopiracy campaign

In the 1990's, a high-profile misinformation campaign, led mainly by NGOs under the banner of biopiracy, highlighted an apparent exploitation of genetic resources from developing countries by developed countries and multinational companies. One example is the uproar over Australia's attempt to place under Plant Varietal Protection two chickpea varieties obtained from the ICRISAT genebank. This campaign fomented an atmosphere of concern in those countries that had hitherto freely provided samples. Developing countries were led to believe they were sitting on a genetic goldmine. This campaign sowed the seeds of distrust: it was inevitable that the former free movement of crop genetic resources was compromised and began to slow. In retrospect, this campaign, which spread like a virus through the international NGO community, was a major long-term danger to global food security.

Convention on Biological Diversity (CBD)

The CBD entered into force at the end of December, 1993. It recognized sovereignty of countries of origin of their existing biological diversity, including crop genetic resources, but it was not retroactive. It did not include the 3.5 million accessions already conserved in national and international genebanks. The CBD had a negative impact on the international genetic resources system: new samples could be accessed and conserved but could not be used or distributed. For example, from 1994-2006, IRRI acquired 27,182 rice accessions from 30 countries for conservation but could not use them (Sackville-Hamilton, pers. comm.). The CBD did not however stop the CGIAR collecting genetic resources. A claim to the contrary (Falcon and Fowler, 2002) was widely disseminated as a justification for the need for an International Treaty on Plant Genetic Resources. In addition, the CBD is still in the process of resolving the issues raised by the biopiracy campaign in regard to expected benefit sharing for developing countries.

International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA)

Because the CBD did not cover the valuable crop genetic resources already managed outside the country of origin, the Food and Agriculture Organization (FAO) subsequently decided on a further international legal instrument, the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA). The objectives of the ITPGRFA are the conservation and sustainable use of all plant genetic resources for food and agriculture and the fair and equitable sharing of the benefits arising out of their use, in harmony with the CBD, for sustainable agriculture and food security. However, unlike the CBD, the ITPGRFA attempted retroactivity – indeed monopoly control. While not recognizing countries of origin, the ITPGRFA invited all countries and all CGIAR institutes to place their existing collections within the `Multilateral System' of the ITPGRFA (in the case of the CGIAR, forever). There were immediate problems with the Treaty which further complicated the collection, exchange and use of crop genetic resources. The number of parties was restricted; the list of crops was restricted[1]; the funding mechanism was based on a tax of plant patents derived from material in the Treaty; and there was a misguided attempt to link deposits in the Svalbard Global Seed Vault to the Treaty (since reversed as developing countries massively avoided deposit of samples in Svalbard). This complexity and conditionality fostered further mistrust among developing countries. As a result, 93% of the samples being distributed annually under ITPGRFA conditions are from CGIAR genebanks. It did however provide a mechanism for

[1] http://www.fao.org/fileadmin/templates/agphome/documents/PGR/PubPGR/ResourceBook/annex1.pdf

the use and distribution of samples collected post-CBD through the IT Standard Material Transfer Agreement (SMTA).

Svalbard Global Seed Vault

The Svalbard Global Seed Vault was established in 2008 as a long-term, underground, permafrost seed store in response to the vulnerability of some of the world's 1,700 genebanks. It cost $8.8 million. Whereas one of the main aims of Svalbard was for safe keeping of the vulnerable and threatened collections from developing countries, of the almost one million samples currently stored, the majority are from the CGIAR and developed country genebanks such as the USDA which are already under secure, safe storage in duplicate locations rather than threatened and vulnerable.
The vault has a major design fault. In 2016, melting snow seeped more than 20 m into the access tunnel forming ice sheets as the meltwater met the permafrost. This significantly compromised the safety and security of the vault for long-term storage of valuable global genetic resources collections. The main flaw in the original design was the downward sloping access tunnel, strongly criticised by local coal mining engineers. The Norwegian government will have to spend $12.7 million to upgrade the seed vault including the construction of a new upward sloping access tunnel and a service building that will house emergency power and refrigerating units (originally thought to be not needed in permafrost).

The total cost of Svalbard after upgrading will be $21.5 million. This would have supported two years of all nine CGIAR crop genebank operations. These funds could have been much better spent in upgrading failing national genebanks and the urgent scientific characterization of key genetic resources collections for crop breeding. For example, in ICRISAT only 1% of the 127,000 genebank accessions have been used in crop improvement due to lack of funding for characterization of useful traits (Upadhyaya, pers. comm.).

Tragedy of errors

The interaction between the various developments outlined above has had largely negative effects for the global *ex situ* management of plant genetic resources for food security. The result is an emerging compl*ex situ*ation where multiple actors can exclude each other from the use of plant genetic resources for food and agriculture (Andersen, 2008). A functioning international system has been compromised by vested interests and ill-informed decision-making. This has led to reduced funding for science useful for agriculture and the redirection of funds vital for science to vanity projects such as Svalbard.

***In situ* conservation**

In the past 25 years, a considerable amount of genetic resources funding has been awarded to time-bound projects on *in situ* conservation of wild crop relatives and on-farm conservation of landraces (Wood and Lenné, 2011). Inevitably, this has redirected funding away from *ex situ* conservation. The proposed value of *in situ* conservation is the belief that plant populations will evolve useful traits (such as drought and heat tolerances or disease and pest resistances) under on-going environmental change. An underlying justification is to retain national sovereignty over samples on national territory.

Monitoring of *in situ* populations has included on site characterization for morphological characteristics, documentation of farmer indigenous knowledge for on-farm projects, and the assessment of overall genetic diversity using molecular tools (Wood and Lenné, 2011).

Functional diversity (identifying materials with resistances to diseases and pests and tolerance of abiotic stresses) was rarely assessed. With one exception, there do not appear to have been any attempts collect material and screen *ex situ* under controlled conditions. The main outputs from these projects have been how-to manuals, numerous sets of guidelines and conceptual frameworks. Although multiple millions have been spent on these projects, there are repeated calls for more funding and more projects (Maxted et al., 1997; Meilleur and Hodgkin, 2004; Bellon et al., 2017).

To date, there is no evidence of successful identification of useful traits with one possible exception. This is not unexpected since evolutionary changes may not be observed for 100 years or more (Frankel et al., 1995). Time-bound *in situ* projects are unlikely to result in measurable change over their lifetimes. In fact, Harper (1990) noted that the occurrence of resistance genes in wild relatives of crops is evidence of powerful long past selective forces.

A recent study of samples of pearl millet landraces collected in the same villages in 1976 and 2003 throughout the entire cultivated area of Niger found a significant shift to a shorter life cycle and a reduction in plant and spike size in the 2003 samples (Vigouroux et al., 2011). In addition, an early flowering allele at the PHYC locus increased in frequency between 1976 and 2003. Selection within the variation in these diverse landrace populations could have been sufficient to support the observed changes in flowering time in response to the shortening effective rainy season duration over this period. However wild pearl millets have shown introgressions of cultivated alleles and cultivated millets introgressions of wild alleles throughout Niger (Mariac et al., 2006). Several ICRISAT improved pearl millet varieties with enhanced earliness were released in Niger from 1990’s onwards. Introgressions between landraces and improved pearl millets cannot be discounted.

An unnecessary polarity has been created in justifying the considerable funding to *in situ* conservation: by storing collections *ex situ* the potential for on-going evolution is stopped while conserving material *in situ* allows on-going evolution with the expectation that the material in the field will improve and be more valuable. Hence *in situ* is being promoted and well-funded by some donors as an alternative and better method of conservation than *ex situ.* The risks associated with *in situ* conservation such as loss of genetic resources due to climatic and biotic factors as well as alternative farmer needs are rarely highlighted.

Much of the material currently conserved through *in situ* projects is not useful for current and, probably, future crop breeding efforts. *In situ* conservation in the absence of appropriate science is an expensive distraction and a waste of funds in the context of food security.

Making science useful to agriculture – integrated *ex situ* and *in situ* conservation of genetic resources for crop breeding

The increasing complexity and conditionality affecting collection, access and use of genetic resources for *ex situ* conservation and the lack of success in demonstrating a major value for *in situ* conservation for food security signals the need for a radical rethink on the most resource and cost effective way to conserve valuable genetic resources. Twenty years ago, the need for an integrated system for conserving genetic resources for crop breeding was highlighted (Wood and Lenné, 1997). By closely linking targeted, structured, science-based *in situ* conservation projects with *ex situ* genotyping, phenotyping and sequencing efforts, the most valuable resources could be identified and conserved for the future. Agricultural scientists have an important role to better inform investment decisions on making genetic resources conservation efforts more useful to future food production.

"By hesitating to enter the debate, we can only accede the field to the biologically naive and find ourselves able to serve only as peripherally significant technicians in the pursuit of the objectives of the uninformed" (Namkoong, 1991).

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Searching for transgenes that improve yield: promise and reality

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Advances in the field of functional genomics over the past two decades have resulted in the identification of many genes that could potentially be manipulated to improve crop field performance. Research investment, both to identify and characterize these genes and to deploy them to benefit agriculture, has amounted to millions of dollars. In both the popular press and in scientific publications, authors are asking the natural question – where are the improved varieties that are expected from the many reports of valuable gene discoveries? Has this investment in understanding the function of genes related to yield potential and yield stability been useful to agriculture? To address these questions in the context of a commercial crop improvement program, we will summarize the general findings from our last 10 years of transgenic experiments for agronomic traits in maize (yield, plant height, and maturity), and highlight several promising leads. We will also describe the gap between gene discovery and gene deployment, which has hampered most efforts to develop products.

Pioneer Hi-Bred International Inc. (now part of Corteva Agriscience™, Agriculture Division of DowDuPont™) undertook the challenge of identifying and manipulating expression of key genes that were expected to affect important agronomic attributes of field-grown maize. Between 2008 and 2017, several thousand unique DNA constructs were evaluated as hybrids in high-quality multi-location field experiments. These constructs included hundreds of different genes of interest; some leads were selected based on specific biological hypotheses, while others were forward genetics leads identified via phenotypic screening in model species. Lead selection was mainly focused on two critical areas for production agriculture: stabilizing growth and yield under drought stress, and improving the capture and use of applied nitrogen fertilizer. Both areas have significant background literature identifying potential gene targets for knowledge-based hypothesis testing, and both have been heavily evaluated in model system screens, so candidates were plentiful. In contrast to more theoretical studies, the criteria for success in the Pioneer work was stark – the construct had to provide a repeatable large yield benefit in most locations, across multiple genetic backgrounds, have no negative side effects, and be functional in a hemizygous state for hybrid maize. This approach differs from that described elsewhere [1], where the expected phenotype was first evaluated in a controlled environment as a preliminary screen prior to field testing.

Our production transformation system evolved over the 10-year period reported, and included various transformation genotypes. The early constructs were transformed into an experimental inbred that did not have the yield potential of our modern commercial inbreds, the intermediate years were mostly in an older commercial inbred first sold in hybrids in 2000, and the later years were in a different commercial inbred sold in hybrids since 2012. Model system-based leads were evaluated mostly in the older commercial background. Most constructs included a relatively strong constitutive promoter. Each construct was represented by 5-10 or more independent events, and was evaluated in its first year as a single hybrid in multiple field locations. Where drought or nitrogen limitation guided gene selection, environments were managed to impose the appropriate limiting factor in some of the locations. Any constructs selected for a second year of field testing were evaluated with multiple testers. Several publications document features of the field testing system [2-4].

1) Most transgene-induced changes did not measurably alter yield or other observed agronomic characteristics in our testing system

Among over 16,000 construct*experiment comparisons for grain yield (2008-2017), about 28% were different to the control for yield (including both positive and negative effects) based on a two-tail test at P<0.1. Chance alone would predict only 10%. While the observed frequency of differences is clearly more than expected by chance, every construct evaluated was included because it was expected to influence crop performance. Grain yield is a complex trait with comparatively low heritability and is affected by both variation among locations and within-location error. When the count of efficacious constructs is based on grain moisture, a more heritable trait, the proportion is still only about 30% across all years. This observation is in marked contrast to less complex traits such as insect control and herbicide tolerance conferred through transgenes, which generally produce the insecticidal/herbicide tolerance protein as expected, with resulting efficacy. The resilience of maize to altered expression of many agronomic trait leads supports the hypothesis that these pathways are complex and strongly buffered, either through activity of other gene family members or simply by the other, non-transgenic, parental line used in the hybrid. In general, the transgenic inbred plants were not visibly different from the wildtype in the nursery, but the transgenic inbred was rarely evaluated in the homozygous state.

Patterns of efficacy differed across transformation platforms. The large influence of genetic background on transgene performance for agronomic traits is one of the clearest findings in this work. The three targets evaluated here included one inbred from the stiff-stalk heterotic group and two from the non-stiff stalk (NSS) heterotic group: one NSS was a fixed-ear type and the other was a flex-ear type. The fixed-ear type differed from the other two in having greater frequency of negative effects on yield and less grain moisture at harvest. These data are not a direct comparison of the same gene because the cohorts of leads evaluated in each platform usually differed, but the pattern is consistent with our other observations of the unpredictable impacts of changing testers, retransforming into different inbreds, or introgressing the construct into other backgrounds.

When constructs affected grain yield, the impact was usually to reduce yield. The proportion of initial evaluations for yield where the transgenic entry out-yielded the control was 4-6%, close to the frequency expected by chance. In contrast, the control was declared significantly better in 18-35% of the contrasts, depending on the transformation background. Of the constructs described here, about a third were derived from open-ended forward genetics approaches and the remainder were from hypotheses based on gene annotation, biochemical pathway, and expression information. After first-year testing, no large difference was observed in the overall frequency of efficacy between leads from model systems (mainly *Arabidopsis*) and hypothesis-based leads, or between leads based on monocot or dicot sources.

2) Changes in expression of single genes in signaling pathways or as transcription factors can improve yield performance

After primary testing, about 10% of the constructs were selected for evaluation in a second year. Over half of those also had a positive effect in at least one location in the retest year, and a number were nominated for further testing. Several constructs with significant positive yield impact have been identified in these evaluations, notably from knowledge-based leads. The great majority of the effects of transgenes for agronomic traits were either too subtle to support direct product development efforts, had negative impacts on key production traits like standability or dry-down, or, most commonly, did not perform consistently across environments and/or genetic backgrounds. The variability of lead performance in different genetic backgrounds is consistent with the hypothesis that these transgenic expression variants act like novel alleles or large-effect QTLs in this highly-selected germplasm.

To date, the only commercialized agronomic transgenic event in maize is reported to provide some drought efficacy via the constitutive expression of a bacterial cold shock protein [5, 6]. In our experiments, clear positive effects on yield resulted from the downregulation of genes affecting ethylene production and sensing; these constructs increased yield across a range of location types [2, 3, 7]. Leads targeting water conservation could, in severe stress scenarios, confer an advantage, but with the anticipated penalty in favorable environments [4]. That example, which is associated with increased ABA production and reduced photosynthesis, reflects the trade-offs predicted by fundamental principles of crop physiology and ecology [8]. Simulations can be used to predict anticipated compensation and narrow the search space for potential leads [9].

3) The gap between gene discovery and gene deployment in a transgenic product is large

For a biotech trait, either transgenic or a gene edit, to be incorporated in a product through a maize breeding program, it must have a large effect size, function as expected across elite germplasm and a wide geographical area, be dominant and easy to introgress, have no negative effect on other traits, and be regulatory and public perception friendly. Concurrently, a transgenic product must be worth more than about $100M to cover product development costs. Very few enterprises can undertake this level of investment and hold the course over the 15-20 years from discovery to commercial launch, particularly in the face of fluctuating commodity prices and changing regulatory policies and consumer preferences.

More compelling cases for biotech modification for agronomic traits are those resulting in step changes in plant architecture or large alterations in sensitivity to environmental signals [10, 11], which are unlikely to be readily achieved through breeding. This type of change underpinned the development of Green Revolution rice and wheat varieties. The incorporation of semi-dwarfing mutations into commercial varieties required extensive breeding effort to optimize the variation and achieve local adaptation, and alteration in the cropping system was required as well [12]. It is unlikely that many individual organizations in either the private or public sectors can commit to this investment, and a long-term consortium plan may be needed to bring about this type of application of novel transgenic variation. Biotech improvements to agronomic traits will be most effective in cases where they can enter forward breeding programs and be co-optimized in concert with elite germplasm.

CONCLUSIONS

It is difficult to claim that the global research investment in evaluating crop transgene functions for agronomic characteristics has been a more effective use of limited resources for agricultural research than alternative, untested, strategies might have been. This effort has greatly advanced our understanding of gene function and regulation as a critical component of plant development and adaptation. There are notable successes that increase grain yield, particularly under stress. Nonetheless, the overall experience of testing agronomic traits transgene for product development has tempered enthusiasm for single-gene solutions for complex yield-related traits, even when yield appears limited by a primary constraint such as drought. There are other lessons from the decades of investment at Pioneer and elsewhere that can inform more efficient approaches to open-ended searches for useful biological variation.

- If the goal of the effort is to produce a commercial product, the roadmap to the product must be clear at the start to fully calculate the investment required for success. That bar may be considerably higher than it first appears.
- The consistency of performance of positive leads over years provides an endorsement of the use of carefully managed archetypal locations over more extensive testing in generally representative locations. Simulations can assist with technology extrapolation domains to accelerate decisions and better focus research investments[13].
- Efficacious leads can indicate areas of unfavorable genetic fixation in commercial breeding programs and provide biotech traits to override them, or guide the search for native alleles to be introduced through marker-assisted introgression or gene editing.
- Like for conventional breeding for complex traits, inconsistent or incremental small effects of either native or transgene alleles across genetic backgrounds is the rule, not the exception. In a commercial setting, this can be addressed by using the most important genetic background(s) in primary testing. In more open-ended searches, another approach must be taken to establish what constitutes meaningful success.

These efforts have supported the development of valuable technologies for plant science. Increased knowledge of gene structure-function, and improved optimization and targeting of transgenes and gene edits may enable trait step changes that could move outside the incremental changes to current breeding landscapes, and develop the fresh germplasm foundations for crops quite different from current ideotypes. Our knowledge of plant architecture and 'domestication genes', and genes under strong selective sweep in the major crops, could be used to bring increased economic vitality to crops in the economic shadows – e.g., flax, tef, chickpea, amaranths, millets, pulses, and others - thereby diversifying agriculture and improving diets, farmer livelihoods, and the environment. Already we are seeing examples of the use of CRISPR-Cas editing to leap near crop species to domestication standards [14]. In all cases, forward breeding is likely essential for authentic progress, and we should consider that cost when making commitments. Finally, high-throughput image-based phenotyping systems, which have been widely used in forward genetics screening, have greatly advanced the technology for plant image analysis; this technology has real-life applications for crop monitoring and targeted pest control that may well transform agriculture as they reach the field.

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Expensive distractions in pre-breeding research: can we do it better?

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Introduction

Making science useful to agriculture needs to be rephrased, it's about making science more useful, delivering more impact per unit of investment in R and D, for there is no doubt that science has been hugely useful to agriculture. I will focus on public investments and crop breeding. This means public investment in pre-breeding because privatized variety production, operating under market economics, now dominates the developed world, as is also the case in Australia. And I will define prebreeding broadly to include the production of improved breeding and selection tools and techniques as well as new germplasm with unique or improved traits (often called secondary traits), whether using native genes and alleles or genetically engineered ones. These products of course must be adopted by commercial breeders, the only route by which this public investment delivers impact to farmers.

Since in 1970 when I joined Norman Borlaug's CIMMYT Wheat Program, I have been involved in wheat prebeeeding, especially trait identification, and only recently reviewed some key early generation yield selection criteria for wheat (Fischer and Rebetske 2018). However I have never produced a prebred line for breeders to use, so it was just ideas, some quite pointedly warning breeders to pay more attention to interplot interference (Fischer 1978). It was interesting science, but was it was all an expensive distraction? Maybe, but to answer the question I must look more broadly at prebreeding efforts in major crops. In this I will focus only on increase in potential yield (PY) and in water-limited potential yield (PYw), noting here in passing the successes of physiological breeding with resistance to certain simple abiotic stresses (e.g., aluminium and salt tolerance in wheat, flooding tolerance in rice).

Potential yield refers to yield in the absence of biotic stress and under top agronomy (Fischer 2014). PY advances derive from new cultivars, new agronomy and their positive interactions, and in turn are the foundation of all farm yield (FY) progress. Yield progress is generally linear with time and here is expressed as the linear slope relative to the predicted PY in the last year of the release in any cultivar series (as percent per annum, % p.a.); it is strongly urged here that this is the most sensible basis on which all yield breeding progress can be compared. Fischer (2018) concluded from a comprehensive reviews of recent estimations that current rates of progress (breeding plus breeding x management) were wheat (0.5% p.a.), rice (0.7%, but variable), maize (0.6%, also variable) and soybean (0.7%), not very different from estimations almost a decade earlier (Fischer et al 2014). This is almost entirely the fruits of "conventional" breeding, aided however by advances in widespread yield testing, statistics, field mechanization, automation and some molecular markers for otherwise hard-to-select non-potential yield traits. There was no evidence rates are less for PYw than PY, dispelling a popular myth that it is harder to make progress under water limited conditions. Secondly, and with 2 exceptions in recent 42 cases, there was no evidence that linear progress has slowed in the last 20 years or so, although relative progress is gradually becoming less, and clearly more expensive to achieve. Where the PY to FY yield gap is large (> 100% of FY, e.g., Sub Saharan Africa), PY progress is not very relevant to FY progress, but for over half the world's production the yield gap is small (< 50%), and further PY progress is critical for continuing FY progress is such situations. Breeding for yield therefore remains central to world food security, and indeed rates of progress are inadequate according to most demand projections. In this effort, prebreeding research is expected to play a role, but what has been its track record and what are its prospects? I will split the subject into physiological and molecular biological efforts and, aware of the subject to be covered by Renee Lafitte, will say little about transgenes in maize.

Physiology applied to prebreeding : Some successes and some "still in the pipeline"

The planned development of erect–leaved semidwarf tropical rice varieties in the 1960s at IRRI is often cited as an early success of physiology interacting with breeding: this is acknowledged by breeder Peter Jennings. The attempt in the 1990s of IRRIs physiologists to design a new ideotype, the New Plant Type, was less successful (Yang et al 2007), but this low-tillering erect ideotype may have helped in part to guide yield progress in China through its very high yielding "super" rice varieties and hybrids (Peng et al 2008).

The first development of semidwarf winter wheats, in Japan and then Pullman, Washington, appeared to derive from the simple observation that this might prevent lodging. Soon after Borlaug pursed the same trait in spring wheats for the same reason, and in 1962 released the first semidwarf spring wheat. Pugsley and Syme first incorporated the trait into Australian wheats in the late 1960s, retrospectively pointing to the associated improvement in harvest index. The truly-physiological contribution from this group at Wagga Wagga, NSW, actually came from seeking to understand the genetics underlying daylength and vernalization sensitivities which controlled flowering. This at last flowed into all Australian wheat breeding with the advent of DNA markers for the key controlling alleles, as exemplified by the accurate prediction of their effects on heading date across the wheat belt (Eagles et al 2010), but whether it is useful for breeders is not so clear.

The impressive progress in temperate maize yield in, for example, the USA owes little to physiology despite early modelling by crop physiologists on the benefits of erect leaves, selection for photosynthetic activity, and the definition of a desirable ideotype (Mock and Pearce 1975). The very successful breeder, Don Duvick, was adamant that Pioneer Hi-Bred's selection targeted only yield at high density along with lodging resistance; that the best hybrids also had small erect upper leaves, enhanced stay green, and small tassels was the indirect result of extensive multilocational yield testing.

Maize for the tropics and subtropics was however a different story. Physiologist, Peter Goldsworthy, and breeder, Elmer Johnson, early on at CIMMYT targeted reduced stature and increased harvest index, while together with physiologist Ken Fischer, they initiated in 1974 a program of selection for drought tolerance based on traits as well as yield, working in a rainless managed environment. Thirty years later, and after near death experiences due to lack of support and then recovery in the hands of Greg Edmeades, Marianne Bänziger and colleagues, the program was delivering outstanding hybrids and OPVs for droughty low-N soils in eastern Africa, with significant positive impact for farmers (Bänziger et al 2006; Edmeades 2013).

A less successful but ultimately enduring initiative coming out of the CIMMYT Wheat Program was the notion of early generation indirect PY selection by targeting high stomatal conductance, a long story summarized in Fischer and Rebetzke (2018). I started the work, prompted by my familiarity from Ph D work with fast stomatal measurements and some promising unpublished results from Israel. In the mid1970s Pat Wall showed remarkable success with F2 selection for leaf porosity (surrogate for stomatal conductance). The work then languished as breeder leadership of the Program funded other priorities, but was revived by Ken Sayre in the late 1980s with the advent of fast porometers and infrared thermometers, with exciting results (Fischer et al 1998). CIMMYT was I believe the first to measure plot canopy temperature remotely by aeroplane, and show its significant relationship PY (Reynolds et al 1999). It remains a very promising selection tool (Fischer and Rebetzke 2018), but has yet to be mainstreamed in the PY breeding programs at CIMMYT, some 40 years after Wall's promising results!

Selection for stomatal behaviour is behind some recent progress in maize PYw in USA. I refer to the transpiration limitation trait, the threshold vpd at which stomata begin to restrict the linear increase in transpiration with increased vpd. First highlighted by Tom Sinclair in soybean, this genetically-determined trait has been investigated by him and his colleagues in a wide number of crops. Pioneer Hi-Bred (now called Dupont Pioneer) believe that the commercial success of their Aquamax hybrids (e.g. 6% yield increase at moderate drought levels) is the consequence of selection for a low threshold vpd, initiated by physiologist Charlie Messina (out of Sinclair's team), thereby conserving soil moisture around the uniquely critical flowering stage of maize development (Gaffney et al 2015). The trait is being pursued at ICRISAT in other summer crops such as sorghum, millet and chickpea (Vadez et al 2014).

There has been much wheat prebreeding at CSIRO since the late 1970s, guided by the widely accepted model of PYw (Passioura 1977) and particularly involving Richard Richards, Tony Condon and Greg Rebetske, targeting traits conferring performance under limited water. These included xylem vessel diameter in seminal roots, waxiness, low tillering, carbon isotope discrimination, long coleoptile, stomatal conductance, stem carbohydrates, and seedling vigour (Richards et al 2002). Some are promising and may at last be receiving attention from commercial breeders (e.g., long coleoptile, seedling vigour)

Many other physiological traits have been proposed and some tested in isolines and breeding populations. These include stay green (especially in sorghum), osmotic adaptation, photosynthetic rate, harvest index, the Donald ideotype communal plant generally, and determinacy in soybean, but none have been explicitly adopted and it is difficult to judge their influence on breeding. New fast phenotyping methods may facilitate their further testing and ultimate incorporation into breeding but some old problems remain.

Other physiological developments have provided breeders with new tools, the most significant of which is probably dihaploidy, now widely adopted in maize and in winter wheat breeding to speed the approach to homozygosity. Achieving the same effect is "Speed Breeding", a new version of single seed descent (Watson et al 2017) facilitated by some simple physiology. I refer to the input of extra photosynthetically active radiation to accompany the longer photoperiod, such that plants grow much more normally in their short lifetime and appear to be more appropriate for trait selection.

Molecular Biology and Prebreeding: So far fewer successes despite more investment

Molecular biology began with the unravelling of the base pair sequences of part or all of genes and their adjacent regulatory environments on the nucleic acid molecule. It started to impact crop breeding in the 1980s from two directions, namely identification of DNA markers for important gene alleles, and genetic engineering, with the first GE variety (herbicide tolerant maize) released in 1995 in USA. Improvements in DNA sequencing techniques have greatly reduced costs for markers, such that the whole genomes of breeding lines are now routinely sequenced under the banner of genomic selection (GS) in the multinational breeding companies. GE however remains less precise than desirable although new gene editing techniques are facilitating planned gene alterations. While there are significant indirect benefits for FY across the almost 200 Mha of GE crops in the world, with one exception to date, there has been no release of a GE variety engineered for greater PY or PYw. The exception is Monsanto's Drought Gard hybrid maize (Nemali et al 2015).

Crop yield is a very complex trait, involving many genes interacting with the growing environment. A few key simple traits are critical for high yield in any E (e.g., height and flowering time), but once they are optimized, many other genes became important and their mapping to yield has proved difficult (Bernardo 2016), although Edmeades (2013) claims some yield gain for QTL-based selection in maize. The rest of this paper will, however, focus on the prospects of GE for greater yield. Since the 1990s there has been many papers in prestigious journals proposing to alleviate, if not solve, world food insecurity by lifting yield with various GE traits. It is applied functional genomics, great science, and there is usually some proof of concept, but very few of these traits subsequently appear to be convincingly field tested: either the testing wasn't done or the traits failed to increase yield in proper field trials. As mentioned earlier maize examples will be left to Renee Lafitte.

Efforts to raise PY via GE are common, with paddy rice often targeted. One illustrative example begins with a promising paper by Ashikari et al (2004) who reported increased grain number per panicle in rice from elegant engineering to down-regulate cytokinin oxidase in the inflorescence growing point, and from pot studies they predicted yield increases. It was almost a decade before follow up papers appeared testing this notion in field plots (Li et al 2013; Yeh et al 2015; Wu et al 2016). Engineering the levels of kinetin and/or GA had the expected effects on grains per panicle or panicle number and proper field plots seem also to have been used but descriptions are poor. Yield per ha increases ranged from 5 to 58% over the wild type, which sometimes wasn't described and generally yielded poorly relative today's best cultivars. Similar problems were also evident in another recent PNAS rice GE paper (Miao et al 2018), who manipulated abscisic acid levels and apparently increased stomatal conductance and plot yield around 28%. Plot management was again not fully described but there was enough detail to suspect that the taller GE plants would have benefitted considerably from edge effects in the small 1.8 x 1.8 m plots, the whole of each was harvested for yield. The authors did at least recognize that the wild type (Nipponbare) was quite old and yielding around only half of the yield of today's cultivars, but they seemed unaware of the fact that this increased yield from conventional breeding in rice has in fact been associated with greater stomatal conductance.[2]

Raising PY by engineering greater leaf photosynthesis is a popular and well-funded target for physiologists with many options (e.g., Ort et al 2015), but again field tests of the GE lines so far are unconvincing. For example excellent field trials in Illinois with soybean showed only small effects under ambient CO2 (Köhler et al 2017) and plots involving transformed tobacco appear to have been terminated before the crop forms a proper canopy (Kromdijk et al 2016). Field trials with wheat in the UK have to date not delivered greater crop growth, despite promising glasshouse results (R. Furbank pers. comm.). Besides, no one seems to worry about the control of photosynthesis in crops by sink strength.

[2] That they used electron microscopy to measure stomatal aperture points to the silo in which they were working: Japanese crop physiologists had 15 years earlier used simple infrared photography to demonstrate the higher conductance of modern rices.

There are even more attempts in the literature to use GE to increase drought tolerance (PYw). One early example reported with several crops is the dehydration-responsive element binding (DREB) transcription factor. However there are no examples of DREB having lifted field performance under drought, for example in wheat (Saint Pierre et al, 2015). Engineering trehalose-6-P metabolism in the young maize cob showed great promise in the lab and even in the field, but over 10 years of silence have past since the field results were obtained (Nuccio et al 2015). Claims of increased drought tolerance in wheat (Yu e al 2017) by overexpression of cold shock protein (CSP) genes (the same type of gene purported to work in Droughtgard maize) appear well substantiated by a 20% yield increase in two years of proper plot trials and possibly results from the measured increased stomatal sensitivity to ABA[3]. This would could to be one of the more convincing GE results.

This has been a long exposition of examples of GE for yield, but it is necessary if I am going to level some serious criticisms at the funding of such work. I certainly have not cherry picked the papers, instead taking ones in prestigious journals and usually highlighted for their likely impact on world food security by the many abstracting e newsletters around these days (e.g., Chicago Council for Global Affairs, Global Food for Thought, or the ISAAA newsletter). Physiologists have predicted and noted (e.g., Turner et al 2014) the lack of progress with GE for crop yield. More telling is the recent and very thorough review of GE for PYw by molecular biologists themselves (Nuccio et al 2018). Even excluding the problem of getting proven GE traits to market, many other obstacles were identified yet they remain optimistic about several GE traits in the pipeline, some of which have already been mentioned above (trehalose metabolism, CSP), some not (ethylene signalling, amino acid biosynthesis, transcriptional regulation). They also pointed to knowledge generated in GE projects which could deliver chemicals such as novel caged (protected) derivatives of trehalose-6-P for direct application to lift crop yield.

Lessons from physiological prebreeding and genetic engineering for yield

Both the physiological and molecular fields are benefitting from new tools, respectively, high throughput precision phenotyping, and cheaper more powerful ways of measuring and manipulation at the molecular level. This does not, however, change the importance of lessons arising from past successes and failures. These show many similarities between the two research approaches and can therefore largely be dealt with together. Briefly they include:

- Yield is product per ha and under multigenic control, highly refined by more than a century of breeding and selection. New alleles or genes are unlikely to have a big impact and their detection will require very accurate field testing.
- Everything has to be linked to performance in crops in the field, which implies excellent agronomic management and maybe some degree of weather control as in managed environments. This also renders futile most trait studies on isolated plants or parts in laboratory and controlled environments, and without field antecedents.
- Innovations in agronomy are part of PY increase and can also drive yield gain through positive interactions with new traits.
- Trait targeting should start in the field with repeatable performance differences, then proceed to the lab, where genetic markers may or may not be a target, and functional genomics should not be allowed to become an endless distraction for the protagonists.

[3] Drought Gard appears also to work because of lower transpiration, but smaller leaves appear to be the cause.

- An exception of the last point is the search amongst untried genetic resources for new trait variants: molecular sequences of known variants can help in this search.
- Clearly validation of traits takes time and needs continuity of support and of staff, especially leadership. Focus on the applied goal is essential and should preclude the temptation to seek deeper understanding as to why something works, until it is an absolutely necessary to do so.
- Almost always there are benefits from the involvement of breeders, and especially sympathetic mainstream breeders. Thus there needs to be sufficient flexibility and funding in commercial breeding programs to allow pilot testing of new ideas, a process which may take many years or several breeding cycles for completion.
- There may need to be a degree of multidisciplinarity, especially when it comes to smart field instruments and to crop physiologists in molecular teams. The latter are very specialized in their own field, and have little experience of doing field experiments and measurements: they need to cooperate more closely with crop physiologists and agronomists in order to conduct proper field work.
- Many new traits will face hidden trade-offs due to the overriding importance of resource limitations (primarily light and/or water in modern cropping); survival traits which sacrifice production are generally useless.
- The starting germplasm in any trait breeding program may be well superseded by conventional breeding progress by the time the new GE cultivar becomes testable in the field.
- Related to the fact that much biotech is nowadays in the private sector, publication of failures may never happen while that of success may lag considerably. This is unfortunate for all other players.
- Journal editors need to be more discriminating, giving more attention to properly-measured yield (per hectare), rejecting dodgy claims of “yield” success and shunting excessive biotech detail to the supplementary pages.

Lacking the obvious constraints faced by large commercial breeders, the major international crop centres were uniquely well situated to test the application of new prebreeding ideas and techniques to breeding, but even there, continuity of funding and staff, was and remains often inadequate. The first victim of funding shortage tended to be the physiology programs, which as well could not resist the onslaught new “band wagons” so attractive to donors and investors for whom “more of the same” was a turnoff. It is worth noting that breeding of soybean, something largely conducted by commercial firms for some time now (except in South America), has not apparently been the target of substantial crop physiological input, but has made solid yield progress. Many private breeding companies are large enough to provide the funding for prebreeding work but one gets the impression that continuity and persistence fall victim to the unique pressures under which business tends to operate. Only Dupont Pioneer seemed to have had the funding and foresight to see something though to success and to timely publication, but it is probably still early days for their stomatal limitation trait in maize.

Whether we like it or not, physiology and molecular biology are drawing closer in prebreeding as synergies are recognized. An exciting development in this field, publications again coming out of Dupont Pioneer, is that of Mark Cooper and colleagues, culminating in Messina et al (2018). This approach marries whole of genome prediction of four key maize yield traits with crop simulation modelling to predict yield across diverse environments, and as a corollary, trait optima for given key environments. The work encompasses climatology, crop physiology and modelling, quantitative genetics, genomic prediction, breeding and agronomy!

Conclusion

Finally it is necessary to return to the general theme of sound investment in prebreeding research, whether through physiological or molecular approaches. This brief review highlights the complexity of the task, the need for collaboration with breeders and other disciplines, for strong goal-oriented leadership and for continuity of direction and support. This implies that funders of the task need patience and persistence, and not to be swayed too easily by every new “band wagon” that comes along. There is nothing very new in this (e.g. Simmonds 1991), but donors appear to have become impatient, expecting transformational developments on an almost annual basis, while showing bias towards the new and inevitably more upstream research. “Not more of the same” is the all too familiar refrain!

The biggest gap in much research in the public sector is the gap between the prebreeding research and the private sector breeders. Such a gap may also exist within the larger private sector firms, others are better able to comment on this. However its solution needs some agreed long-term sharing of resources for the duration of agreed pilot projects to test new traits and methods coming out of the prebreeding pipeline. This is especially difficult to enable when it involves a public-private interface and there is need for better operational models, which give the breeding company some advantage but doesn’t entirely lock in all the new knowledge and lock out competitors. I understand that the EU has a more satisfactory model for such public- private partnerships, although they are unlikely to foster joint GE research in the current climate?

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Intensive maize and wheat breeding efforts at CIMMYT

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CIMMYT

Though great strides have been made to pull millions out of poverty in recent decades, a daunting challenge still lies ahead: how to feed more than 9 billion people by 2050.

While diversifying diets is of highest priority to address malnutrition, hidden hunger and obesity, research on staple crops – maize, rice and wheat – lies at the heart of the solution. Maize and wheat account for a quarter of the total crop area harvested globally and provide, along with rice, 42% of all protein and 48% of all calories for human consumption.

The popularity of staple crops is on an upward trend according to recent reports. For example, as populations and economies grow, people seek employment in cities and their dietary habits change, an increasing number of poor consumers in low- and middle-income countries will reach for wheat-based foods at affordable prices.

In 2017, the number of chronically undernourished people rose for the first time this century, reaching 815 million. Demand growth is particularly worrying as we near 2030, the year when world population growth is predicted to peak.

In order to address this demand in developing countries where help is needed the most, we must reach to pillars of global food security, crops such as maize, rice and wheat. As the world currently stands, productivity of wheat, maize and rice based systems needs to increase beyond historical rates. For example, the wheat yield growth rate needs to rise by about 40% and that of maize by 50% over the current rate in the developing world.

Failing to sustainably produce staple crops today will make it nearly impossible to reach Sustainable Development Goal 2 on zero hunger by 2030. Diversifying from farm to fork requires efficient input use, minimal off-site impact while conserving and safeguarding the productive capacity of land under maize and wheat. These objectives can only be achieved if investments in agricultural R&D are significantly increased and supported by enabling international and national policies.

In order to achieve the much-needed growth in yield sustainably, we need to start with breeding programs. For over half a century, CIMMYT has developed new maize and wheat germplasm adapted to the needs of farmers in the developing world and emerging threats and shared it routinely as international public goods with hundreds of organizations worldwide.

CIMMYT uses a wide variety of advanced technologies to fast-track development and delivery of new maize and wheat varieties that are adapted to climate change-related stresses, and with other farmer-preferred traits, including resistance to major diseases and insect-pests, and enhanced nutritional and end-use quality.

Maize and wheat improvement at CIMMYT

Integration of high-throughput and novel phenotyping tools, doubled haploid technology, molecular markers for key traits, and rapid-cycle genomic selection are core components of the breeding strategy to accelerate genetic gains and the competitiveness of CIMMYT's improved maize products in target regions.

With extensive public and private partnerships, CIMMYT has developed and deployed elite drought-tolerant, heat-tolerant, nitrogen use-efficient, and disease resistant maize varieties in the tropics. Based on technological breakthroughs in the early 1990s and a strong breeding program on drought tolerance initiated by CIMMYT and subsequently by IITA, more than 300 drought-tolerant (DT) maize varieties have been developed and released across sub-Saharan Africa (SSA), and more recently also in India, over the two decades. Intensive efforts on strengthening maize seed systems in SSA, including public-private partnerships and capacity development of NARS and seed company partners, catalyzed delivery of DT maize varieties across 13 countries in SSA, and helped to circumvent market failures. In 2018, more than 100 seed companies in SSA produced an estimated 75,000 tons of certified seed of CIMMYT/IITA-derived improved DT maize varieties.

CIMMYT's maize biofortification efforts led to the development and deployment of elite maize varieties with enhanced concentrations of provitamin A (>15 ppm), kernel Zn (>30 ppm), and protein quality (2-3-fold lysine and tryptophan) in the (sub)tropics of sub-Saharan Africa, Asia and Latin America.

Since 2012, CIMMYT coordinated rapid response to the maize lethal necrosis (MLN) epidemic in eastern Africa, through fast-tracked breeding, release and deployment of MLN-resistant varieties, and capacity strengthening of national plant protection organizations in MLN diagnostics and management, and interface with commercial maize seed sector in production and exchange of MLN-free seed. This has led to containment of the disease within eastern Africa, and curbing its spread to southern and West Africa. This is indeed a clear demonstration of the capacity of CGIAR-led initiatives to respond quickly and effectively to a major challenge, and to galvanize and organize multi-disciplinary and multi-institutional efforts.

Wheat research in developing countries is mostly dependent on public institutions due to the absence of royalty collection systems. An advantage of this is that products and knowledge are still openly shared through the International Wheat Improvement Network (IWIN), which includes most wheat breeding programs in developing and developed countries.

The power of this open access network was illustrated in 2016 when wheat blast was introduced from Latin America to Bangladesh. CIMMYT has tested elite wheat lines in its international nurseries since 2010 in Bolivia for wheat blast resistance. This allowed the release of a wheat blast resistant line in 2017, exactly one year after wheat blast was identified in Bangladesh. ACIAR supported the establishment of a screening hub in Bangladesh which allows South Asian wheat programs to screen their elite wheat lines for resistance to be prepared should the disease spread though the region.

Similarly, in Kenya, every year around 45,000 wheat accessions from breeding programs in developing and developed countries are evaluated for resistance to stem rust Ug99. In many areas, rust epidemics are prevented, where lines with durable resistance are grown, a concept widely used at CIMMYT. However, most breeding programs continue to use single resistance genes and the bust and boom cycles are common.

Recent breakthrough research at CSIRO and 2 Blades at the John Innes Center in stacking rust resistance genes may be a game changer as this should allow to develop varieties with durable rust resistance. CIMMYT collaborates with these institutions and plans to transfer these stacks into its elite lines. Since this technique uses GM technology to combine the wheat originating genes, it remains to be seen whether these varieties will be accepted for release.

Nearly 90% of all irrigated wheat is produced in India, Pakistan, China and Egypt, where heat stress is a further limiting yield. Drip irrigation at CIMMYT's principal wheat breeding station in Obregon, Mexico, and at the Ludhiana station of the Borlaug Institute in South Asia (BISA) in India compensated for the effect of increasing temperature, which with conventional irrigation reduces yield by around 8% for each C^{o} degree increase, it reduced water consumption and has increased yield significantly. While drip irrigation is currently not economic, this may change should water be priced.

In conclusion, to ensure successful crop improvement in the future, it is essential to conserve and also *use* the genetic material housed in genebanks. Through SeeD, a Mexican government funded CIMMYT project, all 28,000 maize and around 100,000 wheat accessions stored in CIMMYT's maize and wheat collection have been sequenced thus providing the global maize and wheat community an incredible treasure trove of genes and data that are ready to be used.

Why organic farming is not the way forward?

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Introduction

The Swedish government promotes organic agriculture as the correct form of agriculture, providing extraordinary subsidies, recommending organic products to public schools, hospitals and homes for old people aiming to transform 30% into organic agriculture. Over many years, the green movement has promoted organic farming with positive connotations such as ‘natural’, ‘superior’, ‘environmental friendly’ and ‘sustainable’ and promising politicians and the public that high food quality, good environmental stewardship can only be achieved through natural means and methods. Facts and essential scientific analyses of organic agriculture were excused, ignored and attributed to denial of open-minded thinking.

The original arguments to abandon mineral fertilizer were opinions not based on science

The founders of organic farming were convinced that soil fertility and food quality declined through the use of mineral fertilizers negatively affecting human health. The philosopher Dr. Steiner, initiator of biodynamic farming, tutored that food products will degenerate, that these cannot be used as food for humans any more within this century (Steiner, 1924). The agronomist Lady E. Balfour, founder of the Soil Association, wrote that if the fertility of soils is built up with adequate supply of humus, crops do not suffer from diseases, crops and animals fed on these plants develop a high disease resistance. Man, nurtured with such plants and animals, can reach a standard of health, and a power of resisting disease and infection, from whatever cause (Balfour, 1943). The medical doctor H-P. Rusch, initiator of biological-organic farming, wrote that quality of food is dependent on the biological functioning of soils and mineral fertilizer is not a normal, physiological adapted and natural form of plant nutrition (Rusch, 1968).

Organic farming cannot feed the world

Recognizing hunger and shortage of food in the world, the questions are whether organic farming would be able to improve food supply and even produce sufficient food of high quality for a growing population. For an examination of these questions, data comparing organic and conventional data were examined. However, there a plenty of pitfalls associated with yield data comparisons: yields derived from crop or mixed crop-animal systems, nutrient input through off-farm manures in organic management, fertilization intensity, catch crops in rotation and specific management practices (Kirchmann et al., 2016).

Yield of organically produced crops in Europe were found 25-50% lower than conventional ones but only 10-20% lower in the USA (Kirchmann and Bergström, 2008). This was explained by nutrient inputs being 25-33% lower in organic crop production in Europe than in conventional whereas regulations in the USA allow large nutrient input through organic wastes of conventional origin. Thus, one main reason for lower organic yields were limited nutrient supply. The other was difficulties to control weeds (Kirchmann et al., 2007). In other words, shifting to organic farming means introducing low-yielding agriculture. Using the metrics 'same amount of crop produced by organic and conventional farming' reveals that more land is needed for organic production. This is unrealistic considering that natural land need to be converted into arable land reducing habitats for wild life conservation.

No reduction of environmental emissions through organic agriculture

Evaluating environmental impact of agriculture on a hectare basis may show that organic systems have similar emissions as conventional ones (e.g. Torstensson et al., 2006; Stenberg et al. 2012). However, if emissions are expressed per unit yield, benefits of high-yielding systems through lower leaching, less greenhouse gas emissions and more carbon sequestration are realized (Balmford et al., 2018).

Energy-analysis reveal of organic and conventional cropping systems

Energy analysis of cropping systems showed that both organic and conventional farming has a highly positive energy balance generating far more energy than energy used. Energy return on inputs (output/input ratio = energy productivity) was about 7 (Swedish conditions) in both organic and conventional cropping systems. However, in conventional systems, energy input was twice as high due to N fertilizer use as compared to organic systems relying more on N_2-fixing crops in rotation. Correcting the total energy output of conventional systems by the energy demand for N fertilizer production, reduced the energy surplus over organic production by only 10-15%. Thus, only a portion of the energy surplus of conventional systems would be required in order to make N fertilizer production fossil-free and sustainable. Furthermore, comparing energy yields of organic and conventional systems correctly, other ecosystem services besides wildlife conservation through spared land must be considered when cropping conventionally (Kirchmann and Bergström, 2008). Including also the energy output through forest or fuel wood by spared land, clearly showed that conventional outcompetes organic farming energetically as a whole.

The way forward – defining aims for sustainable intensification (not claims of methods)

Sustainable agriculture is often characterized by four overall aims – sufficient food of high quality, environmental stewardship, economic viability and social justice (e.g. Kirchmann and Thorvaldson, 2000). Organic agriculture defines claims - prohibiting mineral fertilizers, synthetic pesticides, synthetic feed additives, GMO organisms and synthetic medicines – presupposing that exclusion of these measures will lead to better agriculture. The principal of exclusion may appear attractive but if claims are not based on science, refusal to use modern instruments and methods will block further development, stop advancement of knowledge, limit possibilities to gain answers, and may not guarantee best solutions to solve problems. Only a scientific analysis of problems from which aims can described and solution be developed can improve agriculture.

A challenge for agriculture is to provide sufficient food for more people in future. Due to limited availability of arable land in many parts of the world, yield increases must be achieved on existing land and in an economically and environmentally sound way referred to as sustainable intensification, i.e. increasing production of high nutritious food with less environmental impact. A higher energy, water and nutrient efficiency in crop production should be possible through improved and new farming techniques. Some concepts have been identified: (1) Substituting native resources for fertilizer production by recycled nutrients from wastes and organic residues, not recycling wastes as such; (2) increasing nutrient use efficiency by placement of fertilizer at different depth in topsoil; (3) enhancing root accessibility of subsoils through long-lasting amelioration; (4) using traps in soil drainage systems to adsorb leached phosphorus and pesticides.

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How to increase impact for agriculture from research on the soil biota?

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Introduction

Research effort focused on the soil microbial community has greatly increased in recent years as a "soil health" paradigm (see Sojka et al. 2003) has suggested an urgent need. Molecular techniques have been proposed as useful to provide detailed characterisation of diversity, structure and function. However, relatively little of practical use to farmers has resulted, other than contributions towards on-going research efforts on important pathogens and rhizobia. Whilst soil microbes are undoubtedly involved in many soil processes important for the function and productivity of agricultural systems, the question remains: *when is management required to enhance the functioning of the soil biota?* And, therefore: *when should research resources be allocated?*

Case study: arbuscular mycorrhizal fungi

Arbuscular mycorrhizal fungi (AMF) are a subset of the soil biota that are ubiquitous, often high in biomass and easy to assess in terms of abundance through clearing and staining of roots. It has become common for AMF to be strongly linked with sustainable intensification and global food security (Thirkell et al. 2017; Rillig et al. 2016; Rodriguez & Sanders 2014) based on a literature which correlates their high abundance and optimal function to increased crop productivity, disease suppression and drought tolerance and well as soil structure and other indictors of soil health. Yet in a recent review, Ryan and Graham (2018) conclude that there are very few circumstances where farmers need to consider AMF. This contradiction in the literature is further discussed in two letters published in response to the review (Rillig et al. 2018; Ryan et al. 2018). Why the large agricultural-focussed literature on AMF has not resulted in their useful application in agriculture is explored in Box 1.

Box 1 shows that a key factor inhibiting application of research on AMF in agricultural systems is the failure to adopt a systems agronomy approach. To highlight the impact of this, we contrast the approach favoured in the recent AM-literature to that in the recent agronomic literature.

Box 1. Why little agricultural impact from research on AMF?

Widespread adoption of a "soil health" paradigm which places optimising the function and abundance of AMF and other soil biota at the centre of decision making and tends to advocate an approach of "mimicking natural ecosystems", i.e. , a focus on low-inputs and maximising biodiversity (see below).

Glasshouse trials assumed relevant to field conditions.

Lack of agronomic context leading to key agronomic variables not being measured, poor rigour, incorrect interpretation of data, inability to judge the magnitude of impacts, and failure to understand the agronomic relevance of results.

Complex experiments are revealing increasingly complex (and fascinating) interactions among AMF species and variants, other soil biota, host genotypes and the environment; relevance to agricultural productivity or resource-use efficiency is lost in detail.

Poor refereeing of papers claiming agricultural relevance, including highly cited meta-analyses, due to publication in non-agricultural journals and/or choice of referees and editors. These journals may be much higher impact that agricultural journals and thereby aid authors to gain further funding from some sources.

	AM-centric (soil health) approach	Systems agronomy approach
Goals	➢ "AM-optimised" ➢ Promote beneficial soil biota ➢ Mimic natural ecosystems (low inputs, high biodiversity) ➢ Sustainable intensification	➢ Close yield gap while improving resource-use efficiency ➢ Sustainable intensification
Strategy	➢ Focus on maximising function and occurrence of soil biota ➢ Minimal synthetic pesticides, herbicides and inorganic fertilisers ➢ Focus on increasing in-field biodiversity ➢ Minimal soil disturbance ➢ Minimal non-mycorrhizal crops (perhaps)	➢ Benchmark current yield against physiologically determined potential ➢ Identify factors limiting yield or reducing resource use efficiency, and determine how to best address them, using modelling and field experimentation based on rigorous agronomic methodology. Inclusion of the principles of phosphorus-efficient farming systems ➢ Address in a farming systems context using stepwise or simultaneous multiple (synergistic) practice changes
Outcomes if approach were to be applied in	➢ Prescriptive, inflexible guidelines limit regional adaptability	➢ Adoption of new packages of strategies: flexible, pragmatic and regionally adaptive ➢ Increased productivity

agricultural systems	➢ Low yields that may decrease over time due to failure to identify other key factor limiting yield (especially nutrients) ➢ Greater area of land farmed ➢ Poor resource-use efficiency ➢ High colonisation by AMF	➢ Improved resource-use efficiency; resource base protected ➢ No additional land farmed ➢ Abundance of symbiotically effective AMF likely favoured by default, but AMF not necessarily optimised ➢ Sustainable intensification
Key references	Rodriguez & Sanders (2014), Rillig *et al.* (2016); Rillig *et al.* (2018)	Hunt *et al.* (2018), Kirkegaard & Hunt (2010), Dimes *et al.* (2015), Fischer & Connor (2018), Giller *et al.* (2015), Hochman & Horan (2018), Ryan & Graham (2018), Simpson *et al*. (2015)

How to make research on the whole soil biota effective?

As with the literature on AMF, much of the soil biota literature lacks integration with key agronomic outcomes such as productivity or resource use efficiency and is strongly influenced by the soil health approach. While molecular techniques now allow the characterisation of the microbial community in great detail, the relevance of these studies to agricultural productivity is not clear. Certainly, the assumption that soil health can be easily predicted from integrating measures of the soil biota has been disproven with agricultural soils not necessarily less diverse than soils from natural communities (e.g. Mendes *et al*. 2015, Szoboszlay *et al*. 2017). A recent study exemplifies this problem. Bonanomi *et al.* (2016) did a detailed characterisation, using high-throughput sequencing of bacterial and eukaryotic rRNA gene markers, of the soil microbiome on one conventional and two organic farms. They concluded that there was “higher ecosystem function” on the organic farms, yet yield, diseases and soil nutrient levels were not investigated.

For comparison, 30 years of research in a field experiment at Harden in southern NSW, Australia, compared stubble burning-cultivating treatments with stubble retention and no-tillage. In contrast to expectations, the burn-cultivate treatment did not crash in terms of yields or soil health, and both treatments had similar microbial diversity and function (Bissett *et al.* 2013). However, most importantly, impact from this research was still achieved because of the systems agronomy framework under which it was conducted. Measurement of soil organic matter showed declines in all treatments due to insufficient nutrients being supplied for its maintenance, but soil fertility was then able to be rebuilt through nutrient application (Kirkby *et al*. 2016).

Conclusions

Research on the soil biota is not being effectively translated into useful changes in farming practices. New molecular tools have enabled increasingly complex studies, but practical outcomes are often lost due to lack of a systems agronomy approach. More effective use of research resources is required. We recommend the points in Box 2 to researchers, funding bodies and journal referees and editors.

Box 2. How to increase impact from research on the soil biota?

Avoid the assumptions of the soil health approach.

Have a broad range of expertise in research teams, including agronomists and producers familiar with the target system.

Clear identification of the problem, and the best way to address it, using a systems agronomy approach.

Consideration of a range of potential solutions (e.g. fertiliser, crop breeding, modifying crop management).

Experiments that must be done under controlled conditions (to minimise costs or variation) are carefully planned to ensure field relevance (temperature variation, watering, pot size, soil profile variation, plant density, etc)

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The multi-dimensionality of water use. Simple indicators, society concerns, and scientific rigour: the example of the water footprint (WF)

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Yield, water relationships, and water productivity

Water consumption in food production takes place mostly up to harvest. On a unit area basis crop growth (kg ha^{-1}) results from CO_2 assimilation that is inescapably related to crop evapotranspiration (ET, mm) i.e. the sum of transpiration (T) and direct soil evaporation (E). Crop ET is a passive process driven by energy and vapour pressure deficit when water is available and limited to the water available, implying that crops will use relatively more water, when available, in dry areas where water vapour pressure deficit (VPD) is greater. Consequently, the ratio between biomass or yield and water consumption, known as water use efficiency (WUE) or water productivity (WP, yield/ET; kg L^{-1}; kg m^{-3} or kg ha^{-1} mm^{-1}), decreases significantly as atmospheric evaporative demand increases.

Field measurements of WP of grain, forage, pastures, and horticultural crops in rainfed and irrigated agriculture were commenced in the second half of C20 (see de Wit, Tanner and Sinclair work). WPs show large variations among crops, locations, and time scale, as shown by the scatter plot in Figure 1.

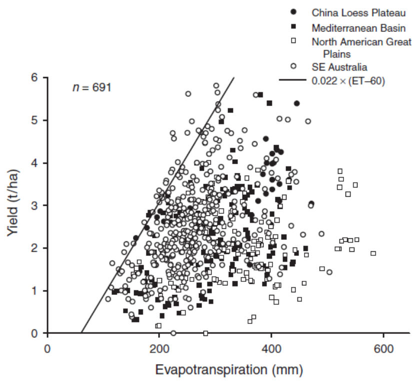

Fig.1. Scatter plot of rainfed wheat grain yield and seasonal ET in 4 mega-environments (Sadras and Angus 2006, based on others).

Water Footprint - a one-dimensional indicator

The water footprint (WF, L of water kg^{-1} of produce), the inverse of WP, is now being used as an indicator for the water used in food and services production (Hoekstra and Mekonnen, 2012).

The WF web page (http://waterfootprint.org/en/water-footprint/what-is-water-footprint/) describes the concept and presents three components of the WF that are considered independent, Green WF (GWF) is supplied by stored soil water, Blue WF (BWF) is supplied by stored water resources, and Grey WF is the amount of fresh water required to assimilate or dilute pollutants.

Some reported large values of WF (e.g. > 1000 L kg^{-1}) shock societies that are currently concerned with water limitations. WF seems a straight forward concept and is offered to decision makers and politicians as a “measurable indicator that may support European water governance” (Gobin et al., 2017) and furthermore, it could be included as a basis for decision making, along with carbon footprint on food packages to inform discerning consumers.

The large variations in WP among locations, time scales and crops are paralleled in WF. WF, and in particular GWF and BWF, are larger in arid and semi arid areas with high VPD which with solar radiation, temperature, wind, and evaporative demand determines crop water demand measured as reference crop evapotranspiration (ETo). For instance the WF of a maize crop in Córdoba (Spain) is ca. 500 L kg^{-1} but only 380 L kg^{-1} in Wageningen (The Netherlands) but when corrected or normalized by ETo, the differences disappear.

The two main flaws of the WF, as indicated by Fereres et al. (2017), are: 1) The GWF of a crop may actually be less than the water consumption of native vegetation and downstream water availability is actually increased by rainfed agriculture; 2) The total water consumption of a crop (“blue” plus “green”) is computed as the maximum potential crop ET, which is often significantly higher than actual crop ET. This error is serious for rainfed systems with low productivity.

The multi dimensional WP in agriculture

Estimation or measurement of efficiency of water use increases in complexity and in measurement errors when scaling up from a leaf to a hydrologic basin. Adding to this complexity is the fact that crops are not just a sum of individual plants because differences in canopy structure affect T control. Continuous canopies of main annual crops are poorly coupled to the atmosphere so their canopy conductance to crop water loss is less affected by stomatal control as are non-continuous, coupled canopies of tree plantations, all this reflecting on WP.

WP of irrigated agriculture is constantly being improved through more controlled forms of irrigation. Precision agriculture with a panoply of monitoring methods and novel irrigation equipment is expanding in large farms and developed countries. In 2017 52% of Spanish irrigated area, corresponding to 1.92 Mha, is by drip irrigation (MAPAMA, 2017). FAO estimates that small-scale farmers produce over 70% of the world's food needs so that the main challenge is to be found in improvement of WP of smallholders in developing countries in Asia, Africa and Latin America.

Concentration and distribution of a resource, such as water, on a small area is a way to increase efficiency of use. Large-scale, irrigation can gain further efficiency because it allows concentration of many productive resources (energy, nutrients, water, labour), thus leaving land available for forests or pastures. In this sense, irrigation has a positive ecological effect at the large scale if we accept the need to produce food. Contribution of irrigated agriculture to food production cannot be overemphasized; 17% of cropped lands that are irrigated globally produce more than 40% of our food, although salinization of irrigated land, siltation of reservoirs, and exploitation of non-renewable water resources clearly can diminish area under irrigation.

The complexity of irrigated agriculture is then de-contextualised when associated to the one-dimensional, usually high, WF, thus diverting efforts from sustainability analyses, improvement of WP in smallholder farms, and scaling up approaches.

Contextualizing WF

Ecological footprints should be established by comparison against a reference natural level. In the case of water, GWF and BWF should be considered as the increase in the water consumed over what would naturally occur relative to the yield produced: WF* = increase in consumed water/yield.

The amount of water consumed by a natural ecosystem in the given location is taken then as a baseline for the WF values. For simplicity we assume that the natural ecosystem would have an ET equal to reference (grass) ET as long as there is water available, thus: WF* = (ET – ET*) /Yield. Where ET is seasonal crop ET and ET* is ETo for periods when water is available in the soil. ET* should be limited by rainfall so if ETo for a given period is greater than rainfall, then ET* = rainfall. This equation may be applied also to irrigated crops. The calculated value of WF* for most rainfed agriculture is negligible, zero or negative because ET is limited by rainfall, in both the natural and the agricultural ecosystems.

In the case of irrigated agriculture, the value of WF* will depend on the scale considered. If we consider a hydrologic basin and the main source of water is that stored in reservoirs, in the long term the sum of ET and runoff out of the basin is equal to rainfall. Will ET increase as compared to that of a natural ecosystem? Not necessarily as it depends on crop distribution and irrigation management. Even if ET increases, the main effect is reduced runoff which may have a positive (e.g. flood control) or negative impact if the water available for natural ecosystems downstream is severely restricted. The actual outcome depends on local conditions which are specific in space and time, so any general assessment based on the water footprint alone is of little value.

If WF* is small or null for rainfed agriculture and positive for irrigated systems, should the consumer or society then prefer rainfed over irrigated agriculture? The answer cannot be based only on changes in ET at the farm scale but on a much larger scale.

Locally, the impact of irrigation on water demand may be substantial, but this just emphasizes the irrelevance of WFs in any global, international or even trans-regional context (Fereres et al. 2017).

Conclusions

The simple, one-dimensional indicator WF is a perverse assessment of agricultural water productivity but is a strong competitor to the scientific ecosystem of ideas. Being simple it attracts researchers that generate an increasing number of papers and then citations which then give "objective" scientific support to the idea. In the end it is not possible to evaluate science without considering how scientists are evaluated (at least in the public sector).

The current emphasis on making science accessible to the general public because “society pays” and society has to be shown the importance of what we scientists do, leads to an over-simplification of complex issues. Scientists and institutions may seek "popular" themes because they feel that science has to "respond" to society. Connecting with the average citizen or politician is a crucial but hard endeavour.

Crops are grown at a field scale which determines the relevance of physiological traits. Information from isolated plants or micro-plots may be biased so breeders should be always aware of the trade-off between plot size and number of plots that can be monitored. Non-destructive methods to determine WP in the field have yet to be improved. Good agricultural practices are at the basis of yield and WP increase. Improving future WP relies on breeding and agronomy efforts to change cropping to periods of lower evaporative demand, reducing water losses, and improving irrigation practice with better above and below-ground monitoring.

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Making climate science useful to agriculture

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Most scientific research is intended to achieve goals beyond science itself. This is clearly the case for funded climate science (Sarewitz and Pielke 2007, Lemos 2012). The large literature on the benefits of stakeholder engagement in science include 1) addressing important problems, 2) better definition of problems, 3) finding more workable solutions including anticipation of negative outcomes, 4) increasing the uptake of solutions, and 5) fine tuning science findings to local situations. Initiating stakeholder engagement in agriculture is relatively easy because farmers like talking about the weather. It has proven more difficult to develop the conversation and foster links between local farmer knowledge which is tacit, informal and context specific and climate science which is quantitative, formalised and often expressed as probabilities.

The challenge of making science beneficial to society can be framed as matching supply and demand (McNie 2007). All metaphors are limited, but the notion of supply and demand indicates a more complex interaction between agriculture and climate science than linear transfer (pipelines, relay teams or transmission lines). Supply and demand captures some of the iteration of the dance metaphor for the application of research (Cox et al.1995).

Agriculture currently has access to a vast amount of information from climate science at time scales of the coming days (weather forecasts), season (climate forecasts), and decades (climate change projections). It is incorrect to cast the delivery of climate science to agriculture as simply supply driven or solutions looking for applications. For a long time agriculture has demanded more information from climate science. The working lifetime of many farmers and their advisers has spanned information scarcity to information dazzle or at least information anxiety. A common complaint is not so much about the amount of information as the vagueness and imprecision, especially the use of hard to understand probability statements. Agriculture consistently wants levels of accuracy and precision beyond what climate science can deliver.

A long wait for reliable information from climate science – some words from the 1800s

Agriculture developed partly in response to the risks of hunting and gathering but developed its own risk profile, much of it climate-related (Hardaker et al. 2015). Agriculture has always been risky but few have described the risks as eloquently as Charles Stern's advice to an investor in Southern USA agriculture about 150 years ago.

> *Returns are subject to several contingencies, such as follows. Your corn may not be planted early enough. The hogs may destroy one-fourth of it, the rains an eighth, and the thieves an eighth; and the drought a large portion of the remaining one half. Your cotton may not come up well, and you may not get a good stand to begin with. It may rain too little, and it may rain too much; and it may be overrun by the grass. Or the rust may take it, the army worm, and the grasshoppers may commence their ravages: or other worms may strip the stalk of its foliage, and then an early frost may nip it in the bud. But if none of these things occur, you are quite likely to get good crops; and*

> *then if none of it is stolen, and your gin house does not burn down, you may be fairly recompensed for your labour. But if any of these things happen, your profits of course will be less.* Charles Sterns 1872, cited in McGuire and Higgs 1977.

Around the same time, George Goyder, the Surveyor General of South Australia was thinking about the riskiness of agriculture in a frontier society as he drew a line on a map indicating the extent of the 1865 drought. South Australia was established as a colony in 1836 and the colony grew inland with significant expansion of cropping in response to a run of unusually wet seasons. The subsequent return to normal or below average rainfall resulted in major land degradation and economic and social disruption. Goyder’s Line became known as a demarcation between land with adequate rainfall for cropping and land suitable for extensive grazing. For most his lifetime, Goyder’s line was ignored and subsequent runs of good seasons were partially interpreted as success due to the “rain following the plough” (Sheldrake 2013). This is not unique to Australia, at a remarkably similar time in history, Captain John Palliser, leader of the 1857-60 British North American Exploring Expedition drew Palliser’s Triangle identifying a region of the Canadian prairie in the rain shadow of the Rocky Mountains as unsuitable for agriculture (Marchildon et al. 2009). Like Goyder, Palliser’s advice was largely ignored.

Writing on the history of cropping expansion into the southern high plains in the US, Opie (1995) argued that frontier agrarian societies armed with more optimism than experience or rainfall records struggle to separate temporarily good seasons from the long-term aridity. Decker (1994) described the westward expansion of cropping in the late 1800s as a lesson in climatology through failure. According to Marchildon et al. (2009), pre-second WW cropping in Palliser’s triangle led to the destruction of dreams, livelihoods and lives. In South Australia, farm house ruins with only brick chimneys are used as a cautionary tale for natural resource planning, but also a reminder of the human cost of trial and error.

Beyond trial and error – predicting the coming season

Charles Todd was a contemporary of Goyder in the colony of South Australia. In 1893 he observed *“the importance to the farmer, the horticulturalist, and pastoralist of knowing beforehand the probabilities of dry or wet seasons, and whether the rains will be early or late, or both, has naturally led to a desire for seasonal forecasts, they have them it is said in India, why not Australia.”* A century later, another eminent South Australian, the agronomist Reg French (1987) urged the study of the variability of weather patterns *“One of the biggest deficiencies in agricultural research is the inability to both predict the probability of rainfall during the growing season and to estimate the yield and economic returns of different crops”.*

In addition to the direct losses of drought, frost and heat, climate variability imposes a more subtle impact on farm profitability. Because the coming season is uncertain, many farmers will make the reasonable decision to apply lower rates of fertiliser, perhaps sow later in frost prone regions and grow fewer high return but more risky crops than is optimal for the long term productivity. These decisions are rational, but they create a drag on long term farm profit. Even risk neutral decision makers are faced with a “moving target effect” whereby it is hard to make the optimal decision for the coming season on crop area, crop type, variety, sowing time and input level.

Guidance from climate science on weather, seasonal climate and climate change

Climate varies on all timescales and at each timescale the variability can be partitioned into 1) a predictable portion, 2) a portion that is likely to be predictable in the near future, and 3) a residual, irreducible uncertainty. The predictable component of weather in the coming 4 days will always be much higher than the nudged chaos of seasonal forecasts, and there are important differences between weather and climate forecasts.

Current weather forecasting relies on numerical models. These large models are initiated from the current state of the atmosphere and used to predict future states of the atmosphere, including the timing and amount of rainfall along with maximum and minimum temperatures for up to 10 days ahead. Seasonal climate forecasts typically give the chance (probability) of the next 3–6 months being wetter or drier (or hotter or cooler) than the long-term average. Rather than being influenced from the inherently chaotic dynamics of the atmosphere, they are based on patterns of the sea surface temperature (SST) or associated atmospheric characteristics. Up until 2013, Australia seasonal outlooks were based on statistical relationships between sea surface temperatures or the southern oscillation index. Since 2013 the Bureau of Meteorology has used dynamic models which are similar to numeric weather models but run at a coarser spatial scale and daily rather than hourly. Multi week (2-6 weeks) or sub-seasonal forecasts bridge the gap between weather and climate forecasts and start to blur the distinctions. Multi-week forecasts are more usefully seen as bringing the forecast period of climate forecasts earlier than extending weather forecasts. Weather and climate modelling at all timescales are increasingly being designed to include adjustments to the radiative properties of the atmosphere from the enhanced greenhouse effect (Baume et al. 2015). Climate change modelling enables an investigation of how different levels of external forcing from greenhouse gasses will interact with internal processes to deliver a range of possible future climates.

Table 1 is loosely based on 2 x 2 matrix used to consider the supply and demand for climate information by Sarewitz and Pielke (2007).

Table 1, based on author's understanding of climate science and Australian agriculture. The supply of climate information (rows) distinguish between information that is currently widely available and information that is likely to emerge in the coming decade. The relative horizontal position indicates current or future estimates of use. The further to the right, the higher the use.

	Information used by relatively few agriculturists	Information used by most agriculturists
Climate information currently available	•Probabilistic SCF •Climate change projections	•Weather forecasts •El Nino warnings •Seasonal outlooks •General direction of climate change
Climate information likely to be available in coming decade	•Downscaled climate change projections?	• Multi-week forecasts • Improved accuracy SCF

The horizontal axis in Table 1 is a subjective ranking but few would argue that weather forecasts should be at the far right. The gains in the accuracy of weather forecasts have been steady, impressive and easy to measure (Bauer et al. 2015). Not only do farmers have access to rainfall and temperature forecast at high spatial and temporal resolution, they also benefit from warnings of fire weather, heatwaves, frost, extreme rain and cyclones and specific variables such as potential evapotranspiration and foliar disease risk. The emerging availability of multi-week forecasts holds substantial promise. However, the expectation that the high accuracy of weather forecasts is likely to be extended into the weeks ahead is likely to lead to disappointment. When using multi-week forecasts, agricultural decision makers will have to consider the consequences of failures to warn and false positives.

In contrast to the steady state of improvement of weather forecasts, seasonal climate forecasts have only been available in Australia since the late 1980s. The discovery of the El Nino Southern Oscillation and the interaction between the atmosphere and the oceans has been described as the meteorological equivalent of DNA and the double helix (Frater 1991) and the premier advance of the atmospheric sciences in the close of the 20th Century (Easterling 1999). The teleconnections between the tropical Pacific and eastern and southern Australia are relatively strong and form the basis of most forecasting systems. The potential in the 1990s seemed sufficient to answer Sir Charles Todd's 1893 request. The confidence is apparent from leading agricultural and climate scientists (Hammer and Nicholls 1996) *"We are confronted with unprecedented opportunities to tune our agricultural systems in a way that improves their sustainable land use. We have a seasonal forecasting capability. We have started to think through how we can best use the knowledge that the next season is not a total unknown"* In the subsequent two decades, the use of seasonal climate forecasts has been disappointing or at least substantially different than was first imagined.

There should be some encouragement from the very high awareness and understanding of climate drivers such as El Nino and the Indian Ocean Dipole. The response to El Nino warnings and general seasonal outlook is ranked much higher in Table 1 than any formal use of probabilistic forecasts in decision making. When the Bureau of Meteorology declared an El Nino watch in June 2018, it was widely reported in the media and rapidly distributed through social media. Recent experience working with agronomists and dryland farmers indicates that almost all are aware of an El Nino warning, some will make adjustments to plans but this is mostly a subjective feeling of confidence in the coming spring. The difficulty of finding cases where farmers or advisers are using the revised distributions is interesting given robust frameworks for decision making under uncertainty (Anderson et al.1977, Hardaker 2015). Furthermore there are many simulation studies that show value from using forecast at current levels of skill. Meza et al.(2008) provide an international perspective, Rodriguez et al.(2018) a recent Australian example, and Parton and Crean (2018) review 140 Australian studies (2018).

Climate change projections have been available in Australia since 1987 (Whetton et al. 2016) but they have only gained widespread attention in the last 15 years. This recent emphasis has coincided with strong political critique of climate science and a range of views held by the Australian farming community. In Table 1 climate change projections are ranked relatively low compared to a general direction of climate change (warmer and that for much of the southern agricultural regions, drier). As with seasonal climate forecasts, the uncertainty in the projections, especially in rainfall presents a barrier to use. A further barrier is that most global climate models have a spatial resolution of a 200km grid.

Table 1 suggests increased use and usefulness in the future by increased accuracy of seasonal climate forecasts and spatial precision of climate change projections. There remains good reason to doubt that these improvements will ever bring the information close to the precision of weather forecasts or even to a point where they can be used without probability statements. It is important to note that downscaling climate models to a finer spatial scale does not resolve the underlying disagreement between global climate models on the extent or even the sign of precipitation changes.

Chess vs Poker

Duke (2018) describes a conversation between Jacob Bronowski (The Ascent of Man) and John van Neuman (Manhattan Project and creator of Game Theory) about whether decision making was more like chess or poker. Chess contains no hidden information, the pieces and positions are there for both players to see, there is no roll of the dice that can make a bishop disappear. Losing at chess is not bad luck, it can be traced to the wrong moves. Poker, by contrast, is a game of incomplete information, of decision making under uncertainty. Losing a hand of poker may well be bad luck and it can take up to 1,500 hands to identify the more skilful player.

Very little in farming is like chess, yet a close reading of most advice and take home messages written by researchers and advisers for farmers in Australia represent chess moves. The best examples break a complicated problem down to a series of steps with IF, THEN ELSE logic. This practical step-bystep approach has made an enormous contribution to decision making and sound agronomy. What is interesting is that even a problem like the appropriate N fertiliser rate in dryland farming tends to be written about as a chess move. Most of the discussion on N budgeting emphasises calculating the supply of N by soil testing and estimating mineralisation and then determining the crop demand by picking a single decile or target yield (Unkovich pers comm). There is often an acknowledgement that information on the coming season is unknown. However, in most of the vast amount of material on N budgeting, there is little formal, practical, step-by-step way to consider this uncertainty. With the notable exception of YieldProphet, most of the advice on N budgeting for dryland crops could be applied to irrigated crops.

Of all professions, farmers are used to dealing with uncertainty. Successful farmers and advisers are expert at managing climate risk. Perhaps the problem is that while farmers are comfortable with uncertainty in everyday life they do not associate uncertainty with science. Advisers vary in their comfort with probabilities, one possible reason is that while most advisers have studied probability theory as undergraduates, the very high confidence intervals on crop protection and animal health products lead to a situation where a working knowledge of probabilities is redundant.

The treatment of climate risk in agriculture has come a long way from trial and error and the enormous international effort in climate science will lead to improvements. In Australia at least, it seems much easier to attract funding resources to promises of increased accuracy and precision from climate science than working with agriculturists to improve planning under uncertainty and develop robust farming systems. Making climate science useful is more than a communication exercise; it is likely to benefit from the substantial developments in behavioural sciences and developing more innovative ways for farmers and advisers to incorporate forecasts of current skill.

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Translational research? Which way?

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"*Translational Research*" is a term in good currency. Last year it attracted 30,000 citations according to the *Web of Science*. Most of these were in the biomedical sciences, perhaps because *Nature* devoted a lot of space to it in one of its issues in 2008, when the annual citations of *Translational Research* were one twentieth of what they are today.

The term has now been adopted in the plant and animal sciences. It encompasses the translation of scientific discovery into new ways of improving health or productivity. More broadly, it also covers basic research that is pursued with an eye to making it useful, as Donald Stokes discussed in his book "Pasteur's Quadrant". It almost always refers to the linear flow of ideas up the ladder of the levels of organisation into which plant biologists divide their subject matter (gene, molecule, membrane, cell, tissue, organ, plant, crop) – a ladder that can also be thought of as a nested hierarchy.

An important feature of this hierarchy is that each level has its own terms that deal with the features and processes peculiar to that level. Thus Translation, if it is to move upwards successfully, requires knowledge of the main features of increasingly higher levels between basic research and its broad application – of the constraints and interactions that inevitably come into play. Gaining such knowledge requires translation in the opposite direction, reality checks that need to be passed.

A good example of neglected reality checks comes from research on salt tolerance in *Arabidopsis*. About 2000 papers on the topic have been published. They attracted 9,000 citations last year. What have we learnt from all this activity? Very little in relation to salt tolerance. Many of these papers involved severe osmotic shock, which plasmolyses the cells of the roots thereby resulting in large changes in gene expression. A second and more important problem with most of these papers is that they typically deal only with short-term responses to salinity, whereas useful variation in salt tolerance takes many days or weeks to become evident across a range of genotypes. This is because the exclusion of salt by the roots is a major determinant of salt tolerance. Bread wheat, which is salt tolerant, excludes about 98% of the salt in the water that passes across the roots to the xylem. Durum, which is sensitive, excludes only about 96%. The salt which is not excluded slowly builds up in the leaves and eventually irreversibly damages them. Ignorance of these processes, the first at the cellular level and the second at the leaf level, ensures that little of practical worth will come out of such research.

A second and more obvious example is the search for genes that might confer drought tolerance. The criterion for drought tolerance in this genre is usually the survival of plants after rapid depletion of their water supply. There are two problems with this criterion. The first is that the survival of crop plants is irrelevant in the real world. The second is that transgenic plants typically grow more slowly than the wild types. Thus the wild-types use water faster and therefore die more quickly than the transgenics.

While it is useful to think of plants and their components as nested hierarchies, it is also worthwhile thinking of them as a closed-loop in which the success of the plants is depicted by the transmission of their genes to the next generation. It is this loop that distinguishes the biological from the physical world; without the loop being closed, none of the structures and processes within it would exist.

The search for single genes that might confer tolerance to abiotic stresses has been intense. Many thousands of papers have been published on it. What then are the circumstances in which transformation of crop plants with single genes can be fruitful without the need for reality checks? The direct route, which bypasses the intermediate levels of organisation, has worked spectacularly well in conferring resistance to pests and herbicides and with improving grain quality or disease resistance. Improving tolerance of abiotic stress is much more difficult.

The reason for this disparity is that dealing with pests and herbicides involves destructive processes that target alien organisms or molecules. Such processes are not involved directly in the major metabolic machinery of the growing plant. Similarly, improving the quality of starch or of edible oils in seeds certainly affects metabolism but it is end-product metabolism and does not affect the way that the plants grow. By contrast, abiotic stresses such as drought impinge on plants over a wide range of different scales of time and space and involve elaborate processes occurring at all levels of organisation.

Nevertheless we seem to be inflicted with a fascination for solving problems of abiotic stress. Is this because it is attractively easy to expose plants to salinity or drought in controlled environments? An analysis by Dalal *et al*. last year shows that there were 5 times more papers published on abiotic than on biotic stress but that both had about the same number of patents granted. That gives an overall ratio of 5 to 1 in probable success rate. In fact, in the sale of cultivars, those claiming biotic stress tolerance exceeded those claiming abiotic stress tolerance by a factor of 13.

The rarity of reality checks in *Translational Research* is a reflection of the linear language used in agricultural R&D. Commonly used terms are: extension; technology transfer; input, output, outcome, impact; delivering outcomes; translational research; and transformational research. This dominant language is well set in our minds so that we are prone to think linearly, from bench to bedside if we are medicos, from lab to field if we are agricultural scientists, from proposals to products if we are funders. Some of these terms do have solid meaning and produce good results. But none of them pay tribute to the innovative richness of conversations across levels, especially those between farmers and field scientists from which much agricultural innovation springs through fertile interplays between imagination and reality.

Funding bodies are under pressure to encourage proposals that aim to solve major problems. This pressure is reflected in the increasing frequency of papers in the plant sciences that have an introductory paragraph on food security, even though there is usually no discernible connection (to an agricultural scientist) between the essence of the paper and food security.

Research proposals that promise utility attract money from naïve funders, who believe that they are fostering useful research. The idea of the reality check does not seem to have penetrated far into the funding process. The many plant scientists who are unused to conversing across levels in search of reality checks will not spontaneously start doing so.

The best way ahead is for the major funding bodies to augment their selection 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 much better chances of practical success. And, if seen as a dichotomous process, it would free up many 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.

Incremental transformation: science and agriculture learning together

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My title is a deliberate abstraction of an artificial distinction often imposed on science and its application as either "incremental" or "transformational". The global food security challenge has prompted many to propose the need for transformational change in food production systems through technological breakthroughs, as distinct from the "business as usual" offered by systems agronomy. At face value, it may seem trite to be critical of aspirations to achieve such breakthroughs, but in a world of diminishing expenditure in agricultural research it will be important to target dwindling R&D dollars well. Proposed transformative changes often focus on one component of a system – a new genetically modified crop; a more effective biological fertiliser; a new satellite-guided planter - often by largely disconnected research disciplines. In reality, and throughout history, few individual technologies have been singularly transformational either in the scale or the speed with which they have influenced productivity on farms. Rather, step changes in productivity have come only when combinations of technologies, often a mix of old and new, synergise within a system (Evans 1998; Duvick *et al*., 2005). So how best to organise research to capitalise on new science and technologies to gain real impact on farm?

During my career at CSIRO, I have been privileged to sit within the "crop adaptation" group where my focus (and motivation) was on-farm crop agronomy, but I was surrounded by more fundamental soil scientists, crop physiologists, geneticists and in time, molecular biologists (the burgeoning "transformational" science of that time). For this presentation I reflected on 30 years working in the stimulating space between innovative farmers (demanding practical solutions), and science specialists (demanding breakthrough science). I genuinely believe it was a strong influence of both, with neither getting to dominate, that was powerful. The involvement of growers and consultants in the research from the outset was also crucial to the speed and scale of impact of two national research programs I will discuss: – the National Water Use Efficiency Initiative (Kirkegaard *et al*., 2014) and the Dual-purpose Cropping Initiative (Dove and Kirkegaard, 2014). Some success factors common to these national programs and other successful agronomy programs globally are worthy of discussion.

It is important for science and agriculture to learn together. Within and beyond the projects mentioned above there have been numerous examples of "common beliefs" among the farming community, usually based on quite reasonable expectations and principles, that have been found wanting when challenged by the careful, penetrating science seeking mechanistic understanding. For example, in the area of conservation agriculture - grazing sheep were not damaging no-till soil with their hooves; stubble-retained systems were not building soil carbon; allelopathy was not the cause of poor canola growth in retained wheat residue; and cultivating long-term, no-till soil did not do irreparable damage. In the area of improved water-use efficiency - summer fallow rainfall is valuable in southern winter-dominant rainfall areas of southern Australia; earlier-sown, vigorous crops do not use water too quickly and fail; deeper root systems are more valuable in wetter areas, and in better years rather than in droughts. Currently a belief in the restorative powers of diverse-species cover crops with tillage radish leading the charge is in desperate need of closer scientific scrutiny.

Likewise conclusions arising from strong mechanistic science, even when biologically sound, can be misleading, or irrelevant at the scale farmers can respond. The realities of risks (e.g. climatic, price), labour supply, logistics, ease of implementation, personal circumstances, motivation and many other factors influence the capacity of growers to adopt innovations. Science that proceeds without being connected to that context, no matter its quality, is unlikely to lead to significant impact (maybe impact factor!). In my own case, very detailed work to elucidate the mechanisms of recovery of grazed crops to suggest better variety choice and manage residual biomass proceeded in ignorance of the practicalities of moving sheep flocks on mixed farms. The level of detail required for significant impact was better communicated as "rules-of-thumb". Another example emerging from the WUE Initiative was the unlikely combination of slower-maturing wheats with long coleoptiles as a solution to adapting wheat to drier, warmer and a potentially frostier future (Hunt 2017; Flohr *et al*., 2018). These are not traits commonly featuring in lists for prospective drought tolerance.

What are the obstacles that prevent greater impact from multidisciplinary efforts in agronomy? Conceptually, more thought about G x E x M interactions; structurally reward for integrators as specialists; culturally better partnering for impact; and institutionally we need to value impact along with impact factor. In my sphere, a shift in focus on the productivity and WUE of individual crops, to that of the whole farming system marks a paradigm shift into which individual disciplinary expertise must be coaxed. Systems agronomy provides an integrative framework and its science should sit alongside the fundamental biology and engineering that underpins modern genetics and digital agriculture. Agricultural science needs the context and integration provided by agronomists, farmers and their consultants in the journey from inspiration to impact.

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Making science useful to agriculture

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This abstract is a somewhat unstructured group of ideas and questions that I hope will touch on some of the issues that will be discussed at the OECD workshop in November. I thought it better to come with a 'rough' text rather than any sort of completed 'vision'.

Developed country food systems are characterized by being linear, powered by sunlight in combination with fossil fuels, include many issues in addition to the production of food and nutrients germane to food and nutritional security, show diminishing returns on investment of external resources but operate most efficiently when all resources are available in sufficiency.

What differentiates a circular food system from a linear one, in theoretical terms? Let us remember the social psychologist Lewis Maxim's aphorism – 'there is nothing so practical as a good theory'!

Before considering this question it is important to realise that all systems - be they closed or open - are subject to the 2nd Law of Thermodynamics (entropy increases) and thus require constant inputs of energy to enable them to function – this energy comes either from natural renewable sources or from fossil fuels. Generally, fossil fuels in linear food systems have been used to increase the amount of sunlight intercepted and the length of time of any interception and thus drive crop photosynthesis and the production of dry matter. Circular systems will still depend on this basis of production – but it is what happens after food production that should characterize a circular food system. The paradigm shift is from 'produce a lot –consume a lot –waste a lot' to 'produce less – consume less – save more'.

HT Odum (2007) 'Environment, Power and Society' defines the local carrying capacity (C) for humans as:

$$C = Pe + (R + Pe)/E$$

where Pe is the local empower per unit area, R is the investment in new empower from local and/or external means and E is the empower use per person. So, C can be increased by decreasing E or by increasing R and/or Pe. In a circular system one would aim for a low and stable E and a higher Pe than R. This analysis needs to be expanded to include other factors important in food systems such as waste.

It also needs complementing with some ideas that have been worked on recently by Eskild Bennetzen, Pete Smith, J-F Soussana and myself. These are summarized in a series of identity relationships used originally to deconstruct greenhouse gas emissions from food system (Bennetzen et al., 2016: Bennetzen EH, Smith P & Porter JR (2016). Decoupling of greenhouse gas emissions from global agricultural production: 1970–2050. *Global Change Biology*, 22, 763–781). The starting point is the Kaya identity that deconstructs GHG emissions into the GHG intensity of fuels (GHG/Energy), the carbon intensity of the economy (Energy/GDP), personal wealth (GDP/population) and the population of a country, region or other spatial organization. This was extended to the Kaya-Porter identity (KPI) to include land-use but can be extended further to include food and diet demand (Figure 1). All the above identities could be used to characterize circular versus linear food systems.

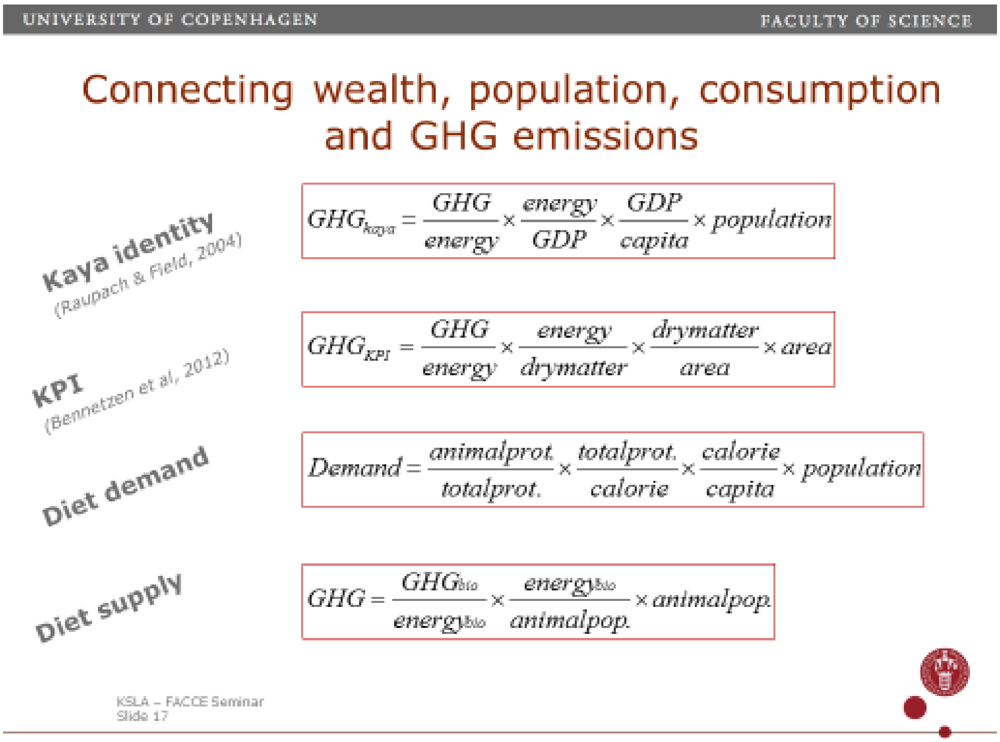

Figure 1. The Kaya, Kaya-Porter and other identities to connect wealth, population, consumption and GHG emissions.

Another theoretical issue besides personal carrying capacity and identities of elements of food consumption is the efficiency of resource use in linear and circular food systems. A comprehensive analysis of alternative models is given in the attached paper below and attention should be given to which of the alternative models of resource use efficiency is most appropriate for linear and circular food systems. It seems to me as though Liebscher's model would be a good one to start with, as it has most generality.

I also wish to highlight two further topics, focused on modelling, important for future assessment of the impacts, adaptation and mitigation of the land-sector and agriculture and their position and role in climate change. Bennetzen *et al*. (2016) showed via a historical deconstruction analysis, using a modified Kaya identity analysis, that GHG emissions from agriculture have decoupled from food production since 1970 and give grounds for optimism that agriculture can make a substantial contribution to reducing global emissions as well as helping to store carbon in the terrestrial sink. A reduction of emissions per unit product means that the utilization efficiency of the principle inputs into food production, namely water and fertilizer, has increased. At the same time crop simulation models have been used extensively to project the impacts of changes in CO_2, temperature and other factors for global and regional productivity of crops, mainly wheat (e.g. Ruane *et al*., 2017). Utilisation efficiencies do not operate in isolation; that is to say that there are interactions between, for example, a crop's utilisation efficiency of water, nitrogen and photosynthetically active short-wave radiation. How far these interactions of resource utilisation efficiencies are incorporated into models is unclear and needs testing, together with a critical need to design and make experiments to test the models. Models should not get the 'right' answers for the 'wrong' reasons such as via cancellation of errors.

To this end, we have used a methodology that decomposes water and nitrogen utilisation efficiencies and portrays their interactions or trade-offs with water utilisation efficiency. The ideas stem originally from the work of CT de Wit and his colleagues at Wageningen, NL and have been developed by others (Teixera et al., 2014; Sadras et al. 2016) but has seemingly not as yet penetrated crop modelling as an issue for climate change impacts (Ruane et al., 2017) . The identity for water utilisation efficiency (WUtE) and its graphical portrayal (Figure 2) show a possible relationship between WUtE and nitrogen utilisation efficiency (NUtE). Grain yield per unit transpiration can be broken down into grain yield per unit intercepted radiation modified by intercepted radiation per unit nitrogen uptake and then N uptake per unit transpiration. Figure 3 shows possible forms for identity components describing efficiency and the trade-offs between radiation and N and N and water; the graphical form of the identities may be different from the theoretical ones in Figure 2. Questions that need responses from crop models include ‘what are the modelled upper limits for NUtE and WUtE in ambient and changed climate pathways and how do they compare with observations?’ and ‘in comparison with a control treatment, how do the utilisation efficiencies change and interact?’

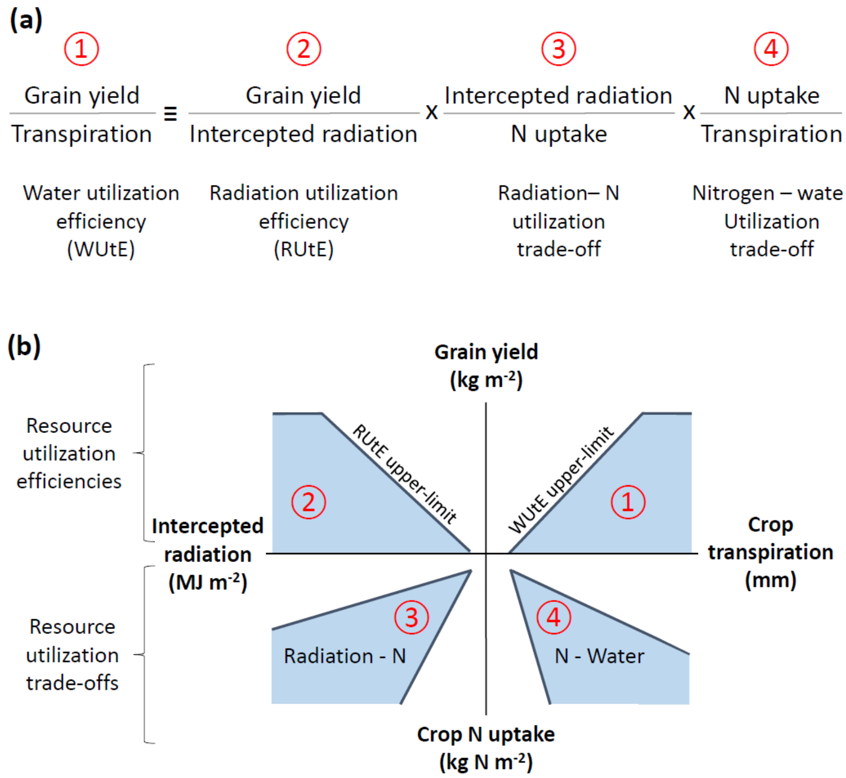

Figure 2. Decomposition of water utilisation efficiency showing the relationships between water and radiation utilisation efficiency and trade-offs (Porter et al, 2018 unpublished).

I suggest that crop models should be able to populate such analyses and we give an example (Figure 3) using the *SiriusQuality* model (Martre *et al*., 2006). The simulations are of a four-year CO_2 enrichment experiment on spring wheat at Maricopa, USA in which the crops were grown in ambient and elevated CO_2 for either high-and-low levels of nitrogen or with or without irrigation (see Figure legend for details).

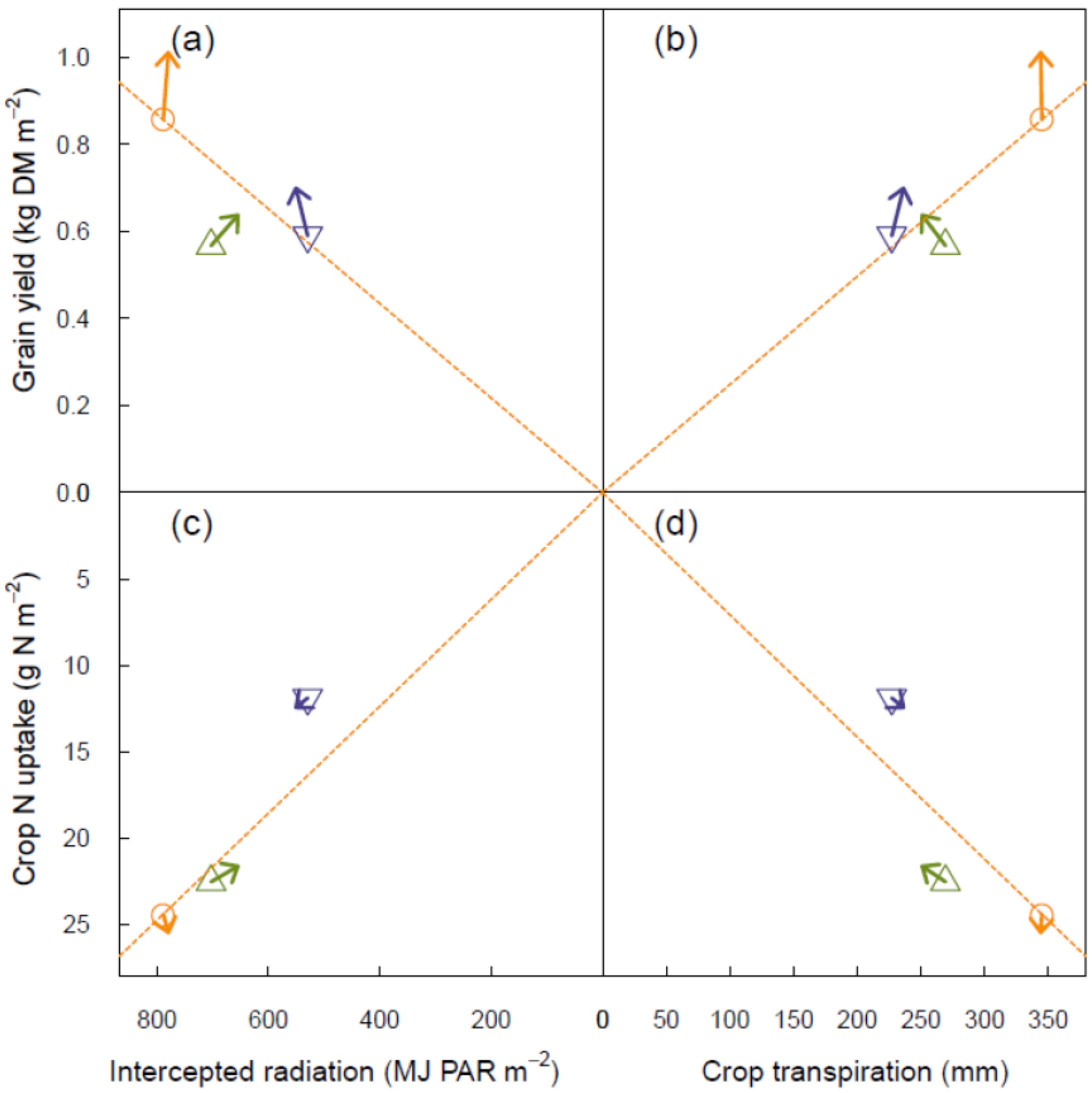

Figure 2. Simulated effect of nitrogen, water, and CO_2 supply on resource utilization efficiency and trade-offs illustrating the identify in Figure 1a. A Free air CO_2 enrichment experiments conducted over a four years period with a spring wheat cultivar at Maricopa, AZ, USA (Kimball et al., 2018) was simulated with the wheat simulation model *SiriusQuality (Martre et al., 2006, 2018)*. In the first two years wheat crops were grown with high (38.9 g N m^{-2}) and low (7.6 g N m^{-2}) nitrogen supply under ambient (370 ppm) and elevated (550 ppm) atmospheric CO_2 concentration. In the following two years a fully irrigated (665 mm) and a water deficit (330 mm) treatments were factorized with the same two CO_2 treatments. Symbols are ambient CO_2 concentration treatments and arrows point to the simulated values with elevated CO_2. Orange dashed lines are isopleths with resource utilization (a and b) or trade-offs (c and d) equal to those of the treatment with non limiting N and water under ambient CO^2 concentration (Control).

Figure 3 (not Figure 2 and directly above) shows resource utilisation (Figure 2) for nitrogen and water when measured as uptake of N or transpiration of water against crop grain yield. Points above the control isopleth mean that utilisation efficiency is increased relative to control and *vice versa*. Thus, low nitrogen decreased intercepted radiation relative to control (Figure 3) but water deficit had little effect (Figure 3). WUeT was basically not affected by either treatment relative to the control. A higher CO_2 level increased both utilisation efficiencies. Elements 3 and 4 in Figure 2, which measure the trade-off between the two utilisation efficiencies, are shown in Figure 3.

Crop N uptake per unit transpiration (ie the N water trade-off) is higher than control for the low N treatment but lower than control for the water deficit. Our conclusions from this very preliminary analysis using a single model are that models should be examined for their ability to represent resource use efficiencies under ambient and elevated CO_2 concentrations and, more importantly, how models portray the trade-offs between resources. Interactions between resource use efficiencies is an important but largely ignored factor in crop adaptations to climate change (Porter *et al*., 2014). Such work cannot be solely model-based but requires the analysis of existing experiments and where necessary the making of new experiments to test our models.

The identity approach can be extended to examining resource use efficiencies, their interactions and how precise and accurate simulation models are at representing them.

Some other important questions:

1. Heisenberg principle is about uncertainty. Measurement affects the measured process. What is measured changes the nature of what is measured – ie GDP means ‘lock into’ the capitalist economic system.
2. Are we dealing with a linear data-highway or an ‘epistemological maze’ in which more data does not help you get out of it – but thinking about what a maze is might help. Does more data equal more knowledge? I don’t think so.
3. What metrics for a ‘circular food system’? Rates or states: relative or absolute measures?
4. How far does what one measures and how one measures it influence the future direction and goals of a human-driven system – like food.
5. What does ‘big data’ say about the type of food system that it leads to?
6. The point is really - how does 'objective measurement' and collecting 'big data' affect the normative decision on the type of food system (or any other system) that we wish to pursue. 'Big data' are not normatively neutral and collecting certain types of data and not others has an effect on the future behaviour and development of the system under study - just like in the Heisenberg principle. This needs thinking about.

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Agricultural systems research to tackle complex problems in agriculture

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The recent increase in the number of undernourished (FAO, 2018) issues a clear warning signal that achieving the UN Sustainable Development Goals (SDGs) by 2030 will require significant transformation of our agricultural systems.

Even though significant progress in increasing food production has been made over the last 20 years, structural constraints, a changing climate, and the expected increase in food demand, create complex problems that shed serious doubts on meeting many of the SDG targets.

When dealing with complex problems, fragmentary science approaches are likely to produce incomplete answers, i.e. information, knowledge or technologies that at best are irrelevant to practitioners. Here we define Agricultural Systems Research (ASR) as a framework for the application of component research, having the overall aim to have impact across the multiple functions of agriculture and sustainable development goal.

Systems Research in Agriculture does not specify a rigid set of techniques. Instead it encapsulates a number of principles relating to interdisciplinarity, trade-offs, client-orientation, and interactions across different scales of operation. This ensures that ASR is equipped to deal with complexity, value conflict, and uncertainty to address key issues and ensure that agricultural research makes measurable contributions to development as encapsulated by the SDGs, including:

- Improved understanding of technical, natural, structural, social, and human barriers and opportunities for the adoption of more productive, sustainable and resilient innovations.
- Participatory diagnosis and implementation of adaptable innovations. These can be embodied technologies such as better livestock breeds or crop cultivars or disembodied ones such as better agronomic methods/approaches. Technologies may be available “on-the-shelf” but the matching innovations to situations and available delivery mechanisms such as extension and local innovation systems may be weak or lacking.
- Continuous monitoring, evaluation, feedback and re-design of market, agricultural practices, that are financially or economically unattractive for individual farmers, communities, markets and policy.

ASR ensures the sustainability of agricultural systems; many such constraints have to be simultaneously resolved. Farm productivity and profits can only be sustained if the resource base is not degraded. Production systems that deliver on economic and environmental benefits require access to technologies, knowledge and skills. The main barriers that frustrate technology adoption and sustainable intensification are often interlinked and must be understood, analysed and addressed as a set of interrelated constraints, something that ASR is expressly designed to achieve.

ASR therefore offers an iterative process, that involves multiple steps, including identification of researchable problems within a socio-ecological context, and a plausible basket of options to address the challenges. Systems analysis through participatory mixed methods and simulation modelling are keys to identify entry points and plausible options, as a starting point for co-adaptation, and a cyclic learning process that includes multiple disciplines and stakeholders. This is illustrated for the case of trade-offs between the uses of limited biomass between alternative uses in smallholder farming in Africa; and the application of systems agronomy approaches to identify optimum combinations of hybrids, and agronomic managements across highly contrasting environments in dryland sorghum production in Australia.

These examples show two contrasting cases where researchers, farmers and other agribusinesses engage to develop innovations that meet multiple functions of agriculture.

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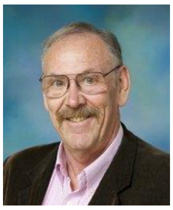

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Peter Appleford was appointed to lead the South Australian Research and Development Institute (SARDI) in June 2017. Peter is responsible for the executive management and oversight of the South Australian government primary industries research capability, investment and delivery. SARDI delivers robust scientific solutions to support sustainable and internationally competitive primary industries. Dr. Peter Appleford is a science graduate of the University of Melbourne, holds a PhD (Science) from James Cook University and is a member of the Institute of Public Administration and Australian Institute of Company Directors. He has spent nearly two decades as a senior leader in key Victorian Government agencies including the Department of Primary Industries and the Department of Sustainability and Environment. Peter is a highly-respected public sector executive with experience in implementing change while driving integrated and improved performance. He is proficient at delivering legacy-style change. He applies his four-fold technical expertise - driving change, delivery improvement, integration and leadership – to maximum impact within challenging and complex environments. Peter brings his visionary and energetic leadership style to inspire and drive better business outcomes. He applies decisive action and sound judgement to deliver value to SARDI’s objectives, their highly skilled people, stakeholders and the wider community.

Pedro Aphalo studied agricultural engineering, with specialization in crop breeding, at the University of Buenos Aires where he also completed his M.Sc. in plant production. He was awarded a PhD by the University of Edinburgh. He held university lecturer positions both in Statistics and Environmental Metrics (University of Jyväskylä) and Plant Physiological Ecology (University of Helsinki). He currently leads the lab Sensory Photobiology and Ecophysiology of Plants at the University of Helsinki and holds a docentship in Physiological Plant Ecology at the University of Eastern Finland. He is communications officer of the UV4Plants scientific association and the editor-in-chief of the UV4Plants Bulletin. His core research in photobiology focused on whole-plant physiology, early with both ornamentals and wild native plants, and currently with trees and more ecologically and environmentally oriented questions. His recent work with highest impact has been related to the study of sunlight perception and signalling using state-of-the-art molecular methods such as RNAseq in plants grown or exposed outdoors.

Malcom Buckby's career has ranged from being the manager of a family farm to being the elected representative for the Light electorate in the House of Assembly in the South Australian Parliament, serving as the Minister for Education, Children's Services and Training, Shadow Minister and Member of Standing Committees. My time as a Research Economist at the University of Adelaide gave me the knowledge of the SA economy and the privilege of working with some of the best economic minds in the state. I am currently the Manager of the Rural Services Division of the Royal Agricultural and Horticultural Society of SA and deliver administration and policy advice to a range of rural bodies including Beef and Sheep Societies, SA's Country Shows and the SA Grain Industry Trust.

David Connor is Emeritus Professor of Agronomy in the Faculty of Veterinary and Agricultural Sciences of The University of Melbourne, Australia, and Research Associate of CEIGRAM de La Universidad Politécnica de Madrid, Spain. His area of expertise is in agronomy, crop physiology and crop ecology. He currently works in canopy management and modeling of olive orchards, reviews research papers for various scientific journals, and offers consultancy in agronomy, resource management and research for agricultural development. Professor Connor is active in professional societies. He has served as President of the Australian Society of Agronomy and of the Victorian Branch of the Australian Institute of Agriculture. He is a Fellow of the Australian Institute of Agriculture (1988) and "Donald Medalist" (2003) of the Australian Society of Agronomy for outstanding contributions to research. During the period 1994–2001 he was Editor-in-Chief of Field Crops Research. Professor Connor has traveled widely and has also undertaken research and development projects in Kenya, Philippines, Bangladesh and Mauritania. He has also held visiting appointments in research and/or teaching in USA, Colombia, China, Argentina and Spain. During his career he has published over 100 papers of original research. He is also author, with Professor R.S. Loomis (University of California) and Professor K.G. Cassman (University of Nebraska), of the recently (2011) revised major textbook, "Crop ecology: productivity and management in agricultural systems" (Cambridge University Press). The book has been translated into Japanese, Spanish and Chinese.

Mariano Cossani is Senior Research Agronomist with SARDI, working on crop ecophysiology and abiotic stress adaptation. Mariano has an Agronomy Engineer degree from the University of Buenos Aires, and a Masters and a Ph. D. by the University of Lleida. His research experience encompasses aspects of resource capture and resource use efficiency of cereals, and adaptation of crops to the climate change effects, such as heat stress and drought. He developed methods based on empirical field data to assess the co-limitation of resources in wheat systems of Mediterranean environments that proved to be useful on other crops as canola. He has been working during five years for CIMMYT of the CGIAR System Organization, where he developed conceptual models for adapting wheat to hot environments through the use of physiological traits, phenotyping and strategic crossing.

Ford Denison earned a Ph.D. in Crop Science from Cornell, and worked for USDA as a Plant Physiologist before joining the department of Agronomy and Range Science at UC Davis. There, he directed the first ten years of a long-term experiment now in its 24th year, taught Crop Ecology, and did basic and applied research on the legume-rhizobia symbiosis. In 2005 he joined the University of Minnesota, where he advises a three-site long-term experiment and continues laboratory and field research mostly on nitrogen fixation and on links between evolution and agriculture. He has published in Nature, Science, Proceedings of the National Academy of Sciences, Proceedings of the Royal Society, Philosophical Transactions of the Royal Society, American Naturalist, Evolution, and Journal of Evolutionary Biology, in addition to multiple publications in Agronomy Journal and Field Crops Research. An article and subsequent book on Darwinian Agriculture led to a series of five lectures at the International Rice Research Institute, the agriculture keynote at the Applied Evolution Summit, and CGIAR's Science Forum 2011.

Tony Fischer came from a wheat and sheep farm near Boree Creek in southern New South Wales, Australia, a commercial operation in which he was involved for over 50 years. He completed degrees in Agricultural Science at the University of Melbourne before pursuing a PhD in plant physiology at the University of California, Davis, USA. He worked as a crop agronomist and physiologist for the NSW State Department of Agriculture and at CSIRO, and in the same capacity at CIMMYT, Mexico, from 1970 to 1975. He later returned to CIMMYT as Wheat Program Director (1988–95), following which he was a program manager in crops and soils at the Australian Centre for International Agricultural Research (ACIAR) in Canberra, Australia. He is now an Honorary Research Fellow at CSIRO Plant Industry, also in Canberra. His research publications in plant and crop physiology and agronomy are widely cited. He has served on several International Center Boards of Trustees as well as the Board of Australia's Grains Research and Development Corporation (GRDC), and has travelled widely in the grain cropping regions of the world, especially those of Asia and Latin America. He has received many awards for contributions to crop science, including the Colin Donald and William Farrer medals, and Fellowships of the Australian Institute of Agriculture, the Australian Academy of Technological Sciences and Engineering, and the American Crop Science and Agronomy societies. In 2007 he was elected a Member of the Order of Australia.

Richard Gray joined the University of Saskatchewan in 1990 after completing his PhD in Agricultural & Resource Economics from UC Berkeley. Over time his policy research has increasingly focused on various aspects of agricultural research and innovation systems. From 2003 to 2013 he led the *Canadian Agricultural Innovation Research Network.* Richard is a Fellow of the Canadian Agricultural Economics Society. He currently holds the grain Policy Research Chair and regularly provides advice to farm organisations and government regarding innovation policy. His active engagement in the family grain farm continues to provide first-hand experience with agriculture.

Peter Hayman is an agricultural scientist who has worked on the application of climate science to farming systems. His focus on low rainfall cropping and irrigated viticulture in southern Australia but has been involved in climate risk projects in Philippines, Cambodia, Sri Lanka and India. In 2004 he was appointed as Principal Scientist, Climate Applications with SARDI, prior to that time he was coordinator of climate applications in NSW DPI. He has worked closely with climate scientists, crop modellers, economists and farmers with a main interest on how the advances of climate science can be communicated and used in decision making.

Holger Kirchmann has a degree in chemistry (Dortmund University), a biology education (Uppsala University) and a PhD in soil science (Swedish University of Agricultural Sciences, SLU). He received a professorship in Plant Nutrition and Soil Fertility at the Department of Soil and Environment, SLU, in 2003. His research includes nutrient turnover especially of nitrogen, phosphorus and trace elements in soil and changes in long-term soil fertility due to different fertilization regimes. Currently, research topics such as subsoil improvement, recycling of plant nutrients, placement of mineral fertilizers and selenium fertilization are addressed. He teaches courses in plant nutrition, soil biology and soil sciences.

John Kirkegaard is a Chief Research Scientist at CSIRO Agriculture and Food, based in Canberra and Adjunct Professor at the University of Western Australia and Charles Sturt University. He was raised on the Darling Downs in rural Queensland, studied agriculture at The University of Queensland where he received his PhD studying the effects of soil compaction on the growth of grain legumes in 1990. The same year, he joined CSIRO Plant Industry in Canberra to work on the Land and Water Care Project, and his subsequent career at CSIRO has focussed on understanding soil-plant interactions to improve the productivity, resource-use efficiency and sustainability of dryland farming systems. Over the last 28 years, his research teams and collaborators have investigated aspects of improved crop sequence, rotational benefits and productivity of canola and other Brassica species, improved subsoil water use by crops, development and integration of dual-purpose crops, and improved productivity in conservation agriculture. He has led numerous national research programs, is a regular invitee to international forums and advisory committees on agriculture and food security, and was Visiting Professor at Crop Science Department, University of Copenhagen in 2012. A hallmark of his innovative research has been his active integration of farmers and advisers into his research teams, which has undoubtedly led to more rapid adoption and impact in agriculture. He was recipient of the grains industry "Seed of Light" award in 2009 for effective communication of research results to industry, and in 2014 his GRDC National WUE team was awarded the Eureka Prize in sustainable agriculture for research to improve the water-use efficiency of Australian agriculture. He was elected a Fellow of the Australian Academy of Science in 2016, was recipient of the Farrer Medal for distinguished contribution to agriculture in 2017, and is an ISI Web of Knowledge Highly Cited Researcher for Agricultural Sciences in 2018.

Martin Kropff joined CIMMYT as Director General in 2015, after working at Wageningen University and Research Center (Wageningen UR) in the Netherlands, where he was Rector Magnificus and Vice Chairman of the Executive Board for almost 10 years. He earned bachelor's and master's degrees in biology at Utrecht University in the Netherlands and a Ph.D. in agricultural and environmental sciences at Wageningen. From 1990 to 1995, Kropff was the systems agronomist at the International Rice Research Institute (IRRI) in the Philippines where he led an international program with National Agricultural Research Systems and Universities in nine Asian countries on systems research and simulation for rice production. Since 1995, he has served successive roles at Wageningen UR, including as Professor and Director General of the Plant Sciences Group and on the Executive Board. He is still connected to Wageningen UR as a Professor. From 2013 to 2015, he was a member of the Board of Directors of CGIAR, the 15-member consortium of international agricultural researchers to which CIMMYT and IRRI belong. He chaired the new System Management Board of the reformed CGIAR from 2015 to 2017 and he is still a member.

Renee Lafitte works at the interface of crop ecophysiology and crop improvement, with the goal of improving the resilience of crops and cropping systems to abiotic stress. She received a M.Sc. in Agronomy and Ph.D in Crop Physiology from the University of California, Davis. Renee began field phenotyping for stress tolerance in 1985 at the International Center for Maize and Wheat Improvement (CIMMYT) in Mexico, using managed drought and low-nitrogen environments in breeding programs. She also developed and delivered courses in on-farm research for breeders and agronomists from partner countries in Latin America, Africa, and Asia. In 1995, she was employed at the International Rice Research Institute (IRRI) in the Philippines, where she was responsible for field-based and greenhouse phenotyping to assess genetic variation in rice drought response, including approaches of QTL analysis, gene expression profiling, and studies of inheritance. She also served as team leader for IRRI's project on genetic enhancement for improving productivity and human nutrition in fragile environments, working closely with national program collaborators and students to advance applied research goals. Renee joined DuPont Pioneer in 2005, with responsibility for developing high-throughput field evaluation of novel transgenic corn lines with greater yield stability under drought and nutrient stress. She was named a Pioneer Research Fellow in 2011 and a DuPont Fellow in 2014. Renee is based at Pioneer's North American managed stress site in Woodland, California.

Lachlan Lake is a pulse physiologist in the Sustainable Systems Research Division, SARDI. Lachlan has been working in agricultural research since 2003 in projects focusing on Australia's major pulse species in projects investigating physiological drivers of yield, stress adaptation, N fixation, disease resistance and modelling. Lachlan completed his PhD in chickpea physiology at the University of Adelaide and is currently undertaking a GRDC funded Postdoctoral Fellowship investigating canopy dynamics and waterlogging tolerance in lentil. Lachlan's work has been driven by the importance of pulses in sustainable farming systems and the need to improve pulse adaptation to Australian conditions in the face of limited resources.

Peter Langridge is Emeritus Professor at the University of Adelaide, Australia. Peter established the Australian Centre for Plant Functional Genomics (ACPFG) and was appointed Chief Executive Officer in 2003. In 2014 Peter resigned as CEO of ACPFG to focus on his role on the boards of several research organisations in Europe, North America and in developing countries. Peter's interests have focused on the role of modern technologies in crop improvement with a particular focus on the importance of science, education and collaboration in helping to improve agricultural productivity.

Jill Lenne has 38 yrs experience in tropical agricultural research, management & development, including 15 yrs with CGIAR institutes (CIAT and ICRISAT) and 8 yrs with UK-based institutes. She also has 18 yrs experience as a consultant in project and programme review and evaluation through short-term assignments (1 week to 3 months) in more than 30 countries in Latin America, Asia and sub-Saharan Africa. She has worked semi-arid cropping systems; horticultural especially vegetable systems; tropical rice systems; tropical fodder and crop/livestock systems; and tropical agro-biodiversity management.

Bill Long is a farmer and for the past 23 years has managed his own company - Ag Consulting Co, a South Australian based agricultural consulting business established in 1995. The company provides agronomic and farm business management advice to farm businesses across SA and manages and conducts research and communication projects to growers on a range of agronomic and farm management issues. He has participated in and managed projects on carbon, climate, snails, controlled traffic, seeding systems, inter-row sowing systems, cereal and pulse canopy management, leaf disease control in cereals and pulses, weed management, plant growth regulants, pollination, soil carbon and stubble. He has been a member of the BCG Yield Prophet team to improve understanding of soil water and the use of crop modeling to assist advisors and farmers knowledge on soil water/plant production relationships. He was a founding member of the Yorke Peninsula Alkaline Soils Group, the SA and Vic Independent Consultant group and the Ag Excellence Alliance and is past Chairman and committee member of; SA GRDC Advisor Update Committee, TopCrop SA, Crop Science Society of SA and the Snail Management Action Group and the Grain Pest advisory group. He served on the GRDC's southern panel from 2011 until 2017. Bill has developed farm business benchmarking programs and was involved in the development of Plan to Profit®, a farm business analysis tool. Bill holds a bachelor of Applied Science in Agriculture, is a graduate of the Institute of Company Directors and undertook studies in the use of decision support tools and farmer and advisor decision-making processes. He has a keen interest in ag extension and adoption practices. In more recent times and as a result of the studies in decision-making, Bill spends more time with clients running farm boards and thinking strategically about their business management and development opportunities. With his wife Jeanette and son Will, he grows lentils, chickpeas, beans, cereals and canola, and runs sheep on his properties on Eyre Peninsula and the mid north in SA. He is passionate about the grains industry and enjoys the complexity and challenges of understanding and managing farming systems across Australia.

Stephen Loss has an Honours degree in Agricultural Science and PhD in Plant Nutrition from the University of WA. He worked as a crop agronomist with the WA Department of Agriculture for a decade, before joining CSBP fertilisers where he managed their field trial program and soil and plant testing services for the 12 years. In 2012 Stephen joined ICARDA based in Amman Jordan to lead an ACIAR funded project promoting conservation agriculture in northern Iraq. When the project ended in 2015, Stephen joined GRDC as an R&D Manager initially in Canberra, and then established their new office in Adelaide. He is currently the Manager of Soils and Nutrition for the southern region.

Allan Mayfield brings extensive agronomy and farming knowledge and 40 years of experience in government and as an independent agronomic consultant to his role with the South Australian Grain Industry Trust. Allan has a Bachelor of Agricultural Science and PhD in Plant Pathology. He was instrumental in setting up the Hart Field Site and starting precision agriculture and associated research in South Australia. His industry involvement is extensive and includes seven years as a GRDC Southern Panel member, six years as research coordinator for SPAA (Southern Precision Agriculture Australia) and 10 years as the research manager for the Hart Field Site Group. In addition to his role with SAGIT, he assists the Grains Research and Development Corporation in project management. He is a life member of the Crop Science Society of SA, a fellow of the Australian Institute of Agricultural Science & Technology, and a Churchill Fellow 2002.

M. Inés Mínguez is Full Professor of Crop Ecology and Agronomy of the Technical University of Madrid (UPM) since 1991. She has also worked at the University of Córdoba, Spain (13 years), at The Grassland Research Institute, UK (1 year), and at The University of Melbourne and Horsham Dept of Primary Industries, Australia (1year). Her research started in nitrogen fixation of grain legumes then extended to the role of legumes in crop rotations focussing on water stress and water use that resulted in the construction of faba bean crop model. During that time she also coordinated reports in the 1990s on projected irrigation requirements under climate change for the National Hydrological Plan of the Spanish Ministry of Infrastructures, and later focussed on the uncertainties linked to impact evaluations and adaptations and tools for defining new adapted cultivars to future conditions across Europe. More recently she has applied yield gap analysis to yield insurance design in cereals and participates in the International Network TempAg. At present she is exploring new cropping system approaches in a European-wide project and is much interested on food security and the need to consolidate studies at territorial scale. She has been principal researcher and researcher in 25 projects; has 85 published references and 10 book chapters. She has undertaken national and international consulting, worked for the European Commission at DG-Research and is currently on the Governing Board of FACCE-JPI, on “Agriculture, Food Security and Climate Change”. She was Director of CEIGRAM (Research Centre for the Management of Agricultural and Environmental Risks, UPM) and is currently its Deputy-Director.

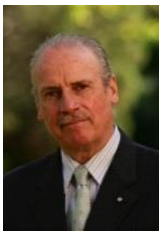
Francis Ogbonnaya is the Program Manager, Oilseeds and Pulses, Grains Research and Development Corporation (GRDC) and has served at various levels within the organization. At GRDC, Ogbonnaya has been involved in setting R & D initiative and strategies that have strongly influenced and promoted innovative R & D options aimed at delivering enduring profitable outcomes for Australian farmers. Ogbonnaya joined GRDC in 2012 from the International Center for Research in Dryland Agriculture (ICARDA), Syria where he led and coordinated multinational and international collaborative R&D initiatives with National Agricultural Research Institutes (NARIs) in Africa, Central Asia and Middle East and Advanced Research Institutions (ARIs) in Australia, Europe and North America and contributed to the formal release of several high-yielding varieties by national research partners in Africa and Central Asia. Together with university lecturers, he has co-supervised thesis research on wheat improvement and mentored many postgraduate students (MSc and PhD), mostly in Africa, Australia, Central Asia, Middle East and European countries for which he received The Jeanie Borlaug Laube Women in Triticum Mentor Award (2012). Prior to starting at ICARDA, Ogbonnaya served as Scientist and Senior Research Scientist and led key scientific research team within the Department of Primary Industry Victoria, Biosciences Research Division working on translational research with emphasis on exploiting primary gene pool of wheat to improve cereal cyst nematode control, pre-harvest sprouting tolerance, salinity tolerance, multiple disease resistance and water limited yield improvement in wheat. Ogbonnaya obtained his PhD degree in Agricultural Science (Plant Breeding and Genetics) from the University of Melbourne, Australia, and a B. Agric Science Honours degree from the University of Nigeria, Nsukka. Ogbonnaya has published over 150 papers in referred journals, book chapters and peer reviewed conference papers.

Kathy Ophel Keller is the Research Chief, Sustainable Systems Research Division, SARDI. Sustainable Systems Division covers SARDI research in cropping, viticulture and horticulture systems. It comprises science programs in Plant Health and Biosecurity, Entomology, Soil Biology and Diagnostics, New Variety Agronomy and Crop Improvement Science Areas, Climate Applications as well as Water Resources, Viticulture and Irrigated Crops. The Division assists the South Australian crop sectors by breeding and evaluation of new varieties, improving crop agronomy and providing practical and productive ways to maintain production by managing risk from SA's variable and changing climate, plant diseases and pests. Dr. Ophel Keller is a recognised expert at an international and national level in development and utilisation of DNA technology to monitor organisms in complex environments such as soil. Over the past 15 years, Dr. Ophel Keller has been involved in the development and delivery of unique technology to measure plant pathogens in soil, including the development of PredictaPT to assess the risks of potato soilborne pathogens prior to planting a crop.

Jairo Palta is an Honorary Research Fellow at CSIRO Agriculture & Food in Perth, Western Australia. He is also Adjunct Research Professor at The University of Western Australia Institute of Agriculture & School of Agriculture and Environment and Visiting Research Professor at the Institute of Water and Land Conservation, Chinese Academy of Sciences, in Yangling, Shaanxi China. He completed a Ph.D in Crop Physiology at La Trobe University, Melbourne, Australia and conducted Post-doctoral research at the Centre for Arid-Zone Studies at University of Bangor, North Wales, UK, and the the Lab of Nuclear Medicine and Radiation Biology of the University of California, Los Angeles (UCLA). He held positions with the International Center for Tropical Agriculture (CIAT) and CSIRO Plant Industry. At CSIRO he was the leader of the Subprogram “Improving Crop and Pasture Production and Quality”, acting leader of the program “Improvement of Rainfed Crops and Pastures”. He also served as Seconded Scientist for the Cooperative Research Centre for Legumes in Mediterranean Agriculture (CLIMA), was member of the Review Panel for the UNEP project “Structure and stability of plant communities in response to drought in East Africa” and the Environmental Physiology Panel for the Ecological Research Division of the US Department of Energy. He is currently involved in several international research initiatives (Expert Working Group [EWG] on Adaptation of Wheat to Abiotic Stress, Nutrient Use Efficiency and Heat and Drought Wheat Improvement Consortium [HeDWIC]. He is one of the Editor-in-Chief of Field Crops Research, Consulting Editor for Plant and Soil, Associate Editor for Crop and Pasture Science, Functional Plant Biology and Frontiers of Plant Sciences. He has published over 160 papers in referred journals and as book chapters and is the editor of two books.

John Passioura has a bachelor’s degree in agricultural science (1958) and a Ph.D. in soil chemistry (1963) from Melbourne University, Australia. He currently holds an emeritus appointment at CSIRO Agriculture in Canberra, and was formerly Chief Research Scientist and Leader of the Crop Adaptation Program there. His research has ranged over: soil chemistry and physics (transport of water and nutrients in soil); plant physiology (water relations, drivers of growth rate and adaptation to abiotic stresses); and wheat pre-breeding and agronomy directed at improving water-limited productivity of dryland crops. He was elected Fellow of the Australian Academy of Science in 1994. He spent 6 years on partial secondment to the Australian Grains Research and Development Organization (GRDC) where he oversaw a portfolio of projects on soil and water management that aimed at improving both the productivity and environmental performance of Australian grain farms. More recently he has written several reviews relating to crop productivity and the pursuit of effective agricultural research. He has also been a consultant to the CGIAR, having undertaking high-level reviews of several of their programs, existing or prospective.

John Porter is an internationally known agro-ecological scientist with an expertise in ecosystem services in agro-ecosystems, including agro-ecology, simulation modelling and food system ecology. His main contribution has been multi-disciplinary and collaborative experimental and modelling work in the response of arable crops, energy crops and complex agro-ecosystems to their environment with an emphasis on climate change, ecosystem services and food systems. Porter has published 145 papers in peer-reviewed journals out of a total of about 350 publications. On average, his peer-reviewed papers have been cited more than 100 times each. He has personally received three international prizes for his research and teaching and two others jointly with his research group. His career H index is 57 and with 131 papers receiving over 10 citations. From 2011 to 2014 he led the writing of the critically important chapter for the IPCC 5th Assessment in Working Group 2 on food production systems and food security, including fisheries and livestock. This chapter was one of the most cited from the IPCC 5th Assessment and formed an important scientific bedrock of the COP21 agreement in Paris in 2015.



Tim Reeves has worked for over 50 years in agricultural research, development and extension, focussed on sustainable agriculture in Australia and overseas. He was a pioneer of no-till/conservation agriculture research when based at the Rutherglen Research Institute in NE Victoria. His professional career includes: Foundation Professor of Sustainable Agricultural Production, Adelaide University (1992-95) and Director General of the International Maize and Wheat Improvement Center (CIMMYT) based in Mexico (1995-2002). His other international roles have included: Member, United Nations Millennium Project Task Force on Hunger; and Member, European Commission Expert Group for Evaluation of Framework and H2020 Projects. He has also been a Senior Expert with the Food and Agriculture Organization of the United Nations (FAO) working on Save and Grow - sustainable intensification of smallholder agriculture - and in 2016 lead a FAO consultation in Cuba, on the development and adoption of Conservation Agriculture. He has recently returned from India (February 2018), where he chaired a review of the project 'Sustainable and Resilient Farming Systems Intensification in the Eastern Gangetic Plains' for ACIAR. He has chaired or participated in many other scientific reviews, including for: FAO; the Bill and Melinda Gates Foundation; Government of India; MLA and Dairy Australia. Professor Reeves has been a Board Director of GRDC; the Future Farm Industries Cooperative Research Centre (CRC); the Molecular Plant Breeding CRC; and of FAR New Zealand. He is currently Board Chair of FAR (Foundation for Arable Research) Australia and a Board Director of the Crawford Fund. Tim is now Professor in Residence at the Dookie Campus of the University of Melbourne, where he has also been recognised as a Centenary of Agriculture Medallist. In December 2016 the University awarded him a Doctor of Agricultural Science honoris causa. Tim is also a former President of the Australian Society of Agronomy and in 2017 the Society awarded him the prestigious Professor C M Donald Medal for lifetime achievement. He is currently a Fellow of the Academy of Technological Sciences and Engineering, where he is also Chair of the Academy's Agriculture Forum. He is an Honorary Professor in the Chinese Academy of Agricultural Sciences. In 2003 he received the Centenary of Federation Medal. He is also Director and Principal of Timothy G. Reeves and Associates. Pty. Ltd., specializing in national and international consulting in agricultural research. His main areas of current focus are on global food security and the sustainable intensification of agriculture and farming systems.

Daniel Rodriguez is a crop scientist with the Centre for Crops Sciences at the University of Queensland. He leads the Farming Systems Research Team and his work focuses on the development and application of quantitative systems modelling approaches in agriculture. He is a leader in the application of these approaches at the crop and whole farm levels. At the crop levels his work focuses on identifying more profitable and less risky combinations of genetic (G) traits and managements (M) across the multiple environments (E) found in the sub-tropical and tropical summer cropping systems of Australia and Eastern and Southern Africa. At the whole farm level, he is interested in quantifying benefits and trade-offs from alternative farm business designs also in Australia and across Eastern and Southern Africa. He was Chief Editor of Agricultural Systems until 2018.

Megan Ryan completed her PhD in Ecology at the Australian National University. In her thesis she compared the growth and nutrition of crops and pastures on organic and conventional farms, with an emphasis on phosphorus and mycorrhizal fungi. Megan then worked at CSIRO Plant Industry in Canberra where she examined the impact of canola on the growth and nutrition (P, Zn, N) of following cereal crops. Since 2003, Megan has been at the University of Western Australia where her main research area has been pasture ecology and nutrition. During this time Megan has researched a wide range of topics including the potential for domestication of Australian native perennial legumes as pasture species, development of phosphorus-efficient pasture systems, and root morphological and physiological adaptations that aid phosphorus uptake in pasture legumes, chickpeas and native plants; she has also continued to work on mycorrhizal fungi. Since 2015 Megan has been an ARC Future Fellow; her project is focused on how plants adapt to fluctuating availability of phosphorus. Other recent grants focus on identification and renovation of highly oestrogenic pastures and improving seed harvest of subterranean clover. Megan is also involved in the newly established ALBA (Annual Legume Breeding Australia) joint venture between the University of Western Australia and the company PGG Wrightsons.

Victor Sadras has measured, modelled and developed theory on the water, nitrogen and carbon economies of annual (wheat, maize, oat, cotton, sunflower, soybean, pulses) and perennial crops (grapevine, olive) in rainfed and irrigated systems of Australia, Argentina, China and Spain. His current international network of scientific partnerships includes Universities (Nebraska, Kansas, Minnesota, Lleida, Helsinki, Buenos Aires, Austral Chile, North West A&F China, Cordoba Spain) and research organisations (CSIC Spain, FAO, INRA France, INTA Argentina, INIA Uruguay, ICRISAT India). His most important contributions to science are a conceptual model of crop yield accounting for ecological and evolutionary factors including genomic conflict, transitions in the units of selection and phenotypic plasticity, and advanced theory of resource co-limitation. He was recognised in *The Australian's Research Magazine 2018* as the national leader in Agronomy and Crop Science. He received an award from the Australian Society of Viticulture and Oenology for his experimental demonstration of thermal decoupling of sugar and anthocyanin in Syrah berries and wine. He was expert consultant with FAO on crop responses to water and yield gap analysis (2005-2015), and delivered the 2017 Elmer Heyne Distinguished Crop Science Lecture at Kansas State University. Sadras published 205 papers in peer-reviewed journals, returning 10,900 citations, and h-index = 61 (Google Scholar, July 2018). He is the co-editor-in-chief of *Field Crops Research*, and member of editorial boards of *Irrigation Science* (since 2013), *Crop and Pasture Science* (since 2009) and *European Journal of Agronomy* (2009-15). He is the senior editor of "Crop Physiology" (Academic Press), a book used in university courses worldwide, and lead author of "Yield gap analysis of rainfed and irrigated crops" FAO Water Report 41.

Primal Silva is a veterinarian and a Ph.D. scientist with several years of postdoctoral training. He obtained his Ph.D. from the University of Sydney, Australia, and conducted his postdoctoral studies at McMaster University and at the Ontario Veterinary College, University of Guelph. He worked as an Assistant Professor at the University of Guelph before joining the federal public service in 1993 where he has held several positions with increasing responsibilities. Dr. Silva is substantively the Chief Science Operating Officer (CSOO) with management accountability for all 13 laboratories of the Canadian Food Inspection Agency. Prior to this he served as Executive Director of the CFIA's Animal Health Science Directorate. As the CSOO, he is responsible for providing strategic leadership and ensuring sound management of CFIA’s 13 laboratories in order to deliver the Agency’s high priority needs in mandated science functions in Food Safety, Animal Health and Plant Health, including the daily operational continuity and stability of the Branch’s laboratory programs and services. He provides strategic leadership and manages the Agency’s research program, the CFIA’s science engagements with national and international organizations and is a contributing member to numerous committees and working groups at domestic and international levels. Dr. Silva is a contributing member to numerous committees and working groups at domestic and international levels, including the Scientific Advisory Body of the Organization for Economic Cooperation and Development (OECD).