Donald Oration 2019

John Angus
CSIRO Agriculture and Food, Canberra and Charles Sturt University, Wagga Wagga
Email: jangus@csu.edu.au

Many thanks to Agronomy Australia for the honour of the award of the Donald Medal for 2019. I met Professor Colin Donald several times, first when he was developing his concept of the wheat ideotype and later in discussions about my PhD research. It is an honour to be associated with Professor Donald and with the 17 previous recipients of the Donald Medal. It's also been a privilege to work in the Land and Plant Industry Divisions of CSIRO, to collaborate in field research in all mainland states and territories and share authorship in scientific papers with 169 colleagues. The most enjoyable parts of my career were conducting on-farm experiments and learning from cooperating farmers. To them my great thanks.

Career

I was lucky enough to be an undergraduate in the Agriculture faculty at the University of Melbourne in the mid-1960s. The course offered a thorough education in the biological and physical sciences that underpin agriculture, as well as providing enough training in farm production to stay abreast of changing practices.

The outstanding academic in the faculty was Geoffrey Leeper who, as well as teaching agricultural chemistry, peppered his lectures with insights into science generally. One insight that stays with me was his reference to Karl Popper's philosophy which, in brief, claimed that science could *falsify* a conjecture but not *prove* that it was correct (Popper 1963). Followers of Popper design experiments that are capable of disproving an hypothesis. As long as an hypothesis is not falsified, it remains a possible explanation of a result. Falsification in agronomy is messy because of the variability of field experiments and the uncertainties of extrapolating their results in time and space. Despite these difficulties it is worth persevering with experimental tests of an hypothesis until it is falsified, but then either refining the hypothesis or searching for another. Some examples of this approach are later.

Another insight that Geoffrey Leeper passed on to students was about soil organic matter (SOM), based on research by Hans Jenny about regional differences in SOM throughout the continental United States (Jenny 1941, available online for free). The level of SOM depended primarily on mean temperature (high temperature gives low SOM), water supply (high rainfall gives high SOM) soil texture (clay soils give higher SOM than sands) and vegetation (forests give higher SOM than grasslands). Management of crops and pastures over a period of a few years or decades to influence SOM has a small effect against the background of the natural processes. It takes many decades of crop or pasture to have an effect comparable with the environmental effects. Jenny's insights about SOM stimulated my interest in the supply of N from the soil, which is still the major N source for Australian agriculture. Anyone interested in soil carbon sequestration would do well to read Jenny's book.

Jack Wilson, my PhD supervisor, encouraged me to investigate how foliage structure affected photosynthesis in cereal canopies (Angus et al. 1972) but by the end of PhD studies I had decided to move from crop physiology to agronomy and to work on topics that had more immediate impact on farm management and food production. Research training in crop physiology was not wasted because it helped develop my understanding of processes and in thinking about rates. I joined the Land Division of CSIRO in the early 1970s working with Henry Nix and Bob Myers, having worked as a technician at that division's Katherine Research Station in the Northern Territory before starting my PhD. I transferred to the Plant Industry Division when the Land Division refocused on water research in 1987. I remained there until retirement and later as an Honorary Research Fellow. I also had the opportunity to work at two overseas Institutes. The first was the International Rice Research Institute in the Philippines where I modelled rainfed rice systems and started to learn about rice agronomy. This knowledge was relevant to a later ACIAR project on the potential for growing multiple rice

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crops in the Philippines and to research on N in Riverina rice, of which more later. My other overseas research was at the Swedish University of Agricultural Sciences working with Bengt Torssell to develop a crop simulation model calibrated with the use of an optimiser, also discussed later.

Research on crop and soil N

The attraction of agronomy was partly inspired by the research of the late Michael Dalling with whom I shared a laboratory and an experimental paddock at Mount Derrimut, the University's farm in the late 1960s. Michael showed that wheat gave quite poor yield responses to applied N, even in average and wet seasons (Dalling 1971). This contradicted the expectations at the time when scientists and the fertiliser industry expected Australian dryland crops to provide a big market for N fertiliser following the boom in adoption in other developed countries during the 1950s and 60s. One of the fertiliser companies hurriedly imported an ammonia-urea plant in the late 1960s to cash in on the expected bonanza. While some of the locally produced urea was used by horticulture and sugar cane, relatively little was sold for domestic dryland crops and most was exported on the world market where it struggled to compete with foreign producers who had access to subsidised natural gas.

Research funded by government and industry laboured from the early 1970s to the late 1980s, vainly attempting to show profitable N responses by dryland wheat in south-eastern Australia. The government-funded program, called the National Soil Fertility Program, found the same miserable N responses that Dalling had found earlier (Colwell and Morton 1984). Grateful non-participants renamed it the National Soil Futility Program. Fertiliser companies persisted with testing rates and chemical forms of N fertiliser into the 1980s, applying almost all fertiliser N at sowing, as had been the practice with phosphatic fertilisers for generations.

By the early 1970s it seemed likely that the miserable yield responses of dryland wheat to N were limited by one or more constraints and by the early 1980s I had the chance to investigate what constraints, if any, were responsible. There had been reasonable crop responses to N in Western Australia (Mason 1975) where the level of soil mineral N was generally low, and in southern Queensland where there had been no legume-pasture rotations to replenish soil N (Syme et al. 1976). My conjectures for the low N responses in south-eastern Australia were (1) high soil strength (2) foliar disease, particularly Septoria leaf spot (3) sulfur deficiency (4) applying N at sowing rather than topdressing at the stem elongation phase.

In 75 experiments on farms in southern NSW from 1981 to 1989, Tony Fischer, Anthony van Herwaarden and I tested the wheat yield response to N applied at sowing or topdressed at DC30. Fig. 1 shows the unexpected result of these experiments: wheat growing after break crops gave more consistent and generally larger yield responses to applied N than wheat growing after wheat (Angus et al. 1989). Yield responses were greater for crops with low shoot density at DC30 (main shoots plus tillers). Shoot density was the most accurate measure of N status out of several soil and crop methods tested. Fig. 1 also shows that N fertiliser reduced yields when applied to high-N crops due to haying-off. This is not an uncommon response in south-eastern Australia and yield decreased in response to applied N in one third of the experiments where wheat was grown after a break crop. van Herwaarden et al. (1998) later explained that depletion of water-soluble carbohydrates by high levels of N in crop tissue was the main mechanism of haying-off.

Of my four conjectures for the low N response three were falsified and one was almost falsified. Deep ripping to reduce soil strength gave variable and generally poor responses, as was shown in a review of research in south eastern Australia (Kirkegaard et al. 2008) although the practice worked well in Western Australian soils (Delroy and Bowden 1986). Leaf disease was also not the problem, as shown by little response to foliar fungicides. *Septoria* leaf spot had been controlled with resistant wheat varieties released in the 1980s (Murray et al. 1990) but it may have been responsible for earlier low N responses. No sulfur responses or S × N interactions were found in extensive experiments, probably because soil-S levels were generally adequate following historical S applications in single superphosphate. Mid-season topdressing gave no significant yield advantage over application at sowing but did increase grain protein concentration and nitrogen use efficiency (NUE). Tactical

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topdressing also gave growers time to assess the likelihood of profitable response in relation to weather, crop condition and the fertiliser:grain price ratio.

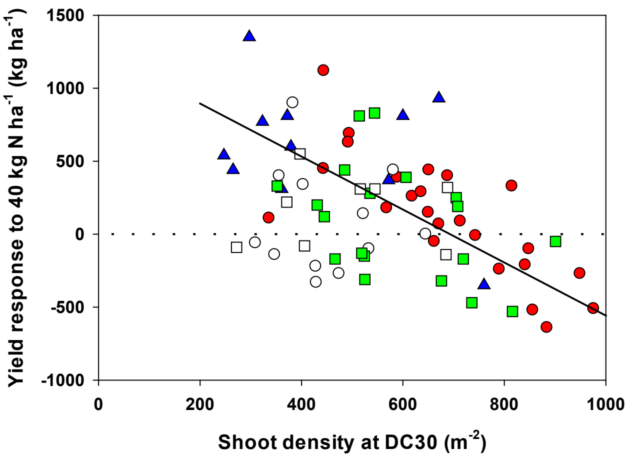

Fig. 1 Yield responses of wheat to N fertilizer as urea, topdressed at DC30, in relation to shoot density (main stems and tillers). Each point represents the yield response at one of 75 replicated experiments on farms in southern NSW (circles, 1987; squares, 1988; triangles, 1989). The coloured symbols refer to wheat following break crops (mostly canola), and open symbols refer to wheat after wheat. The dashed line represents no yield response to applied N. The solid line represents a significant negative (r=-0.63) relationship between yield response and shoot density for wheat after break crops. The response for wheat after wheat was not significant.

Another theme of my N research was testing the injection of N fertiliser in bands. This opportunity arose when a fertiliser company promoted injection of anhydrous ammonia into the soil in the period between late summer and the time of sowing. The soil disturbance that accompanies fertiliser injection reversed the growing practice of direct drilling and was inconsistent with conservation farming. A solution was devised by Tony Good who built a linkage seed-drill that injected anhydrous ammonia or urea midway between seed rows in a one-pass operation. Passioura and Wetselaar (1972) had shown that banding N-fertiliser produced a zone of high ammonium concentration that inactivated nitrifying microbes within the bands but left them unaffected around the perimeters where they slowly converted ammonium to nitrate (Fig. 2). Roots did not grow into the bands but did grow around their perimeters where they took up nitrate. Mid-row banding effectively provided a slow-release fertiliser and, because fertiliser was retained in the ammonium form, reduced the risk of denitrification and, on light soils, leaching below the root zone. A possible advantage is that fertiliser-N concentrated in bands is less exposed to immobilisation than when distributed throughout the topsoil.

In some experiments with dryland wheat in the late 1990s N fertiliser applied in one-pass, mid-row bands outyielded N incorporated by sowing or topdressed at the stem-elongation stage (Angus et al. 2014). There was little or no adoption of mid-row banding during the millennium drought that started soon after this research was completed. Research resumed after the drought and showed yield benefits for one-pass injection at sowing (Sandral et al. 2017; Vial and Kaylock 2018) and for mid-season, mid-row injection using precision guidance (Wallace et al. 2016). Future adoption of mid-row banding may not be as rapid as other innovations because purchase of suitable machinery will normally await replacement of old machinery.

My final collaboration on N research was about replacing the large amount of N removed when a crop was grazed during the vegetative phase (Virgona et al. 2006). This showed that NUE was less on grazed than on ungrazed crops. In later multi-location experiments, Sprague et al. (in press) confirmed that NUE was low for fertiliser applied soon after grazing. Their explanation was that defoliated crops had low N demand, giving time for microbes to immobilise mineral N. To improve NUE they suggested applying fertiliser N in bands to reduce immobilisation and to delay application until N-demand increased as the grazed plants regrew.

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Fig. 2. N-fertiliser band in soil shown by a pH indicator. The fertiliser was applied as urea in a one-pass, mid-row injection while sowing a wheat crop. The photo was taken during the late vegetative stage. Photo: Leigh Vial

Grazed crops are not the only system in which N demand is important. The optimum rate of fertiliser N depends on matching N supply and demand. Supply consists of residual N from previous crops or pastures, in-crop mineralisation and the rate and timing of N-fertiliser. Demand depends on factors such as water supply, sowing date, the species of previous crop, diseases such as *Rhizoctonia,* the status of other nutrients and, in Western Australia, soil strength. Yield potential is a useful surrogate for demand. Supply and demand are equally important determinants of yield response to N, but there has been an imbalance of research, with more research on N supply than N demand.

Break crops

I became curious about the mechanism by which break crops affect cereals after seeing how they improved the magnitude and reliability of the wheat-yield response to N (Fig. 1). One explanation was that wheat-root pathogens were suppressed when deprived of a host. This explanation alone did not explain why wheat yielded more after Indian mustard than after canola in some experiments. It seemed possible that there was an active process by which brassicas suppressed root pathogens in addition to depriving them of a host. Laboratory studies showed that isothiocyanates released from brassica roots supressed the fungal pathogen that caused take all in wheat, *Gaeumannomyces graminis* (Sacc.) Arx and Oliv. var. *tritici* Walker, in the process called biofumigation (Angus et al. 2004). Reviews of much research showed that the effect of break crops on subsequent wheat was similar in different parts of the world (Kirkegaard et al. 2008b; Angus et al. 2015) and that the average yield benefit of break crops was not proportional to yield (Fig. 3). These reviews also discuss lesser-known processes, 'hydrogen fertilisation' and mycorrhizal suppression, by which break crops increase yield of the following wheat crop.

Hydrogen fertilisation is the process by which gaseous hydrogen is released into the soil by *Rhizobia* in nodules on the roots of legumes. The hydrogen stimulates growth-promoting microbes that are then responsible for the yield increase. It must be emphasised that this process is in addition to the effect of residual N from legumes and is due to H_2, not H^+. The second lesser-known processes is suppression of arbuscular mycorrhizal fungi (AMF) by isothiocyanates released into the soil by roots of brassicas. AMF have a symbiotic association with many plant species, supplying immobile nutrients such as P and Zn in exchange for the products of photosynthesis (Ryan and Graham 2018). Where these nutrients are supplied in fertiliser the possible benefits of AMF are more than offset by the negative effect of reduced photosynthates. When this happens, AMF effectively become parasitic.

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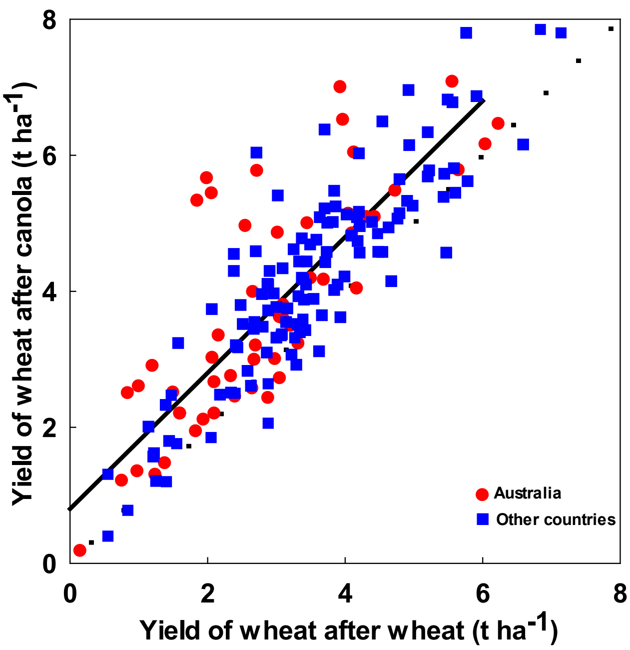

Fig. 3. Yield of wheat after canola exceeded yield of wheat after wheat by 0.80±0.17 t ha^{-1} in 180 replicated experiments and there was no evidence that the yield response was proportional to yield level. There was no significant difference between results of experiments in Australia or other countries (Angus et al. 2015). The dashed line is 1/1 and the solid line is fitted to the data.

There were additional benefits of introducing break crops into previous cereal and cereal-pasture systems in Australia. Most break crops (canola and grain legumes other than narrow-leaf lupin) could not be grown on soils that had been acidifying unchecked since the 1950s. The liming that underpinned the canola/wheat system enabled barley and lucerne, both of which are acid sensitive, to return to regions where they had not been grown for decades. Both these species are important for the growing animal protein market.

Crop modelling

Models of canopy photosynthesis were first developed in the 1960s when I was a PhD student. My involvement with these was to compare their predictions with measurements and I found that the accuracy of a simple model of a process was as good as, or better than, a complex model. No subsequent modelling has shaken this conclusion. Photosynthesis models had evolved into crop growth models by the early 1970s when I joined CSIRO. Probably the main advance in crop simulation modelling then and now was made by my boss Henry Nix, who proposed that a sub-model of phasic development should be the 'template' for the growth-related components. The pattern of the many crop models ever since has been a growth model superimposed on simulated phasic development. Equations for growth processes such as carbon assimilation and redistribution, nitrogen uptake and grain-filling are based on relationships observed in experiments conducted in controlled conditions. Use of these relationships implies that their functional form and values are applicable to field crops. The accuracy of a simulation model is typically tested by validation, usually consisting of a comparison of simulated and measured yield data. This is a less rigorous form of test than falsification, as discussed earlier. A test that could falsify a wheat model would involve evaluation of processes such as haying off and grain properties such as grain protein and biomass, as well as yield.

When model predictions are found to deviate from field data they are frequently 'tuned' to improve the fit. It remains unclear which parameter or parameters should be tuned. The practice of model tuning was criticised by deWit (1970) with the celebrated comment "the technique [of tuning] reduces into the most cumbersome and subjective technique of curve fitting that can be imagined". The response of some modellers has been to develop an efficient and objective method of parameter tuning using an optimiser to minimise the sum of squares between simulation and measurement. The

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equations can be based on known physiological functions, as in any simulation model, and the starting values of the parameters are best estimates. Optimisers such as LMM (Miller 1979) then vary the parameters within specified boundaries and, by a process of iteration, estimate the parameter values that cause a model to most closely fit field data. Parameter estimation using an optimiser is an objective method whereas a manual method is subjective, as deWit recognised.

Probably the first application of this method to agronomy was a simple dynamic potato model in which parameters were 'tuned' by an optimiser using yield data from well conducted field experiments (Sands et al. 1979). An extension of this approach was to fit a crop simulation model to several crop properties in addition to yield, and to include data from different seasons and regions in the data used for fitting. This approach is an improvement on tuning on yield alone since it overcomes the possible problem of compensating errors in different parts of a model. Gustavsson et al. (1994) used this approach by fitting parameters to simulate growth, protein concentration and digestibility of perennial grass.

The real value of linking an optimiser with a simulation model is to improve the model structure. If there is a poor fit of a model to data after optimisation, the likely fault is in the functional form of an equation rather than its parameter value, in which case the functional form should be changed. A limitation of using an optimiser with a crop simulation model is that no more than about five parameters can be estimated at one time, but it is possible to test different combinations of parameters in sequence. There is no limitation on the number of data points or crop properties that can be simulated.

Decision support tools

Some simulation models have evolved into tools that provide useful information to individual growers and advisers for tactical or strategic management of crops and pastures. One such tool was maNage rice, which was developed in collaboration with Rob Williams of NSW Primary Industries using an optimised simulation model.

Table 1. Screen inputs and outputs of the maNage rice decision support tool

Inputs	
Automatic downloads	Current season's daily weather. Annual costs and prices to estimate profit
Manual inputs	Variety, sowing date, water depth and NIR data on crop N-status
Outputs	
Temperature data	Historical daily data for 40 years in four regions and downloaded daily data for the current season
.Phasic development	A horizontal slider that predicts dates of panicle initiation, microspore development, anthesis and maturity, aligned with low temperature
Yield response to N	Yield response to N related to variety, sowing date, water depth, temperature and crop-N status
Response probability	Yield and financial responses, estimated from 40 years of weather data
."Show me"	Display of results from an experiment that resembles a grower's crop
Water balance	Estimated irrigation requirement from the present date until maturity
	Estimated date for harvest and percent whole grain

It was designed to be run in-season to predict the optimum rate of topdressed N for irrigated rice in the Riverina, based on a simulation of yield in response to N fertiliser, crop-N status, cold-damage at the microspore stage. and water depth (which affects cold damage). The first version of maNage rice started in the mid-1990s and was updated annually until the mid-2000s when drought shrank the rice industry and funding for continued research. maNage rice started out as a single-screen Ap that ran on Windows. It evolved to multiple screens through annual revisions and by adding new features requested by ricegrowers, consultants and other members of the rice industry (Table 1). The later versions were distributed on DVDs by the ricegrowers' cooperative, Sunrice, to ~1700 members.

The intended use was for ricegrowers to run the ap during the rice-growing season but some farmers used it off-season to explore the complex interactions of the manual inputs listed in Table 1. A popular output was the amount of water needed until crop maturity. Growers used this estimate in purchasing water on the market. Another popular output was the screen showing the alignment of daily minimum temperature with the cold-sensitive stage of microspore development. This provided an estimate of cold damage.

maNage rice contributed to improving the nitrogen use efficiency of Riverina rice by encouraging more of the N fertiliser to be applied at or before the time of sowing (Russell et al 2006). The weakness was poor succession planning following the cut in funding and the changed career path of the developers. Decision support tools can provide information to growers that is not available in other forms but at considerable cost.

Adoption

Canola, lime and N-fertiliser were not significant parts of Australian dryland cropping systems until the mid-1990s. At that time there were simultaneous and sudden increases of the canola area (nationally), lime application (in NSW) and N-fertiliser application (nationally) and the increases were mostly in the dryland farming regions (Fig. 4). The reason for quoting NSW data is that it is the only state that reports long-term data for agricultural lime use. Canola had been briefly adopted the early 1970s but had been wiped out by the blackleg fungus (*Leptospaeria maculans*) and did not re-emerge until resistant varieties were released in the late 1980s. Likewise, little N fertiliser had been used for dryland crops. The increase shown in Fig. 4 is greater than needed for canola and it's likely that most would have been applied to wheat after canola. Almost all the agricultural lime would have been applied just before canola crops. The need for lime had been anticipated by Williams and Donald (1957) but their conclusion had not been acted upon for almost 40 years, apparently until profits from the canola-wheat system were sufficient to pay for the lime. It was the release of disease-resistant and well adapted canola varieties in the late 1980s that triggered the use of lime and the increased yield and N-demand of following wheat crops.

The simultaneous and sudden adoption of the three innovations shown in Fig. 4 was inconsistent with the theory of diffusion of innovations, from early adopters to laggards, described by Rogers (2003). For N-fertiliser there was a lag of >30 years between the start of the National Soil Fertility Program and the start of the large increase in fertiliser-N use. This lag was similar to the lag in adoption of agricultural research by farmers in the United States reported by Alston et al. (2009). The lag was not due to Australian farmers' reluctance to adopt research but because the early research on N was irrelevant to the real limitation on N fertiliser (Fig. 2). Farmers became aware of the synergy between these factors in the late 1980s but there was a lag of 6-8 years for the widespread adoption of canola, lime and N fertiliser. This lag can in part be explained by the time to acquire new machinery for mid-season topdressing, and windrowers and pick-up fronts for canola harvesting. Another reason for the sudden adoption was the introduction of premiums for grain protein in the mid-1990s. These provided some incentive for topdressing in dry conditions when there was a positive protein response and a zero or negative yield response.

An alternative explanation for the increase in N fertiliser is that it was needed to replace biologically fixed N because pastures were being replaced by crops. This may have been a contributing reason but the slow reduction in N input by pastures is inconsistent with the sudden increase in fertiliser-N usage. The rapid adoption of canola, lime and N-fertiliser suggests that diffusion of innovations was less important than a reliable profit.

Another example of rapid adoption was the practice of grazing cereals and canola during their vegetative phase and allowing the crops to mature and produce grain. Dual-purpose crops were mainly long-duration soft and biscuit varieties until about 2000 when long-duration milling wheat varieties were released (Wedgetail, Whistler and Wylah). These opened up opportunities to a larger area of crops for grazing. Within two years some farmers had started grazing these varieties before any agronomic research had started. Within about five years the practice was widespread in southern

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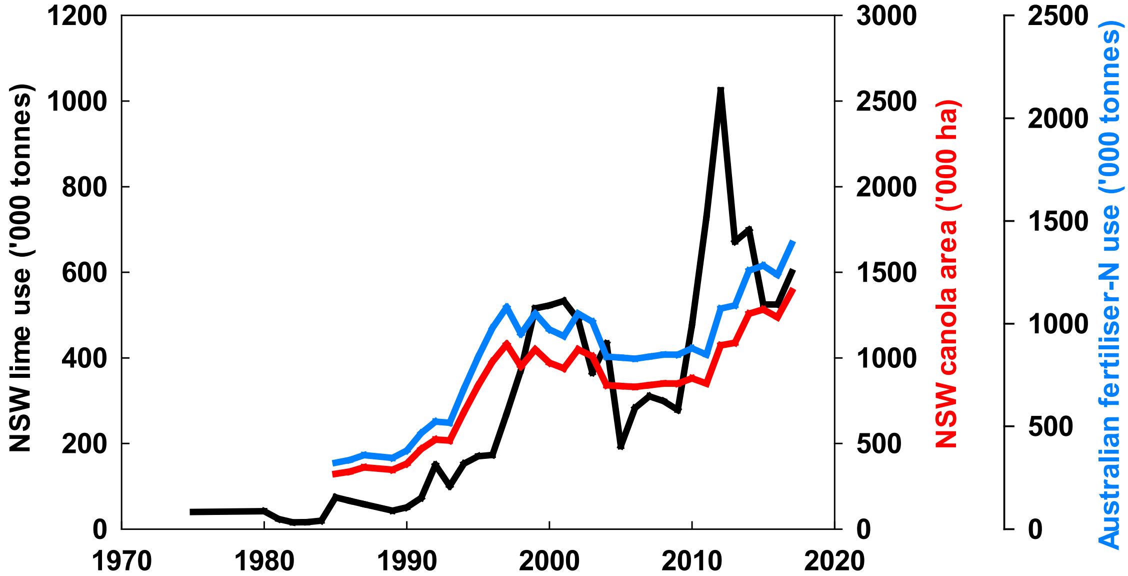

Fig. 4. Simultaneous and sudden adoption of canola, lime and N fertiliser in the 1990s. The plateau from about 2000-2010 coincided with the millennium drought and the subsequent increase followed wetter seasons. Long-term lime data are available only for NSW and fertiliser data are available only on a national scale.

NSW and was spreading to the rest of southern Australia (GRDC 2017). Adoption of dual-purpose crops was sudden and widespread but, unlike adoption of the canola × N synergy, preceded agronomic research. The common feature of these practices was that both followed release of radically new crop varieties. One was blackleg-resistant canola that provided the break-crop benefit. The other was release of long-duration wheat, barley and canola cultivars for grazing during the vegetative phase. In both cases the synergy was not anticipated but became obvious after the new cultivars were released. It is likely that future gains in productivity and sustainability will come from synergies, if only because the low-hanging fruit of single-factor improvement have been exploited. Future breeders and agronomists face the task of anticipating synergies.

Conclusions

Writing scientific papers can be satisfying but nothing in agronomy compares with the satisfaction of seeing research widely adopted on farms. Research leading to adoption needs luck and persistence, in addition to the following protocols.

Conduct field experiments replicated in time and space, preferably on-farm.

Multi-site experiments help to define regions and seasons where practices are likely to apply or not apply. On-farm experiments provide opportunities for agronomists to learn from farmers. Agribusiness agronomists should report all results, not just positive responses.

Ensure that results that are consistent with known science

This smartly excludes much organic farming and exaggerated claims such as impossibly high values of water use efficiency. Where productivity in a dryland experiment is below the water-limited yield, search for the real limiting factor.

Obtain independent evidence of some adoption, even after only a few years of research

Non-adoption of a practice that seems promising in experiments may indicate that there are unanticipated limiting factors rather than farmers' recalcitrance.

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