Farming Systems Agronomy: it is rocket science

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Summary

Those not immediately involved in managing a dryland farm sustainably in a risky water-limited environment such as Australia may think a comparison with rocket science a bit of a stretch. But if the level of challenge, the importance to humanity, the long-term multidisciplinary team approach and planning required, and the level of uncertainty inherent in the pursuit are measures, then I think the comparison is warranted.

The importance of the farming systems research that has supported agriculture and food security in Australia and globally since Farrer's time perhaps receives less public attention than some other science areas such as genetics, genomics or digital agriculture – indeed agriculture is now literally "rocket science" as satellite-guided machines and sensors gather volumes of data about the soils, plants and weather on farms at scales and speeds hitherto impossible. Yet despite spectacular advances in individual genetic or management technologies, few have been singularly transformational. Rather significant productivity improvements generally arise when a combination of technologies, often old and new are integrated in specific ways within a system.

William Farrer himself was clearly aware of this fact, as we shall see later, and he placed as much importance on maintaining the fertility of the soil in which he grew wheat as on improving the wheat plant itself. In my Oration, I would like to first provide some background to Farrer, to his influence on my own family's fortunes, and on his interests in genotype x environment x management (G x E x M) interactions (though he certainly didn't use that terminology). I will then describe some examples from my own research teams, to demonstrate the ongoing impact that arises from research to capture synergies from new genetics and improved management.

William Farrer

I have enjoyed the opportunity through this award to become more familiar with the achievements of William Farrer, and I direct those seeking interesting yet accessible understanding of his work to the publication of his collaborator FB Guthrie (1922), and the interesting summaries contained within previous Orations such as that by LT Evans (1980) and many others found on the Farrer website at https://www.dpi.nsw.gov.au/about-us/who-we-are/interacting/farrer-memorial-trust/farrer-memorial-trust-medal-recipients-and-orations. More complete and comprehensive biographies are of course also available (e.g. Russell 1949).

Farrer was born in England and sailed to Australia in 1870 with the intention to buy a sheep property, but through various circumstances found himself instead working as a surveyor in central and southern NSW from 1875 to 1886. It was clear in his notes and writings that he had developed an interest in wheat from as early as 1882, and by 1886 he was in a financial and personal position to settle on the farm at Lambrigg near present-day Canberra with his wife Nina, and to intensify his passion and his hobby in wheat breeding and selection "to improve the constitutional fitness for the locality". At Lambrigg on his 3 acres of experimental plots (one half of which he rotated in alternate years), he embarked upon what was to be 20 years of work (until his death in 1906) that was to transform wheat production in Australia.

During that period Farrer was in constant contact with wheat breeders, growers and experiment stations in Australia and overseas and in 1898 accepted a position as wheat experimentalist with the NSW Department of Agriculture and Mines that allowed him to expand his testing environments. By making crosses and selections from Indian, Canadian and improved Fife wheats he was able to combine earlier maturity, improved disease resistance (and escape) along with better milling quality. Most of his improved varieties including *Federation* were made available to farmers during 1901-1903, and he was certainly able to see of some the success of his efforts prior to his death in 1906. Wheat production quadrupled in NSW in the 15 years from 1900 to 1915, and by that time 22 of the 29 varieties grown in that State were Farrer's (Wrigley 1981). His variety *Federation* which helped to open up much of the drier western area to wheat production was the leading wheat in Australia from 1910 to 1925. These impressive national statistics can sometimes mask the impact Farrer had on the lives of individual farming families, such as my own Danish immigrant family on the Darling Downs in Queensland.

A personal debt of gratitude

Not long after Farrer set sail for Australia, my own great-great-grandfather, J.A.C. Kirkegaard left western Jutland in Denmark with his family in 1872 and purchased a portion of Glengallan Station on Freestone Creek near Warwick, where he farmed on "Marydale" until his retirement in 1892. His own fortunes were therefore not touched to any extent by Farrer's work, but those of his youngest son, B.C.C. Kirkegaard who took over the farm in 1892 and farmed until his retirement in 1936 were significantly so. As well as a wheat farmer (over 100 acres of his 234 acre holding was sown to wheat), B.C.C. Kirkegaard was a lifelong member of the Warwick Farmers Milling Association (from 1891 to 1941) and a founding member of the Queensland Wheat Board (member for 14 years from 1920). The impact of Farrer's earlier maturing, disease resistant and higher milling quality wheats must have certainly had an enormous impact on his farming fortunes, and as a consequence, on my own family. The variety *Florence* bred specifically for smut resistance, but which was also early maturing and suited to the Queensland environment was considered to underpin Queensland's success in wheat production in the 1920's (Guthrie 1922) and was still the 2nd leading wheat in 1938 (Wrigley 1981). The quality of *Florence* was so superior that a separate category has to be established for it for wheat quality prizes at the Sydney show. In trial results from Tamworth published in the Sydney Morning Herald in December 1930 (accessed on Trove, National Library of Australia), *Florence* yielded twice that of *Federation* (2.4 vs 1.1 t/ha) demonstrating its superiority in more northern environments at that time.

It is clear that this Farrer wheat variety, and no doubt others such as *Flora* that followed, underpinned the industry in the early decades of the century in Queensland. As a farmer, a miller and a member of the Queensland Wheat Board, Farrer's personal impact on my great-grandfather's career and his business success must have been immense. Impressive as Farrer's national (and international) achievements are, they can mask these impacts he had at this more individual (and personal) level, on the lives of so many individual immigrant and resident farmers as they opened up new lands to wheat farming in the more marginal areas of Australia. Though widely lauded for these breeding efforts, Farrer's interests and insights also extended beyond breeding and selection.

Farrer and agronomy – an early "G x E x M" advocate

In 1873 Farrer published a pamphlet entitled *Grass and Sheep Farming*, and though his continuing interests became focussed on wheat growing and the unsuitability of the existing wheat types sown, he was also aware of the importance of maintaining the fertility of the soil in which wheat was grown. In his letter of acceptance for the position of wheat experimentalist in 1898, in which he set out his manifesto of work, he wrote:

> *"In addition to **improvements in the wheat plant** itself*
> *it is <u>of even greater importance</u> that I should conduct*
> *experiments to ascertain the **methods of soil management***
> *which are the **most suitable for our climate**, and the conditions*
> *under which our **wheat growers** are working"*
> William Farrer 1898

The bold and underlined text are mine, however though Farrer would not have used the term "G x E x M", he demonstrates a clear understanding that to improve wheat productivity in farmer's fields one must be simultaneously aware of the management systems (M) in which the new varieties (G) are expected to perform, as well as the environment (E) and other limitations that may face farmers themselves in combining those technologies.

Farrer had interests in pasture agronomy, green manuring, the development of alternatives to fallowing and in humus and nitrogen fixation by legumes. He was instrumental in setting up long-term soil fertility experiments at Wagga Wagga as a compliment to those in Rothamsted and was disappointed when they were discontinued (Evans 1980). Farrer's interests extended even further beyond the farm gate and included the interests of the whole "value-chain" (another term he would not have used) including market, miller, baker, exporter and consumer. In my Oration I will remain focussed on the farming systems aspects of his work, and will emphasise the ongoing importance of the G x E x M thinking that Farrer captured so elegantly above in his thinking more than a century ago.

How revolutions really happen in agriculture

The global food security challenge has prompted many to propose the need for "transformational change" in food production systems through technological "breakthroughs". These transformative technologies are often distinguished from the "incremental" advances generated by agronomy and breeding which are dismissed as business as usual, and inadequate to achieve the productivity improvements sought. The urgency for transformative change has been heightened by the reported (though contested) of a slowing in the productivity trends of major food crops, as well as declining or expensive resources of land, water and nutrients and predicted climate change (Fischer *et al*, 2014). 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 change 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. Rather, step changes in productivity have come only when combinations of technologies, often a mix of old and new, synergise within a system. Lloyd Evans (1998) in his wonderful book "*Feeding the Ten Billion*" points out that the first agricultural revolution arose from a combination of pre-existing, individual technologies most of which were centuries old, but it was the combination that made them so effective:

"*individual components of the revolution had a long history but the* ***synergistic interactions*** *in the Norfolk system made it such an effective agent of improvement*"

The **Norfolk** system (Young 1771)
(1) enclosures without Government assistance
(2) use of marl (lime) and clay *(known to Romans)*
(3) rotation of crops *(Ancient Greeks)*(4) turnips, hand hoed (in rows) *(Chinese in 6th century)*
(5) culture of clover and rye *(Ancient Greeks)*
(6) long leases, large farms

A more recent example of major productivity gains arising from such synergies is the high input hybrid maize systems in the USA (Duvick *et al*, 2005) in which maize hybrids adapted to high density protected by genetic tolerance to soil and insect pests and with cold soil tolerance can be sown earlier and at high density to capture the physiological benefits related to improved biomass production and conversion to grain. Improved precision seeding technologies and protection with new fungicides and herbicides have assisted to progressively transform productivity (Figure 1) – in a process I describe as "incremental transformation".

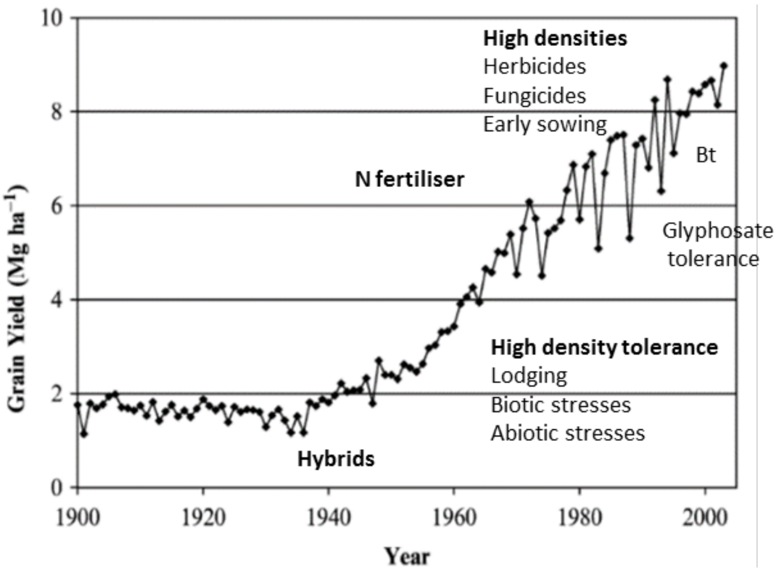

Figure 1. The combination of genetic and management factors underlying the increase in US maize yield (from Duvick 2005). Duvick commented that "the two tools interact so closely that neither of them could have produced such progress alone".

In Australia, similar examples of these synergies can be found throughout the history of wheat production - from the time that Farrer first transformed productivity with better adapted varieties aided by the advent of super-phosphate, to the step changes offered by semi-dwarf wheat varieties with appropriate nitrogen supply and disease management (Donald 1965, Fischer 2007, Kirkegaard *et al*, 2014). My own career with CSIRO commenced in 1990 within a multi-disciplinary team within the Land and Water Care Project, focussed on improving the sustainability of dryland cropping in southern Australia through promotion of the "3R's" better Rotation, Reduced tillage and Retained stubble. I will describe some of the recent examples of the incremental transformation that my own colleagues and collaborators have been involved with that to me exemplify the success and impact that can be achieved by multi-disciplinary teams who adopt a G x E x M framework in pursuit of increased productivity.

A more recent revolution

The recent evolution of southern Australian dryland farming systems was comprehensively reviewed by Kirkegaard *et al*, (2011) but the changes in southern NSW systems during the 1980s and 1990s are worth briefly describing as a background to more recent innovations. Until the 1980s, the area grew mainly cereals (mostly wheat) in rotation with annual grass–subterranean clover pastures and fallow, with some areas of early-sown oats for sheep. Grain legumes (lupin and pea) remained a relatively low proportion of the cropping systems throughout the 1980s and 1990's while canola (*Brassica napus*) became a significant component of the cropping system during the 1990s (Kirkegaard *et al*, 2016) after better adapted varieties with high yield, good quality (i.e. "double low", glucosinolate and erucic acid) and that were resistant to the main disease Blackleg (*Leptosphaera maculans*) were developed and released.

Canola was an acid sensitive crop and so was usually only grown on the acid soils in the area following an application of lime. Canola reduced the cereal root diseases that had been rife in the grassy pasture-wheat-barley systems, and as a consequence responses to tactical N fertiliser application were observed for the first time in the newly responsive, disease-free wheat crops (Angus 2001). This combination of limed canola, and N-fertilised wheat saw significant improvements in average crop yield throughout the 1990s (Angus 2001), and lifted the yield of the semi-dwarf wheats closer to their unfulfilled potential (Cornish and Murray 1989). Liming also improved the establishment and persistence of lucerne which contributed greatly to the annual clover-based pasture production in the area on what were largely until then mixed farming systems. The system of lucerne-based pastures phased with sequences of mostly wheat and canola crops fertilised with tactical N application and lime was a highly productive system throughout the 1990s with echoes of the same individual components that combined in the first agricultural revolution described above. Since then the Millenium drought (2002 to 2010) and the prospects of hotter and drier springs, and a more extreme and variable climate has led to ongoing evolution of the farming system. There has been a strong focus on genetic and management strategies that capture, store and use rainfall more efficiently, while protecting the resource base and maintaining business profit.

Canola – an exceptional crop for Australia

Canola production in Australia has increased 10-fold since 1993 from 0.3 to 4.0 Mt and it is now Australia's 3rd most important food crop after wheat and barley. It's development and expansion relied on talented breeders and agronomists targeting similar issues as Farrer did in wheat – adaptation to the environment with improved phenology, resistance to the devastating disease Blackleg (*Leptosphaeria maculans*) and improved oil quality (Kirkegaard *et al*, 2016), requiring a combination of European, Canadian and Japanese ancestry. In fact the original ARAB (Australian Research Agronomists and Breeders) group that met in 1977 was rooted firmly in the philosophy of shared knowledge and genotype and management interactions to underpin productivity increases (Buzza 2007).

The important rotational benefits in southern NSW described above and attributed mostly to cereal root disease control continue (Angus *et al*, 2015), although in contemporary systems it is herbicide-resistant weed control that has become a greater focus of canola's benefits in the farming system. Though rotational benefits drove initial adoption it has been important to continually increase the productivity and profitability of the canola crop itself. A first step, as in wheat, was to benchmark performance against a defensible estimate of yield potential. Robertson and Kirkegaard (2005) used an expected seasonal water-use efficiency approach to establish and upper boundary of 15 kg/ha.mm above an estimated evaporative loss of 100mm in southern NSW to investigate canola performance. Simulation approaches have also been used to account more fully for crop, soil, climate and management impacts on yield potential. The latter approach suggested current yields in farmer's fields may only be 42 to 68% of potential, an observation supported by the yields achieved in well-managed National Variety Testing experiments (Kirkegaard *et al*, 2016). Two recent GxExM approaches to increase productivity and profitability of canola are worthy of mention here.

Earlier-sown canola – a GxExM challenge

Canola has traditionally been sown from ANZAC Day (25 April) in much of southern Australia, and the importance of timely sowing is well known. However, larger farms, changes in autumn rainfall and improved seeding technologies have seen a trend towards even earlier sowing in early to mid-April (Kirkegaard *et al*, 2016). However current fast-spring canola varieties without vernalisation and adapted to late-April and May sowing flower too early from earlier sowing dates which limits biomass production and yield potential and exposes the crop to increased frost risk. Since 2014 we have been evaluating the potential to move to earlier sowing systems in canola by developing suitable GxExM combinations to capture the yield, oil and profit benefits made possible by the physiological benefits of early-sown crops. As a first step we identified the optimum flowering period for canola to maximise yield across variable seasons, and then identified sowing date and variety combinations that reliably flower in the optimum window. Figure 2 shows how some varieties (e.g. Archer) with a vernalisation requirement retain a more stable flowering period from a range of sowing dates compared to existing spring varieties (e.g. Stingray) and stabilise yield accordingly.

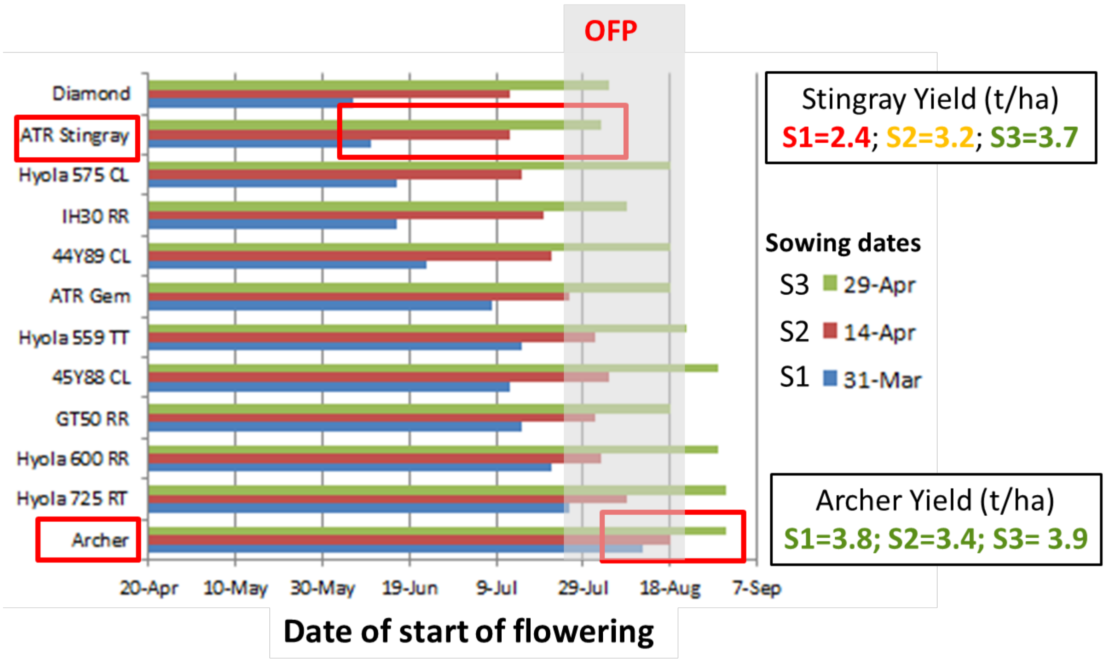

Figure 2. At Wagga Wagga in 2016, the slow spring variety Archer flowered in, or close to the optimum flowering period (OFP) from a wide sowing window with high and stable yield across the sowing dates. In contrast, fast spring varieties such as Stingray only flowered in the OFP from later sowing dates and were not suitable for earlier April sowing (Courtesy Rohan Brill, NSWDPI).

Understanding the biomass required to achieve the estimated yield potential, and the cheapest way to achieve the required trajectory of biomass through the season by manipulating sowing time, variety type (e.g. hybrid), seeding rate and nitrogen management is the next step. Finally, understanding varietal traits and management strategies to achieve a more efficient conversion of biomass to grain crop may offer further avenues for improvement. In southern NSW, the shift towards aiming to finish sowing canola by ANZAC

Day (rather than starting) has seen significant yield increases at the farm level. The agronomy required to capture the benefits of these systems include strict summer weed control, good residue management to facilitate ease of sowing and weed control, careful seed and fertiliser placement at sowing in rapidly drying soils and good early management on insects, weeds and diseases. New narrow-spectrum fungicide, herbicide and insecticide products are improving the success with early sowing.

Early-sown canola *can be grazed*

An additional advantage of early-sown crops on mixed farms is that the rapid early vegetative biomass production can provide grazing opportunities (Dove and Kirkegaard 2014). Dual-purpose canola provides an excellent break-crop for wheat in high rainfall zones where diseases and weeds can limit high value grazed cereals, and in the low rainfall zone can reduce the riskiness of canola by provided some upfront income to offset the cost of establishment. The development of dual-purpose canola was a truly interdisciplinary exercise that again required attention to selection of varieties with the right phenology and crop vigour, understanding interactions between grazing and disease (especially Blackleg) (Sprague *et al*, 2013), and the potential impacts of grazing on oil quality. In addition, animal grazing management to optimise both crop and animal production was essential (Bell et al., 2015). Newly developed herbicide and disease resistant, winter hybrid types have been released as dual-purpose grazing options in the medium and high rainfall zones of southern Australia and can achieve in excess of 2000 dse-grazing days and recover to yield up to 4 t/ha of high oil canola seed (Lilley *et al*, 2015). The rotational benefits flow to succeeding wheat crops in a crop sequence, and assist to control intractable grass weeds such as serrated tussock to allow successful establishment of perennial pastures. Careful grazing management linked to both crop phenological stage, and residual biomass allows grazing without a loss in seed yield potential adding clear profit to the bottom line of mixed farming systems. The integration of dual-purpose wheat and canola into these traditional grazing systems has lifted farm profits by at least $100 <u>per farm hectare</u> and achieved increased animal and crop production from the same farm simultaneously.

It is perhaps not surprising that the issues William Farrer focussed on in wheat over 100 years ago – phenological adaptation, disease management and crop quality – have also dominated the research agenda in a relatively new crop such as canola, and require ongoing refinement in a G x E x M framework to capture the full benefits from innovative systems such as early-sown, grazed crops. It is perhaps more surprising that in wheat itself, significant productivity gains should still be emerging from manipulation of these same factors.

Improving farm-level water-use efficiency

In 2009, the Australian grains industry through the Grains Research and Development Corporation (GRDC) challenged growers and researchers to demonstrate how they could improve the water use efficiency (productivity per mm of rainfall) of their systems. A network of 17 existing regional grower groups were funded by the GRDC and co-ordinated by a CSIRO farming systems research team to provide an integrated and consistent approach to the work. Not surprisingly, the grower groups nominated numerous different ways in which they believed progress could be made. These were essentially collapsed into 4 linked themes of research for the 5-year program: (1) long-term soil management (2) improved crop sequence, (3) better summer fallow management, and (4) in-crop water-use patterns. Kirkegaard and Hunt (2010) demonstrated how these activities are all linked in terms of the water-use efficiency framework established earlier by Passioura (1977). They used simulation modelling of different management scenarios for wheat systems at Kerang in the Victorian Mallee to demonstrate that the largest benefits came when all of these approaches were simultaneously optimised, and that improving any one factor in isolation generated relatively small shifts in productivity from the 1.6 t/ha baseline (Table 1).

Table 1. Effect of individual management changes either singly, or when combined, on the mean yield of wheat at Kerang in the Victorian Mallee region when compared to the baseline yield of 1.6 t/ha (from Kirkegaard and Hunt 2010). The baseline scenario consisted of:

Burn/cultivate, grazed weedy fallow, continuous wheat, spring wheat sown after 25 May

System change	Mean Yield (t/ha)	
	Single effect	Additive effect
1. No-till	1.84	1.84
2. Fallow weed control	2.37	2.80
3. Pea break crop	1.76	3.45
4. Sow earlier (from 25 April)	2.10	4.01
5. Long coleoptile wheat – sow on 25 April	1.45	4.54

Interestingly the novel genetic trait, long coleoptiles that allow wheat to emerge from deeper sowing, and thus to be sown reliably on stored water in April, actually reduced yield if adopted without the rest of the agronomic package that provided the increased water capture and storage to capitalise on the higher yield. The subsequent 5-year, on-farm experimental program confirmed most of these predictions (Kirkegaard et al, 2014) with the combination of good rotation (to manage disease and weeds), weed and stubble management in the summer fallow (to preserve water and N), earlier sowing of appropriate varieties (to capitalise on the stored water and N to increase yield potential), and modified in-crop agronomy (to manage the balance of pre- and post-flowering water use) provided significant gains in productivity. Further analysis identified how earlier sowing in some paddocks generated flow-on effect across the farm allowing the sowing program in all paddocks to move into an earlier window with a multiplying effect across the farm. Until recently suitably adapted varieties with a phenology appropriate to earlier sowing have only been available as grazing options in some areas with no options in large parts of southern Australia. Hunt (2017) and Flohr et al., (2017) have recently demonstrated the potential of better adapted “fast winter” wheats across a broad range of sites in southern Australia with yields exceeding current spring or existing winter wheats by 8 to 18%. This research, greatly assisted by the knowledge of the underlying genetic control of crop phenology in wheat, and the availability of phenology isolines (Trevaskis 2010) has recently culminated the first commercial fast winter wheat variety widely adapted to southern Australian soils

(Longsword) released to growers in 2017. Farrer himself would possibly be amazed that such productive research on adapting wheat to the Australian environment continues to this day, although perhaps less so had he envisaged how climate and management technologies would shift across the same period.

Farrer's fight continues

Much of the yield benefits from early-sown canola and wheat crops can be traced to the improved access to deep water late in the season, afforded by the deeper root systems made possible by a longer vegetative phase (Kirkegaard et al., 2015). This raises the issue of legacy effects – in dryland environments how often can we expect that water to be there once it is used? (Kirkegaard and Ryan 2012). Lilley and Kirkegaard (2016) investigated that question at several sites across Australia and found that in lower rainfall areas, or on shallow soils, the yield benefits from deeper roots over a series of years are less, due to those legacy effects – in essence subsoil profiles often do not re-fill from season to season. However in medium and higher rainfall areas on deeper soil, such as those in southern NSW there appears to be considerable scope to use early sowing to capture water that is otherwise evaporated in summer and early autumn, or drains during the wet winter. A simulation study using data validated over 28 years at the CSIRO Harden long-term experiment demonstrates this potential (Table 2). We first validated the model against the actual data for the 28-year crop sequence where crops were generally sown in May, and then re-ran the model with scenarios in which the wheat (15 crops) and canola (5 crops) crops were sown earlier (according to actual sowing opportunity each year). We used appropriate varieties for the earlier sowing to maintain optimal flowering dates and investigated whether we achieved overall yield increases, or if the higher yielding crops simply "stole" water or N from subsequent crops and diminished the yield advantage. The simulation predicted an overall increase in wheat and canola yield is possible, but that the full extent of yield potential is not realised without a simultaneous increase in the nitrogen applied (in this case an extra 50 kg/ha to every crop). It seems fitting that here, as was predicted by Farrer in the cropping systems of his day, that the nitrogen nutrition of the crops should be such a key driver in realising the higher yield potential of the adapted wheat and canola varieties that are now available.

Table 2. The predicted impacts of sequential changes to management on the long-term mean yield of wheat and canola at the CSIRO Harden long-term tillage site.

Crop	**Baseline**	**Weed control**	**Weed control Early wheat**	**Weed control Early wheat Early canola**	**Weed control Early wheat Early canola + 50 kg N/ha/yr**
Wheat	4.5	4.7	5.6	5.5	6.0
Canola	2.9	3.1	2.9	3.3	5.0

Conclusion

The exercise described in the previous section, as yet to be confirmed with data from experiments that are now underway, again highlights the need to be manipulating several management and genetic components simultaneously in order to reach the water-limited potential of the system. Were we to also consider the grazing potential of these new early-sown wheat and canola crops, and the increases in winter stocking rate for sheep made possible by the winter forage on-offer (at no cost to grain yield), the whole-farm profitability implications become even more profound. This recent shift in thinking from the focus on the productivity and water-use efficiency of individual wheat crops, to that of the whole farming system (Hochman et al., 2014), to me marks a paradigm shift into which individual disciplinary expertise must be coaxed. Farming systems agronomy provides such an integrative framework and its science should sit alongside the wonderful fundamental biology and engineering that underpins modern genetics and digital agriculture. Rocket science needs its “mission control” and agricultural science needs the context and integration provided by agronomists, farmers and their consultants in the journey from inspiration to impact.

Acknowledgements

I would like to thank the Farrer Memorial Trust for the great honour of this award, for providing me the chance to reflect on the achievements of William Farrer, and in doing so to find such an interesting professional and personal connection to his work. The Theme of my Oration has been teams and interactions - and so collectively I would like to thank my colleagues and collaborators, mentors and managers, family and friends who have all contributed to the work discussed and sustained my energy and enthusiasm for our collective effort. I especially thank John Passioura, Tony Fischer, Mark Conyers and Mike Robertson for their stimulating contributions to the Program and wise council. Finally and most importantly, to my partner Julianne and my children Isabelle, Angela and Minette - I thank you all for your patience, tolerance and support of my passion for agriculture.

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