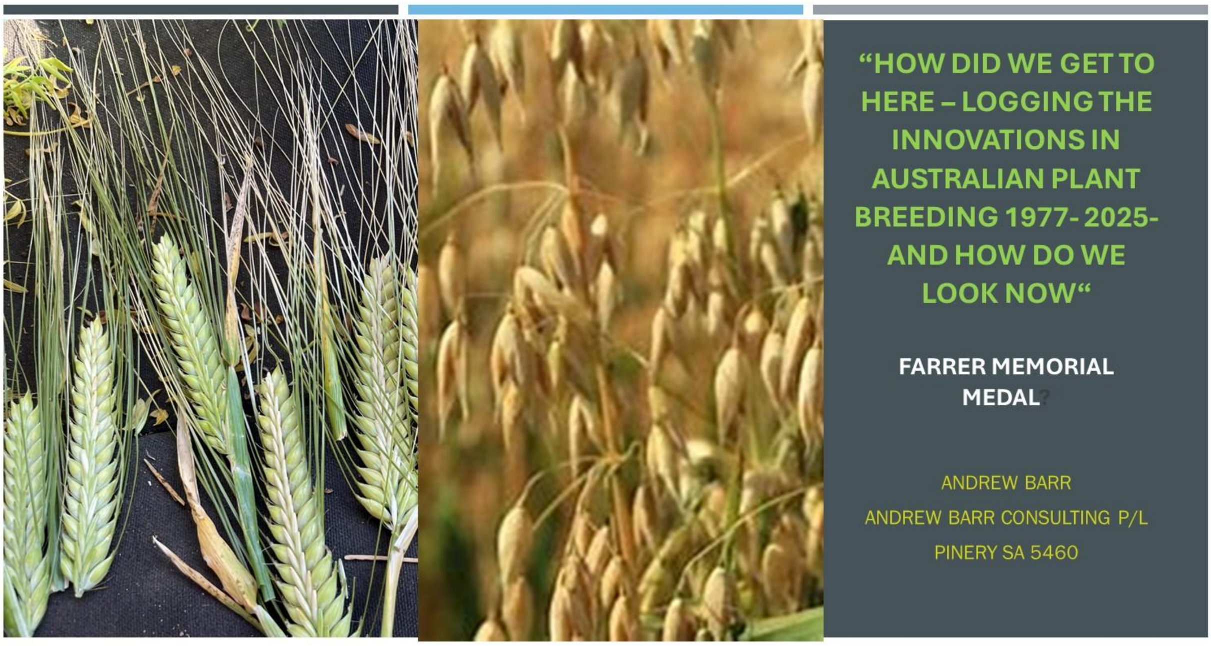


Good evening. I am here to celebrate the memory and legacy of William Farrer (Figure 1). I am very honoured to receive the Farrer Memorial medal and thank you all for attending.

Figure 1 ; William Farrer depicted on the Australian $2 note and the 2 1/2d. stamp

Farrer's incredible achievements are documented by previous medallists including LT Evans (1979), Watson (1958) and McIntosh (1976), so I will not recount their discussion but encourage you to read their papers on the Farrer website (https://www.dpi.nsw.gov.au/about-us/who-we-are/interacting_2/farrer-memorial-trust). My take on Farrer's approach was that he focussed on four key areas: 1. rust 2. quality 3. adaptation 4. agronomy. I will refer to the significance of those four pillars through my talk. He forged strong collaborations albeit he had a fraught relationship with his rust pathologist. Farrer's approaches were strongly influenced by the theories of Charles Darwin - even though Darwin's work was not held in high esteem at that point in Australia.

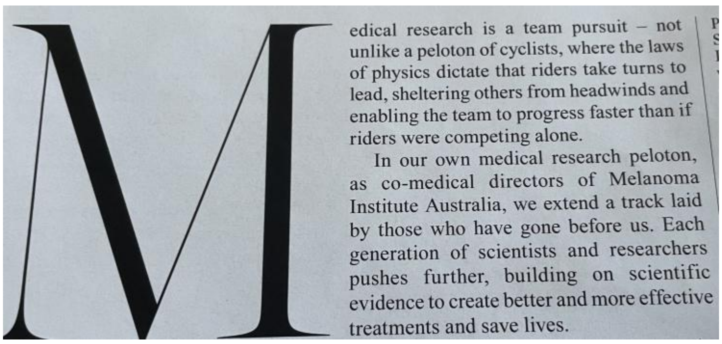
My talk tonight, will cover the following areas;

- **Introduction**

- **Section 1 - Who were the most influential plant breeders and geneticists on my career?**
- **Section 2- How did we get here? Key innovations in 6 important components of plant breeding**
    - Mechanisation and logistics
    - Experimental design and analysis
    - Genotype x environment analysis
    - Selection for disease resistance
    - Breeding methodologies
    - Organisational, financial and policy changes
- **Section 3 - How are we looking now? Some key questions .....**
    - Does your selection system mimic current and future farm practice?
    - Are the breeding priorities appropriate?
    - Is disease resistance being maintained?
    - Are low rainfall areas well serviced?
    - Are farmers getting the information they need to reliably choose varieties?
    - Do we take enough risks?

Introduction

Plant Breeding is an integrative science. Plant breeders must combine the knowledge of genetics, statistics, genomics, agronomy, plant pathology, food, feed and fibre quality science, soil science, computing/IT, machinery design, logistics and farming to be successful. So, this anecdote from our Australians of the Year 2024 seems a particularly relevant description of the way forward in science, and in this case, plant breeding (Figure 2).



Medical research is a team pursuit – not unlike a peloton of cyclists, where the laws of physics dictate that riders take turns to lead, sheltering others from headwinds and enabling the team to progress faster than if riders were competing alone.

In our own medical research peloton, as co-medical directors of Melanoma Institute Australia, we extend a track laid by those who have gone before us. Each generation of scientists and researchers pushes further, building on scientific evidence to create better and more effective treatments and save lives.

Figure 2: Richard Scolyer and Georgina Long, The Australian, December 2024

Section 1 - Who were the most influential plant breeders and geneticists on my career?

I was employed by the South Australian Department of Agriculture to begin an oat Breeding Program in 1977, after Mr Rex Krause undertook a study tour to determine the crops which the Department should focus its improvement work. It was an exciting project to initiate a breeding program, and the first varieties were released in 1984 (“Echidna”, “Dolphin”) with summer nurseries allowing the breeding cycle to be shortened to 7 years. Echidna was very successful as it was the first semi-dwarf oat, offering much higher yields than previous varieties as well as greatly improved lodging and shattering resistance.

At the time, cereal cyst nematode was the most important yield limiting factor in wheat, barley and oat crops with losses typically of 25%,10% and 40%, respectively. The focus of all the cereal breeding programs in SA was resistance (reducing the multiplication rate of the nematode) and tolerance (yield in the presence of the nematode). Galleon barley was the first resistant variety released in 1981 by David Sparrow and it was adopted quickly and widely by growers. It was enormously important as it rapidly reduced nematode populations and contributed to dramatic increases in yield of wheat and oat crops grown in rotation. Wheat breeders followed with the varieties “Molineux”, “Frame” and “Yitpi” and the oat program released the multipurpose varieties (grain, hay, grazing) “Wallaroo” and “Marloo” in 1988. Together these varieties (and those that followed) lead to a dramatic decline of cereal cyst nematode to the point where young farmers today could not identify the symptoms of cereal cyst nematode infection !

By the late 1980’s, interest was growing in producing oaten hay for export. More resources were directed to fitting varieties to this role, with emphasis on hay yield, hay quality, resistance to leaf disease and green leaf area duration. The lines which would later be released as “Wintaroo” and “Brusher” were identified prior to my leaving to leaving the oat program in 1994 and they became the basis of the oat hay industry in SA and Victoria.

In 1994, I joined the University of Adelaide to lead the barley improvement program. This was a large, multi-disciplinary program with excellent support from the Department of Plant Science and SARDI. The program joined with Victorian DPI staff and, with funding from growers, maltsters, brewers and other investors, sought to improve the yield, quality and cereal cyst nematode resistance of malting barley varieties. This “Malting Barley Quality Improvement Program” (MBQIP) was an exciting program which used molecular marker technology, whole grain NIR and wet chemistry measurements of malting quality, rapid cycle times and doubled haploid technology to breed the first CCN resistant malting varieties (“Sloop SA” and “Sloop Vic”, “Commander”). The program also had a successful feed barley program which released cereal cyst nematode resistant varieties such as “Barque”, “Keel”, “Fleet” (adapted to sandy soil types) and “Maritime” (tolerant of manganese deficiency).

In 2003, I joined Australian Grain Technologies P/L which had been built on a number of formerly public sector programs including University of Adelaide and Roseworthy College breeding programs and worked in their wheat breeding team. In 2006, I became a full-time farmer growing wheat, barley, canola, lentils, chickpeas and oat hay on the Adelaide Plains. In the period since 2006, I have served on the boards of ABB Grain, CIMMYT, GRDC, Australian Grain Growers Cooperative and South Australian Grain Industry Trust as well as undertaking reviews of plant breeding programs in Australia and internationally.

I would like to pay tribute to some the key influencers on plant breeding in my generation (Figure 3). I remind you that this is a southern Australia perspective as that is how breeding was organised in my first 20 years (1977-1997). While dangerous to leave some very important influencers out, I feel it is useful to understand the diversity of skills and perspectives that this group encompasses. The footnotes to the following graphic highlight (amongst their many other achievements), the key issues that were most important in shaping my breeding programs.

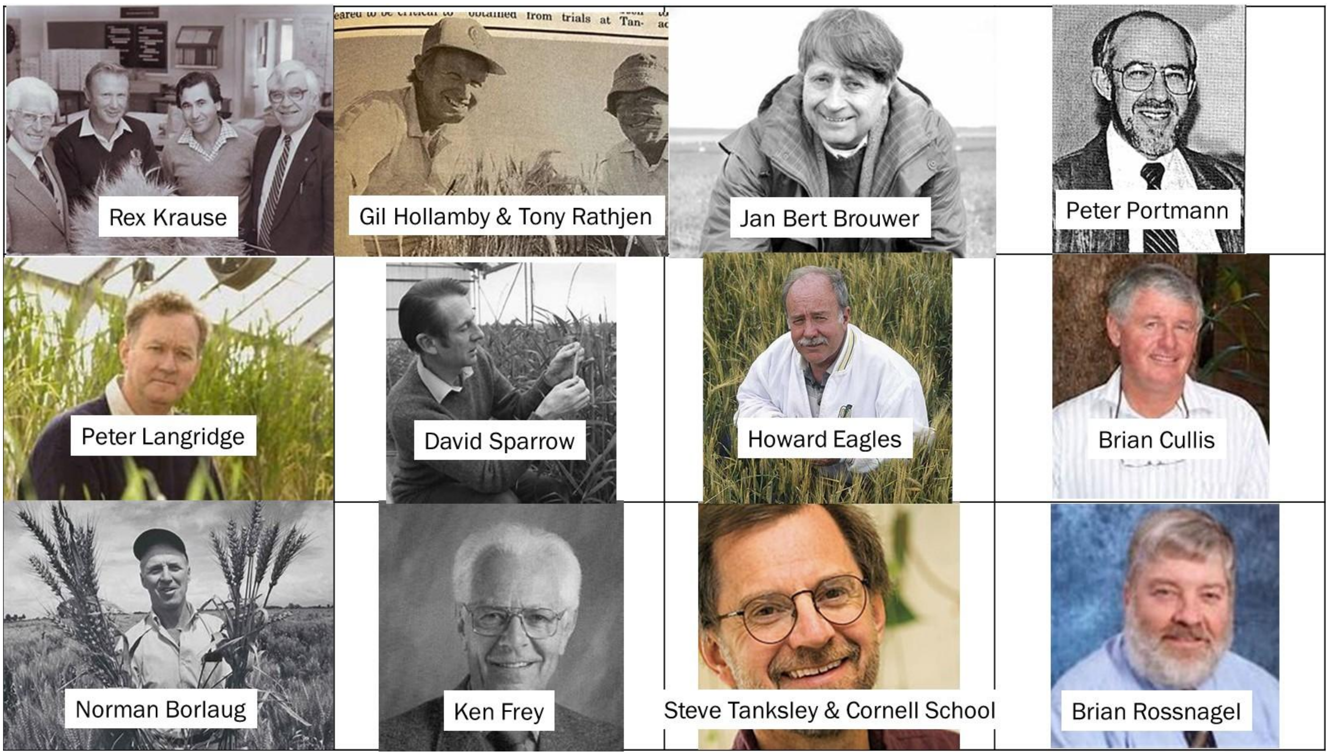


Figure 3 : Plant breeders and plant scientists who influenced my plant breeding programs

Key to photo wall (Left to right, progressing down the page)

Rex Krause, at right **(Roseworthy Agricultural College, SA Department of Agriculture)–** a classical breeder trained in pedigree breeding and backcrossing. Recommended the start of an oat breeding program in SA Department of Agriculture and my first manager.

Gil Hollamby (Roseworthy Agricultural College, University of Adelaide)– a pioneer in the understanding and practical application of the science around genotype x environment interactions which is especially important for Australian plant breeders

Tony Rathjen (University of Adelaide)– an innovator in computing, experimental design, plot machinery and in understanding the biological basis of genotype x environment interactions. Adopted the F2 progeny F5 reselection breeding system.

Jan Bert Brouwer (Victorian DPI)– a European trained perspective underpinned with strong plant physiology

Peter Portmann (Western Australian Department of Agriculture)– a master of logistics, plot machinery and achieving scale in plant breeding

Peter Langridge (University of Adelaide) – brought molecular markers & biotech out of the lab into practical applications in Australian crop breeding

David Sparrow (University of Adelaide) – Trained in classical UK pedigree breeding systems but adopted a different approach. Very clever with landraces. He had a meticulous approach to understanding germplasm and record keeping

Howard Eagles (Victorian DPI) – for his depth of understanding of quantitative genetics especially applied to the genetic control of crop development

Brian Cullis (NSW Department of Agriculture) – in association with Gleeson, Gilmour and Smith, for revolutionising the design and analysis of plant breeding experiments

Norman Borlaug (CIMMYT)– for his shuttle breeding approach (allowing two useful generations per year) and his dogmatic pursuit of political support for plant breeding in the developing world

Ken Frey (Iowa State University)– the most prolific of publisher on oat genetics and breeding

Steve Tanksley and colleagues (Cornell University)– for publishing some of the key papers of the era that influenced my approach e.g. the AB QTL approach to introgression of wild germplasm

Brian Rossnagel (Crop Development Centre, University of Saskatchewan)– for emphasising the single-minded focus required to be an effective breeder for growers and industry, and the need to forge international collaborations

Section 2- How did we get here? Key innovations in 6 important components of plant breeding

In this section, I will attempt to list the key innovations in six different components of plant breeding and provide an approximate date when these innovations were added to plant breeding programs in which I was involved.

- **Mechanisation and logistics**
- **Experimental design and analysis**
- **Genotype x environment analysis**
- **Selection for disease resistance**
- **Breeding methodologies**
- **Organisational, financial and policy changes**

2.1 Mechanisation and logistics

Table 1 : Machinery and logistics innovations impacting plant breeding 1977-2025

ACTIVITY	First seen	Date impl.	ACTIVITY	First seen	Date impl.
Belted cone seeder	1977	1979	No till seeders		1995
PBSYS Rathjen et al	1977	1978	Robotic seed packer Mk1	1996	
Summer nursery	1978	1978	NIR Whole grain	1997	1997
Herbicides for summer weeds	1979	1980	Robotic seed packaging Mk2 &3	2000	2000
Shielded pathway sprayer	1980	1981	Agrobase II	2000	2000
Whole head hill plot seeder	1982	1982	Automated tray planter	2000	
One man harvester	1982	1983	On harvester data acquisition	2005	
Precision seeder for seed production	1982	1982	High throughput phenomics	2008	
Crate and pallet logistics	1983	1985	GPS guidance on seeding tractors		2015
Magazine seeding	1983	1984	Machine learning/scanning technologies	2015	
Interrogate scales with NEC 8201		1984	Automated tripping of seeders	2018	
Automated seed packer Portmann et al	1985		Drone scanning	2018	
Windows PC		1985	AI	2025	
Agrobase I	1980	1985	Disc seeding systems	2026	
Bar codes		1991			

Footnote to Table 1 ; The dates when each innovation in Tables 1 to 6 was first seen and then implemented are approximate. Many of my oat and barley breeding records were destroyed in the Pinery bushfire of 2015.

Innovation in the machinery used for plant and the logistics of managing hundreds of thousands of plots and samples has long been a focus and strength of Australian plant breeding. From my starting point in the late 70's, breeding programs were sowing a few thousand to small tens of thousands of plots. By the late 80's, that capability had ramped up to 100,000's and enabled breeders to dramatically increase population sizes, increase selection intensity and better characterise genotype x environment interactions by increasing sites and replications.

Figure 4 ; University of Adelaide Waite Institute plot seeder circa 1968

Many seeders in the 1960's and 70's were designed for paper seed packets (Figure 4) but late in 70's people began making magazines of various types – wood framed with plastic vials, foam blocks with precision cut holes for seed, wood frames with PVC pipe cells, etc. The real breakthrough came when an injection moulded plastic magazine (Figure 5) was designed by Peter Portmann and his team in the WA Department of Agriculture – this allowed mechanical, air assisted and later electronic shunting of the magazine across the seed delivery table during seeding but also opened the way for robotic seed packaging, thanks to ideas developed in Perth, Adelaide and Horsham (Figure 6).

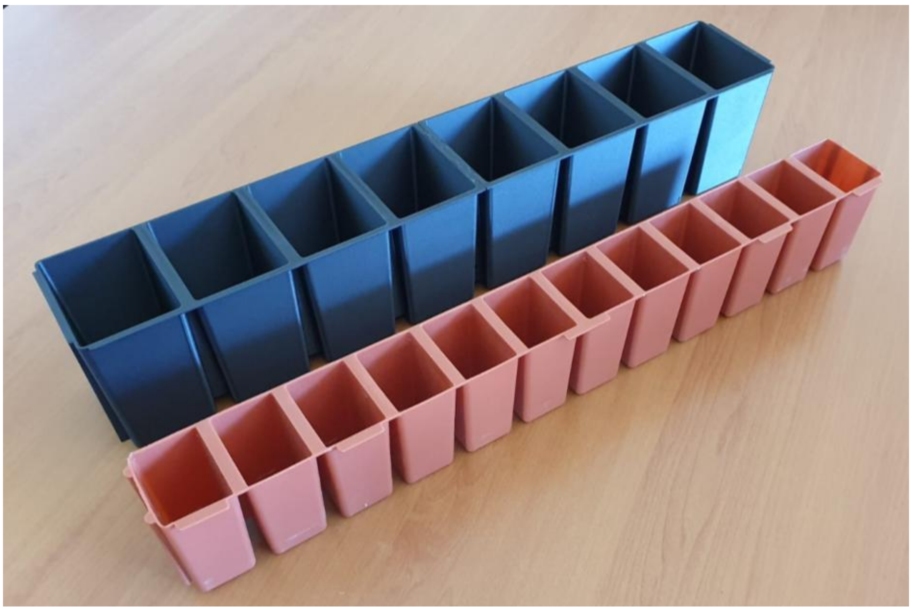


Figure 5; The Portmann et al. seeding magazine for cereals (with prototype 8 cell magazine currently under development for larger seeded species)

Figure 6 ; Robotic seed packer built by Asytec circa 2000

Many processes in plant breeding required manual labour and were time consuming and rate limiting. For instance, precision plantings of segregating materials often were planted by hand, limiting population sizes (Figure 7).

Figure 7 ; My first F2 nursery precision planted by the whole family! Such jobs certainly inspired one to think of a better way.....

In the 1980's, precision planters became available for the vegetable industry and so these were able to be modified to suit field crops allowing the space planting of seeds from segregating populations and the seeding of very low rate multiplication blocks (Figure 8).

Figure 8 ; Nodet Gougis precision seeder used in the seed multiplication of Echidna oats. 2t ha grain yield from 4 kg ha seeding rate in 1982 drought – a 500 times multiplication!

Plot harvesting too was a labour intensive and slow process in 1977 (Figure 9), with the time taken to harvest a 5m plot over 1 ½ minutes. Portmann and his WADA group modified their Hege harvester fleet to one man operation, by diverting grain from rear of the machine to beside the driver, with capture of the sample in a vented cyclone (Figure 10).

Figure 9: Plot harvesting in 1977 (Hege)

Figure 10; Around 1980, Portmann et al. modified the Hege harvester so that seed is delivered to the driver's side, allowing one man operation. Not surprising allergies became a problem, given the exposure to grain dusts

By the mid 1980's, two man harvesting systems were developed which improved plot harvest times further to one per 30 seconds (Figure 11). Current plot harvester have made great advances in operator comfort and safety, while allowing on board weighing (Figure 12).

Figure 11 ; Two-man harvester for oats (SA Dept Agriculture) circa 1985

Figure 12 Contemporary Wintersteiger plot combine circa 2020 plot harvester featuring air-conditioned cabin, on board weighing of plots and sample collection.

Peter Portmann presented a paper at the 1983 Australian Plant Breeding Conference where he outlined work in the WA Department of Agriculture to improve the mechanization of field experiments, and he concluded by having his cartoonist draw a picture to outline his vision for the future. It was a cartoon of himself lying by a pool with a remote control, while a robotic plot harvester worked in the distance harvesting his plots. I asked CoPilot to redraw this cartoon – you get the picture ……(Figure 13)

Figure 13 ; Two attempts by CoPilot to recreate the 1983 cartoon of a Peter Portmann look alike lolling by a swimming pool with a remote-controlled plot harvester working in the background

The combined impact of improvements to seed magazines and seeders, weed sprayers, plot harvesters, palletisation of seed storage (Figure 14) saw plot numbers rise for many southern programs into the 100,000 – 300,000 range by the late 1980's.

Figure 14 ; NSW DPI Tamworth seed store for Chickpea Breeding

One of the other most impactful innovations was the development and refinement of over-summer nurseries. Borlaug at CIMMYT demonstrated the impact that shuttle breeding could have on progress. That involved shifting the material from Obregon in northern Mexico to Toluca near Mexico City, a distance of over 1600 km. In southern Australia, we just had to provide water, control fast growing summer weeds, protect the crops from marauding birds (since nothing else is available at that time of the year), desiccate prior to harvest and turn around the summer harvest into the winter crop planting season in 3 weeks (Figure 15a and 15b). Simple.

This innovation allowed many programs to take 3 years off their breeding pipeline, as the F1, F3 and early stages of pure seed multiplication were all conducted over summer.

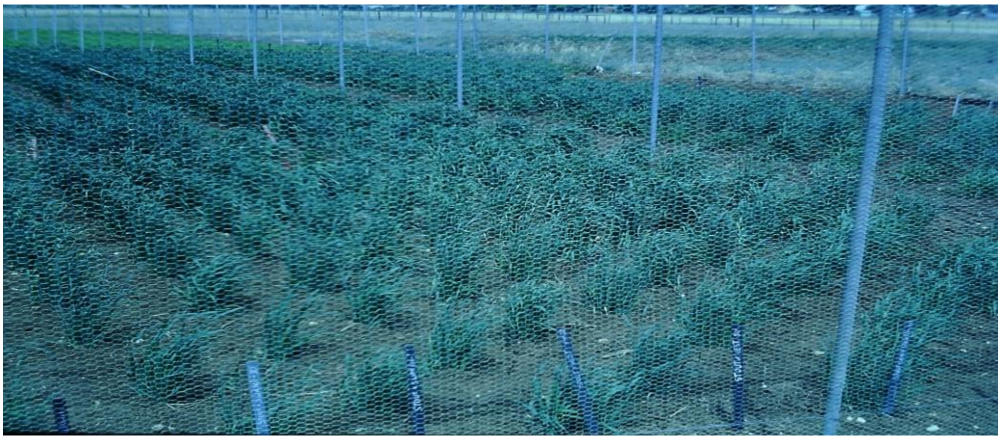


Figure 15a ; My first summer nursery in 1978 (suitable for hand operations or a small tractor) and later 15 b (below - mid 80's) in a "Rolls Royce" Bird proof cage with automated irrigation control and clearance for seeding and harvesting machinery

2.2 **Experimental design and analysis**

There seemed to be a long period after Fisher and Yates pioneering work on the design of field experiments when little changed, but things started moving in the 70's when the power of computing began to be applied to plant breeding and it became possible to implement more sophisticated designs and analysis (Table 2).

From the late 1970's, experimental designs moved quickly from the standard randomised block designs, to designs incorporating grid controls or check varieties, to incomplete block designs, nearest neighbour designs, and finally to 1D and 2D spatial designs. Each of these innovations reduced the error variance of the experiments and gave breeders more confidence in their selections (Figure 16). Breeders made two important changes to their methodology, reallocating the available plot numbers to more genotypes and less replications. As even more sophisticated designs such as the partially replicated designs and designs incorporating the family relationship of genotypes were published and adopted, this trend became even more pronounced.

Table 2 : Experimental design and analysis innovations impacting plant breeding 1977-2025

ACTIVITY	First seen	Date implemented
Randomised block Fisher	1926	
Square & rectangular Lattice Yates	1936	
Control plots Baker & McKenzie	1967	1977
Moving means Townley-Smith & Hurd	1973	1977
Alpha lattice Paterson & Williams	1976	1980
PBSYS Waite team	1977	1977
Nearest neighbour designs Wilkinson et al.	1983	1985
1D spatial designs Gleeson & Cullis	1987	
Agrobase I Mulitze	1980	1985
2D spatial designs Cullis & Gleeson	1991	1994
Agrobase II	2000	2000
Partially replicated designs Williams et al.	2011	
Pedigree / Spatial Cullis et al	2020	

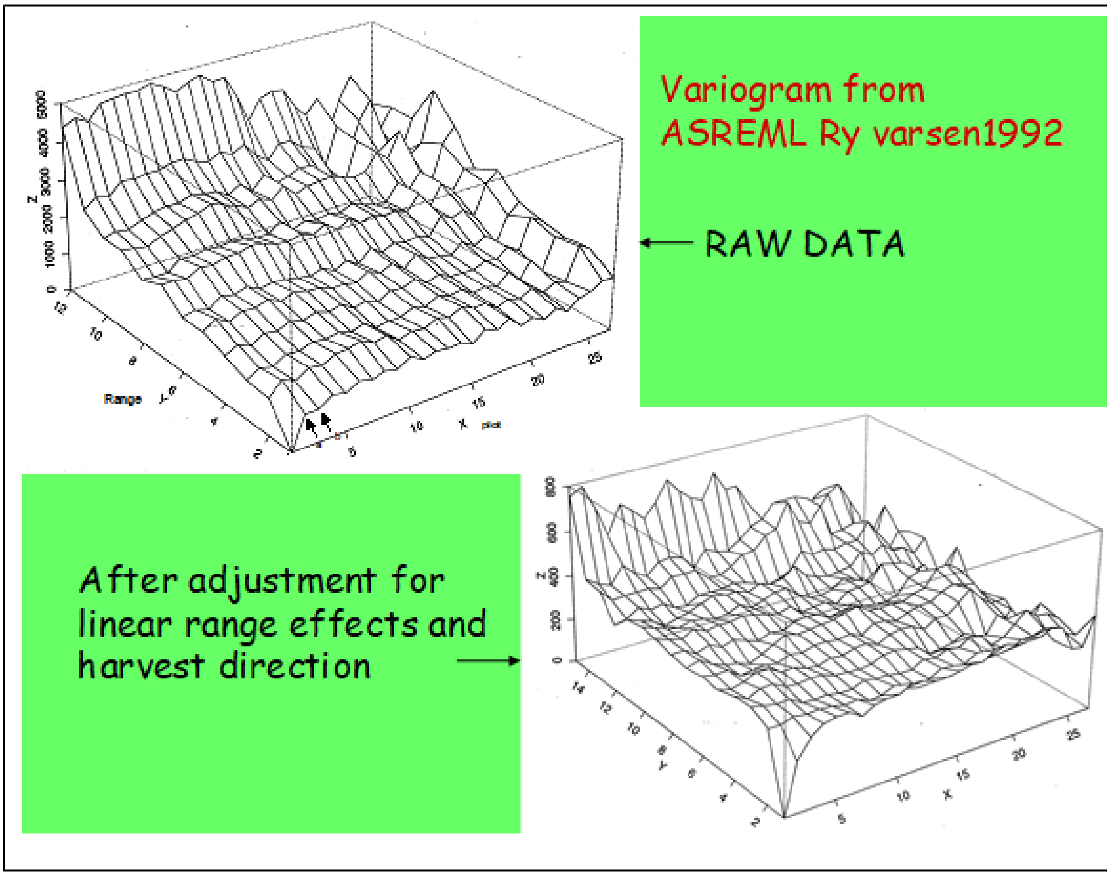


Figure 16; Who can remember the sheer joy of examining your first variogram?

Interwoven with the innovations in design and analysis, was the need for greatly increased computing power and much better software to manage the pedigree, line details, merit testing data and selection history of material within the breeding program. Jim Lewis (formerly working in the Waite wheat program) explained that their breeding program first used a computer at the Defence Science and Technology Organisation at Edinburgh Air Force base to manage their trial designs and analysis. My first exposure to a plant breeding management system was “PBYSYS” developed at the Waite by Rathjen and coworkers and implemented on a CYBER mainframe computer. Later, some breeding programs wrote bespoke PC based software, but these were largely dis-adopted when the AGROBASE package was released. This PC based system was widely used from the late 1980’s and Australian breeders interacted strongly with the Canadian developers led by Dieter Mulitze to further improve its capabilities.

2.3 Genotype x environment (g x e) interactions

My first trip overseas really reinforced to me what a difficult task Australian plant breeders have! In Europe and North America, I saw many programs that had one or two selection sites that characterised their selection environment and simple systems for merit testing and variety release. In contrast, Australian breeders deal with genotype x year (g x y) and genotype x location (g x l) interactions requiring us to have many sites and 3 seasons of yield data – then the rule of thumb for characterising the “true merit” of a potential variety. Thankfully we have made enormous progress in the understanding and analysis of g x e. Gil Hollamby significantly influenced the strategies used to characterize adaptation and reduce the time and sites needed to establish true merit (Table 3).

Table 3 : Genotype x environment measurement and analysis innovations impacting plant breeding 1977-2025

ACTIVITY	First seen
Finlay Wilkinson G X E Regression analysis	1963
Eberhart & Russell refinement	1966
Biological approaches (indicator,probe)	1982
Breeding for 2 states adaptation (wheat,oats)	1990
Multi environment Trials (MET)	1995
QTL mapping	1996
Cluster analysis	1999
Principal Component Analysis	1999
QTL mapping yield	2000
Breeding for Australia wide adaptation	2002
NVT program	2005
Eagles et al developmental genes	2013
Genomic selection	2015

Hollamby as part of the Roseworthy Wheat Breeding Program ran a series of unique trials he dubbed "indicator trials". These trials had a limited number of genotypes grown across his most important yield testing sites which were chosen because they might help characterise the most significant factors affecting yield and genotype x environment interacts. For instance,

- Related lines with and without a gene for boron tolerance
- Related lines with and without tolerance to cereal cyst nematode
- A range of maturities, which could be used to plot flowering date against yield across the sites

These trials were first conducted in SA but then the program was asked to expand into WA, and so over time Hollamby was able to compile a large data set over numerous sites and seasons. He then analysed this data using a number of tools including factorial analysis, regression analysis, cluster analysis and principal component analysis. He used these analyses to compare sites and seasons on the ranking of varieties with the indicator trial set. Hollamby identified "triplets of sites" (Figure 17) which were able to predict the mean performance across all sites and seasons. He inferred that judicious site selection could reduce the time to characterise true merit (and breed for wide adaptation) from 3 years to 2 years and that often this involved including sites from both SA and WA. Breeders at Australian Grain Technologies (AGT) post its inception in 2002 expanded this analysis to include sites from Victoria, NSW and Queensland and a wider range in WA. This analysis formed the basis for the now common approach for breeding for adaptation across the entire Australian grain belt.

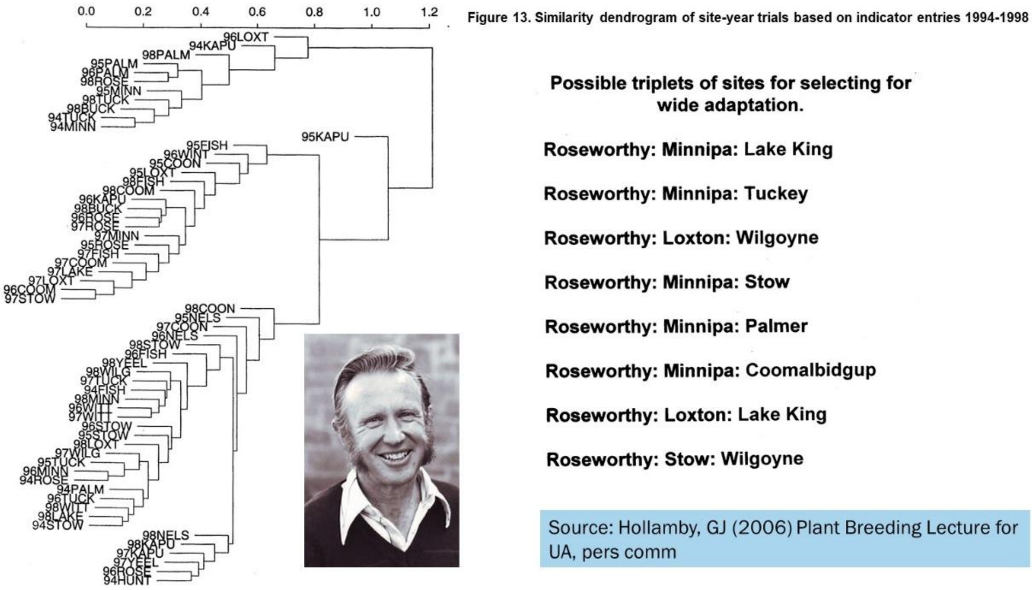


Figure 17 ; Similarity dendogram of site -year trials based on indicator series 1994-1998 (Hollamby, pers. comm.)

2.4 Disease screening

The fourth area of innovations to cover is that of disease screening. Resistance to disease is always an important part of plant breeding and certainly oats had plenty of problems. Two rust species, septoria, two bacterial blights, a virus (BYDV) and two nematodes (cereal cyst nematode and stem nematode) were all serious issues for oats and cereal cyst nematode was an even bigger issue as the other cereals grown in rotation were susceptible to damage (wheat and barley). In general (with the possible exception of rust screening at University of Sydney Castle Hill then Cobbitty), disease screening was slow, laborious and intermittent in the 1970's. When I began plant breeding, selection systems for the highest priority targets enabled one to screen 10's of individuals. By the mid 1980's, we were able to screen 100's, by the 90's, it was possible to screen 1000's (Table 4).

Table 4 : Disease screening innovations impacting plant breeding 1977-2025

ACTIVITY	First seen	Date implemented
Castle Hill / Cobbity rust screen	1977	1977
High rainfall nursery for rust, BYDV	1979	1979
Bioassay for CCN Tolerance sites	1980	1980
Tube test CCN	1982	1977
European study tour	1985	1986
Northfield disease nurseries	1988	1988
Root ball surface CCN test	1992	1992
Cloning disease resistance genes Baker, Ellis	1992	
POTS test on Terraces	1994	1994
Turretfield disease nurseries	1995	1995
MAS using RFLP for CCN	1996	1983
BiParental Genome mapping for QTL ID	1998	1998
PCR / SSR markers	2000	2000
Association mapping	2015	
"Big 5" Rust resistance cassette Luo et al	2021	

Two innovations made the biggest impact on the oat breeding program. In 1985, I travelled through 11 European countries looking specifically at their disease screening systems. At CC Benoist Plant Breeding in Orgerus near Paris, I saw an irrigated nursery for foliar disease screening sited in a small, blind river valley where a wooded creek ran. As one stepped down into the valley, the increase in humidity and decrease in temperature was immediately apparent (Figure 18). This, coupled with the overhead sprinklers. created ideal conditions for disease and the plots were indeed heavily infected. On return to Australia, funds were sought to set up an irrigated nursery at Northfield labs and subsequently, disease nurseries were established at Turretfield Research Centre where a small creek runs through a blind valley. These nurseries were very successful at consistently creating epidemics and thus enabled much greater selection pressure to be exerted.

Figure 18 ; CC Benoist nursery in Orgerus, France in 1985 in a small river valley, coupled with irrigation to give high humidity and long leaf wetness to high disease intensity

Cereal cyst nematode (CCN) was the single biggest identifiable cause of yield loss in southeastern Australia in wheat, barley and oats in the 1970's and 1980's. John Fisher, at the Waite Institute, had devised a growth cabinet test where CCN larvae were inoculated onto germinating plants. The plants were subsequently removed, the soil carefully washed away and the CCN cysts counted. This test was used to identify sources of resistance and start the backcrossing program to introgress resistance. However, it was a labour intensive and costly test, so numbers were limited. The oat breeding team decided to try a different technique in 1985. The Dube lab in SA Dept Agriculture tested paddocks for CCN egg levels prior to the growing season and identified paddocks with high populations. After the seasonal break, when the eggs hatched, we dug the field soil and placed it into clear plastic tubes. After growing the plants for 12 weeks, we then counted the number of white females (cysts containing the eggs) visible through the plastic (Figure 19). This number correlated very highly with the total number of females but saved the time-consuming root washing stage in the previous testing regimes (see photo below). This allowed a 20 times increase in testing numbers and so progress toward resistant varieties accelerated markedly. In subsequent years, we tried a range of different containers and further increased the efficacy of the test (Figure 20).

The Plant Pathology team in SARDI adopted a similar test which they named the POTS test which they offered for many years to all of the cereal breeding teams. It was a huge boost to CCN screening. By the early 1990's, agronomically acceptable varieties of feed barley, wheat, oats and triticale had been released from the various breeding programs in SA and Victoria and in 2001 the first malting barley varieties were released. The adoption of this suite of varieties has relegated CCN from public enemy #1 to barely detectable – a truly remarkable feat.

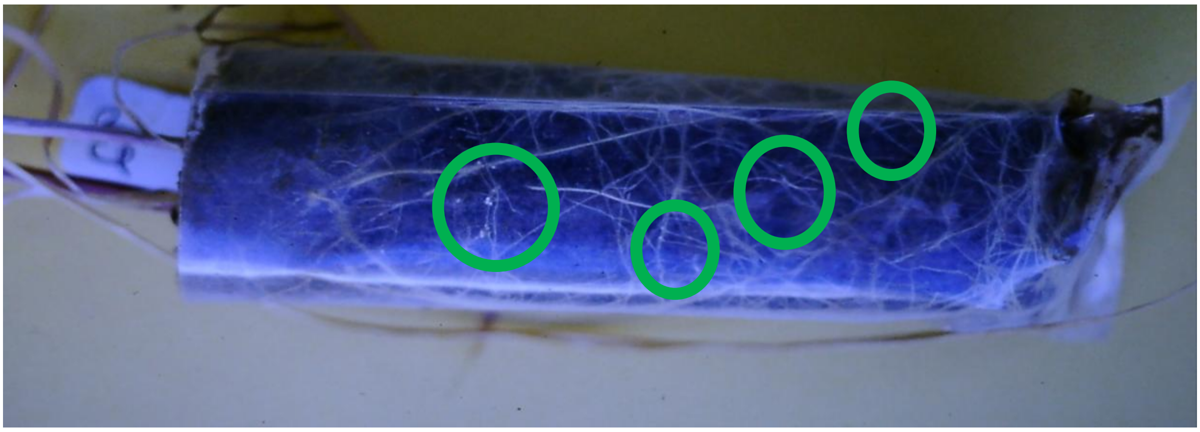


Figure 19 ; 1986 CCN plastic bag test – counting cysts through the plastic only

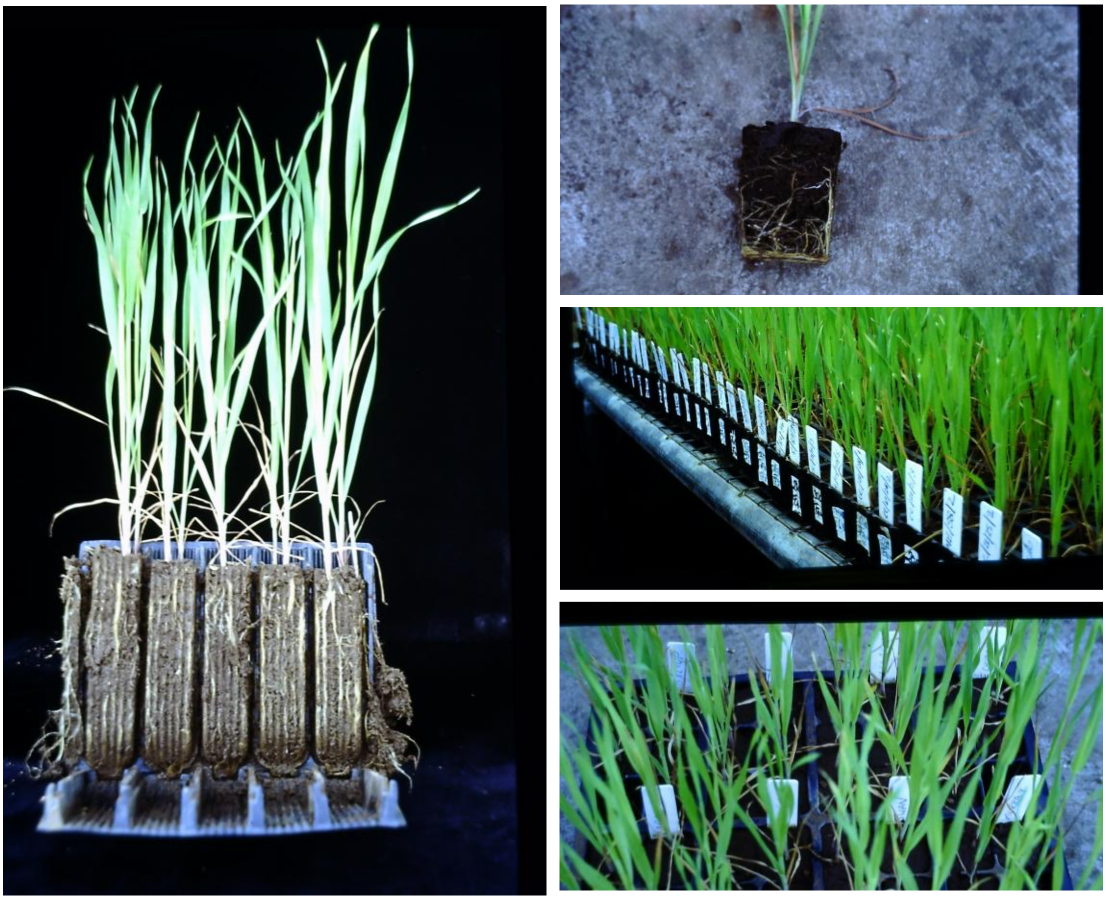


Figure 20 ; 1989 We tried many different vessels for CCN screening – all counted cysts on the exterior of root ball to increase throughput.

2.5 Breeding methodology

At the beginning of my breeding, the choice of breeding methods was pedigree, F2 progeny and backcrossing – in the case of the oat program we chose F3 progeny and backcrossing to the BC2 stage (Table 5). The incorporation of out of season nurseries to accelerate the rate of generation advancement was very important, facilitating release of our first varieties Echidna and Dolphin in 7 years from crossing to commercial production.

In my barley breeding days beginning in 1994, the most significant change was the introduction of molecular marker technologies and QTL mapping. This revived backcrossing as a strategy, of plant breeders turning it into a much more powerful and controllable tool. QTL mapping started to reveal the genetic basis of first simple, then more complex traits. In the next generation of plant breeders, genomic selection will have equivalent or even more significant impact.

With the quest for tolerance to herbicides, mutation breeding has had a revival and its use by Vic DPI, SARDI and Global Grain Genetics has resulted in valuable new germplasm in many crop species with tolerance to range of modes of action of herbicides e.g. imidazolinone (imi) herbicide tolerant lentils, barley, faba beans, chickpeas, oats; metribuzin tolerant lentils and clopyralid tolerant lentils.

The Australian Plant Breeding Conference first discussed GM technology in 1983 but it was many years before we saw the first GM cotton and canola commercialized in Australia. Perhaps the pinnacle of this technology thus far has been the development of the omega 3 oil canola by CSIRO which required insertion of 8 transgenes – a truly remarkable achievement. Disappointingly, GM technology has not been commercialized in the cereals or pulses, even though potential roles have been identified. We stand now (2025) on the cusp of perhaps a commercial GM wheat and hopefully CRISPR edited varieties.

Table 5 : Breeding methodology innovations impacting plant breeding 1977-2025

ACTIVITY	First seen	Date implemented
Line Breeding	1900's	
Pedigree	1900's	
F2 Progeny	?	1977
Backcrossing Harlan and Pope	1922	1977
Mutation breeding Stadler	1920's	
Shuttle breeding	1940's	1977
GM Bevan, Flavell, Chilton	1983	
AB QTL Tanksley et al	1994	2000
MAS backcrossing		1996
Doubled haploids in barley		1995
MAS backcrossing with recurrent genotype		1998
CRISPR CAS9 Charpentier & Doudna	2012	
Genomic selection Meuwisson, Hayes Goddard	2001	2015
Speed breeding	2003	2012
Speed breeding and GS	2024	2024

2.6 Organisational, financial and policy changes

When I began breeding, most breeders were employed by a state department of agriculture, CSIRO or a university and were funded from that organisation with a top up from a range of relatively small industry funds. Then the Grains Research and Development Corporation (GRDC) was formed in 1990, and funding was increased and better coordinated across the country (Table 6). In a similar time frame, plant variety rights (PVR) legislation was passed and while its initial focus was on horticulture, field crop breeders jumped on board too. My last oat variety in 1994 was granted PVR. Then the end point royalty scheme was introduced in 1996 and this had repercussions that still reverberate around the plant breeding industry, with first wheat (2002), canola (2010), barley (2013), lupins (2016) and oats (2021) being privatised.

Table 6 : Organisational and legislative innovations impacting plant breeding 1977-2025

ACTIVITY	First seen
Federal commodity-based research councils	1957-1990
State based commodity-based research committees	1982-1991
PVR passed	1987
GRDC formed	1990
SAGIT Formed	1991
MBQIP	1992
PBR updated	1994
EPR starts	1996
CRC for Molecular Plant Breeding	1997
Privatisation wheat	2002
Privatisation canola	2010
National Variety Trials launched	2005
Startups e.g. Global Grain Genetics	2012
Privatisation barley	2013
Pulse Breeding Australia launched	2014
AGT start Lupin Breeding	2016
International eg Secobra Barley Breeding	2017
Chickpea Breeding Australia formed	2020
Intergrain Oat Breeding	2021
Trigall Australia	2022

Summary of Section 2

What was the result of all these innovations and changes? Breeding of field crops in Australia is now undertaken with

- A sound business model,

- sowing more plots,
- with more genotypes,
- from a wider genetic base,
- cycled faster,
- assessed more accurately,
- in current farming systems,
- for more traits,
- released more quickly,
- with a higher level of confidence in merit,
- with generally better data for farmers, and
- delivering a profitable return on investment to farmers and breeders.

Figure 21 ; So, the peloton has done its work and plant breeding is much more efficient in 2025 than when I began in 1977

Figure 22 ; Even though in strong winds it has divided at times ......(some breeding entities both public sector and private companies have been lost along the way)

Section 3 - How are we looking now? 6 questions that examine where we are now and how might we proceed?

- Does your selection system mimic current and future farm practice?
- Are the breeding priorities appropriate?
- Is disease resistance being maintained?
- Are low rainfall areas well serviced?
- Are farmers getting the information they need to reliably choose varieties?
- Do we take enough risks?

3.1.a Does your selection system mimic farm practice? Disc seeder & Dry sowing

From Farrer to the Rathjen & Hollamby era, I have always been convinced that breeders must manage their nurseries using the farming systems of the day and given the lag in breeding, must actually predict where farming systems are heading to be ahead of the game. And so it was that we adopted no till seeders in the 90's. Is that true today? In my area, 40% of the crop is sown with disc seeders and last year 80% was sown dry (Figure 23). To my knowledge there are no NVT contractors and only one breeding company who can sow experiments with disc seeders. Dry sowing is not commonly practiced in either breeding or variety evaluation, because of the perceived risk of poor establishment rendering the experiment void. Does this matter?

Figure 23 ; Montage of disc seeding systems – clockwise from top left- disc seeder of the minimal disturbance type; stripper front on harvester; long straw remaining after stripper front harvest; disc seeder working through long straw

So, how would disc seeding systems, especially dry sown differ from knife point systems sown after the seasonal break, and could it affect variety rankings?

- Higher humidity in canopy -> more powdery mildew, septoria, eyespot, crown rot, net blotch etc
- Dry seeding – some resistance to "malting" & longer growing season
- Higher yield potential

Hence it is likely selection under a disc seeding system might (at very least) favour lines with improved disease resistance and improved lodging resistance to realise the higher yield potential.

3.1.b Does your selection system mimic farm practice? - Amelioration of soil constraints

There are estimated to be 5m ha of sandy soils in SE Australia. As the price of rural land escalates rapidly, farmers are investing more in ameliorating under-performing land. Estimates are that 25% of these sandy soils have already ameliorated, by deep ripping, clay spreading, spading or delving and much more to come (Figure 24). Barley and lentil breeding programs have shown clearly G x E for yield on the dune compared to the swale. Traditionally, wheat is not grown on the dune but with amelioration this has changed dramatically. So, the questions arise should and can wheat breeding trials be sited on ameliorated dunes? As with the disc and dry seeding question, we need to consider if there are likely to be special adaptations to take advantage of this new niche. Ameliorated dunes deliver higher yields and plants achieve greater rooting depth, accessing more soil moisture and nutrients. Nutrition on soils remains a challenge and in the case of the barley g x e on sandy soils, efficiency of phosphorus nutrition was likely one of the reasons.

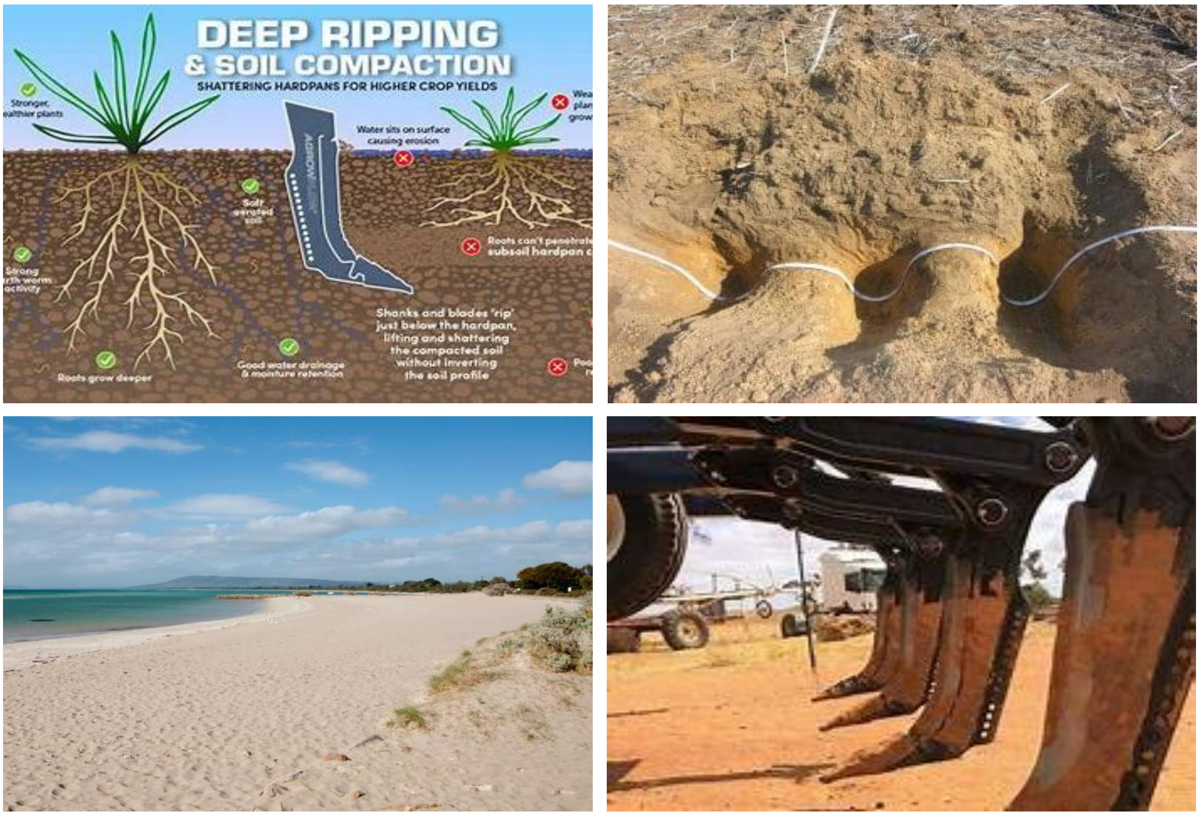


Figure 24 ; Montage of sandy soils amelioration – clockwise from top left- the effects of deep ripping; excavation of ripped lines in compacted soils; a cheeky look at some of our sandy soils; deep ripper

3.2. Are the BREEDING priorities appropriate for sustainable or organic grain production?

Agricultural systems around the world are under increasing pressure to reduce their environmental footprint. In some jurisdictions, the response is to examine the sustainability of agriculture. In the EU, a "Farm to Fork" program was implemented in 2020 with some goals as listed below by 2030 (Figure 25).

The 27 actions proposed in the strategy include the following:

- • a 50% reduction in the use of pesticides (with 2020 serving as the base year);
- • a 20% reduction in the use of fertilizers, including manure;
- • a 50% reduction in sales of antimicrobials or antibiotics used for farm animals and aquaculture; and
- • requiring 25% of agricultural land be farmed under organic practices (an increase current level of around 8%.)
- • a 10% reduction in farmland used for growing crops. -10% from total

Figure 25 : Farm to Fork strategy of the European Union, to be met by 2030

How should a breeder respond to these changes if something similar were proposed for Australia? How would a breeder respond to a switch from current farming systems to more sustainable systems (Table7)?

Table 7 ; What would Farm to Fork wheat breeding priorities look like ? (Note MR = Moderately resistant; MS = Moderately susceptible

	Current	"Sustainable" / Low pesticide	Organic
Disease resistance	MS + fungicide	MR GM resistance cassettes	MR-R to multiple diseases Extremely difficult
Yield	High selection intensity Genomic selection	Moderately high selection pressure	Low selection pressure
Lodging	Growth regulants + moderate lodging	High selection for lodging resistance	Less pressure on lodging resistance as yields lower
Selection environments	Moderate fungicide, high N, growth regulant	No fungicide, growth regulant, less N on breeders plots	No pesticides ? But breeders cant afford failures !
Nitrogen use efficiency		Becomes important	
Competitive ability	Herbicides working	Moderate selection	High selection pressure

The table above highlights in red the most important breeding priorities under each system and in yellow, the changes from current priorities.

Table 8 What would Farm to fork canola breeding look like ?

	Current	"Sustainable"/ Low pesticide	Organic
Disease resistance	MS + fungicide	MR GM resistance cassettes	MR-R to multiple diseases Extremely difficult
Yield	High selection intensity Genomic selection	Moderately high selection pressure	Low selection pressure
Agronomic traits	Growth regulants + moderate lodging	High selection for lodging resistance	Less pressure on lodging resistance as yields lower
Selection environments	Moderate fungicide, high N, growth regulant	No fungicide, growth regulant, less N on breeders plots	No pesticides ? But breeders cant afford failures !

- Need GM trait – Bt for insect resistance – but no ! Not acceptable
- Much higher level of Blackleg resistance

Just as major changes in wheat breeding priorities may be needed, there would be major changes in canola breeding priorities

3. 3 Is disease resistance being diminished?

In the public sector wheat breeding era, breeders conformed to an agreed set of minimum disease standards for resistance to stem, stripe and leaf rust. These standards have been abandoned in the private wheat breeding era as breeders have pursued high yields as this is the trait that sells varieties. Farmers use progressively more fungicide because the products are cheaper, better and include more modes of action. However, fungicide resistance is on the rise and there is mounting pressure to adopt sustainable practices. So, has the level of disease resistance diminished over time in wheat or barley?

The situation in barley was examined by David Moody, Intergrain (See Proceedings of the 2024 Australian Barley Technical Symposium) and he concluded.....

"Foliar disease resistance improvement has kept pace with pathogen evolution but yet to reach stage of reducing fungicide costs"

In the case of wheat breeding, I looked at the sowing guides for South Australia from 2006, 2017 and 2025 and examined the disease ratings for the varieties listed in the guide for each year. The analysis shows (Table 9)

- No change in the percentage of triple rust resistant varieties (rated at least MR)
- No clear trend in broad spectrum resistance (resistance rating of at least MS to the 5 most significant diseases (stem rust, strip rust, leaf rust, septoria, yellow leaf spot))
- A clear decline in the percentage of varieties with at MS rating to all 3 rusts

Table 9 ; Resistance ratings of varieties presented in the South Australian wheat sowing guide in 2006, 2017 and 2025

Year	Number of varieties SA guide	"Triple rust"	"Moderate Triple Rust"	"Broad Spectrum"	"Moderate broad spectrum"
		(All MR +)	(All MS+)	(5 x MS+)	(4 x MS+)
2006	27	4%	41%	7%	22%
2017	32	3%	22%	0%	9%
2025	45	4%	9%	7%	27%

3.4. Are low rainfall areas well serviced?

The heritability for grain yield is higher in higher yielding environments and higher yield environments can pay more for new seed and pay more royalties. So, are low rainfall environments being targeted and improvements being made in the current era?

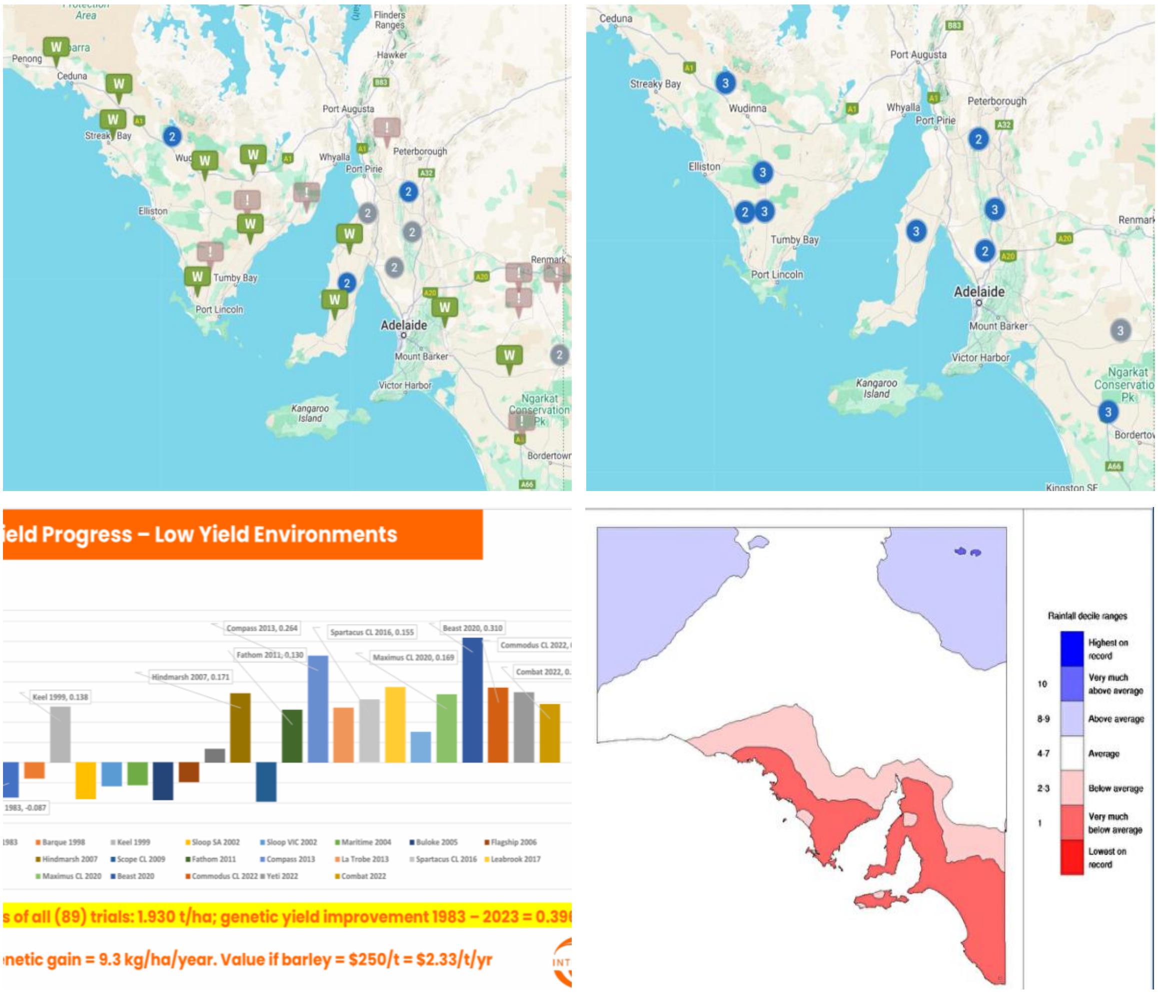


Figure 26 ; Clockwise from top left- SA wheat NVT trial sites (well spread around the lower rainfall areas of SA); SA canola NVT sites (concentrated in higher rainfall districts); David Moody analysis on the return on investment from barley breeding for low rainfall areas published in the 2024 ABTS; Rainfall for 2024 in SA

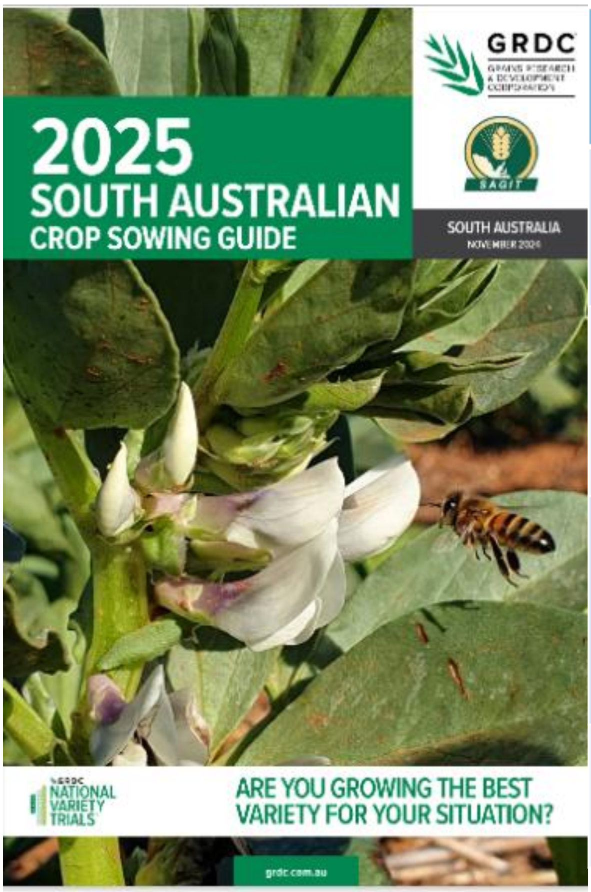
Again, David Moody provides some answers (Figure 26). He found in barley breeding that very attractive returns on investment by growers flowed for medium and high yielding environments but that rates of improvement were not as attractive in low rainfall areas. I am not aware of a similar analysis for wheat, oats or canola, so all that is possible here is to look where the effort is directed. Wheat breeding and wheat NVT sites cover the whole wheat belt, right to the edges of cultivated areas. In contrast, the canola effort is definitely skewed to the higher rainfall end. A much more detailed analysis of both crops would certainly be useful.

The situation is oats is clear. Oats struggle relative to wheat and barley as the rainfall decreases. I found that the oat germplasm pool was narrower than I would like – this I believe is due to the way in which oats were domesticated. While the small grain cereals all originated and evolved in the fertile crescent (Iran, Iraq, Syria, Jordan, Israel), oats were domesticated in central Europe from wild oats thought to be carried in wheat and barley crop seed grown there. Hence the cultivated oats were adapted for central Europe and were derived from a very small subset of the genus, given they were transported out of their centre of origin. This explains why they struggle relative to wheat and barley when grown back in harsh mediterranean environments like ours. When you have a problem with cultivated wheat or barley, you go back to the land races or wild relatives from the fertile crescent or mediterranean. These land races in barley have been absolutely pivotal to the development of modern cultivars e.g. Galleon, Schooner, Chebec, Barque, Keel. More recently, the variety Fathom was derived from a wild barley from the fertile crescent crossed to cultivated barleys. With oats, there are no mediterranean adapted land races and precious few people have looked at using wild oats from the fertile crescent in a systematic effort to broaden the genetic base of oats for mediterranean environments.

3.5. Are farmers getting the information they need to reliably choose new varieties?

What is the data quality at point of release? Some varieties have only breeding company data at point of release (even though one year of NVT trials may have been conducted). To examine this question, I examined the 2025 Sowing Guide for South Australia. The table below shows the important variety trait information that is missing (Figure 27). As a practicing farmer, I now find this guide does not provide me the information I require to make good choices of variety. I cannot afford to find out that the wheat variety I have chosen was susceptible to sprouting after I have sown half my wheat crop to that variety. Nor can I afford to discover late that my chosen barley variety was susceptible to head loss after a big wind event, or that my canola variety produced very low oil in a dry year.

This problem will need a whole of industry response to fix. SAGIT, GRDC, NVT, state agencies and the breeders will have to work together to solve this. Some traits are measured in NVT, but the data is not presented whereas other traits are not measured in NVT.



Crop	Missing information
Wheat	Sprouting, coleoptile, HW, Screenings
Barley	Lodging, Head loss, Sprouting, Coleoptile, HLW, Screenings
Canola	Shattering, oil, Yield across herbicide groups, Lodging,
Oats	Lodging, shattering, Hay Y & Q, HLW, Screenings

Figure 27; Traits missing from current South Australian crop sowing guides for 4 field crops

3.6. Do plant breeders take enough risks?

The allocation of resources in plant breeding programs is always a complex issue. How much effort goes to crossing the best x best and hoping for the best? How much to introducing a new trait? How much into using landraces or wild relatives? In this section, I considered 13 cases where I took a risk to introduce a new trait as a breeder or as a research administrator over a 50-year period and looked back later to see if the risk was warranted.

Table 10 ; "Risky" breeding objectives sought in my career across oats, barley and maize and in the case of vetch as a trustee of the funding body. Traffic lights indicate degrees of success from green = very successful, yellow – breeding successful but no commercial impact yet, red – breeding failed, no commercial value, blank ???? – too early to tell. The comments column lists key collaborators in the effort.

Type	Traits	Success?	Comments (collaborators)
Dwarf oats	Dw6 from Canadian parent into "Echidna"," Dolphin" et al.		
Hay Oats	Hay yield, quality and eaf area duration in "Wintaroo", "Brusher"		
Naked oats	High oil high feed value hulless oats in " Bandicoot"		
Herbicide tolerant oats	Tolerant to Group 1 grass herbicides in SAVENA 1 and Avena sterilis SAS 1		
Wild oat introgression	CCN tolerance and reistance in "Potoroo"		
Canadian malt quality barley	Rapid modification, high DP and extract in "Flagship"		Waite team
Naked barley	High feed quality in "Torrens" et al.		Amanda Box
Boron tolerant barley	4 genes transferred from land race to boron tolerant breeders lines		Steve Jeffereis, Peter Langridge
Managanes efficient barley	2 genes from Japanese parent into "Maritime" barley		Reg Lance, Jim Lewis, Robin Graham
Wild barley introgression	Stress tolerance and yield in "Fathom" barley		Jason Eglinton
Frost tolerant barley	Tried to find genetic variation		Jason Reinheimer et al.
Cold tolerant maize	Select for early germination in cold soils	??????	
Toxin free vetch	CRISPR edit of neurotoxin locus	??????	Iain Searle

Some cases were very clearly successful

- **Dwarfing genes in oats** – the introduction of the Dw6 gene into Austrlian oats (eg Echidna and Dolphin released in 1984) markedly reduced lodging and shattering and provided a 25% yield increase.
- **Release of CCN resistant hay oats** Wallaroo and Marloo and then varieties with a better leaf disease and green leaf area duration such as Wintaroo laid the foundation for the export fodder industry in SA
- **The use of the wild oat germplasm** Avena sterilis Cc 4658 provided a big lift in CCN tolerance in oat varieties eg Potoroo (Figure 28)
- The work by multiple groups and people to breed a **barley tolerant to manganese deficiency** resulted in the variety Maritime, which performed very well in those areas (and more widely) reaching peak adoption of over 20% of SA

- Jason Eglinton's work on **introgression of *Hordeum spontaneum* germplasm** in the SA barley progrram resulted in the release of Fathom – a variety widely regarded as the most stress tolerant variety of its era (Figure 28)

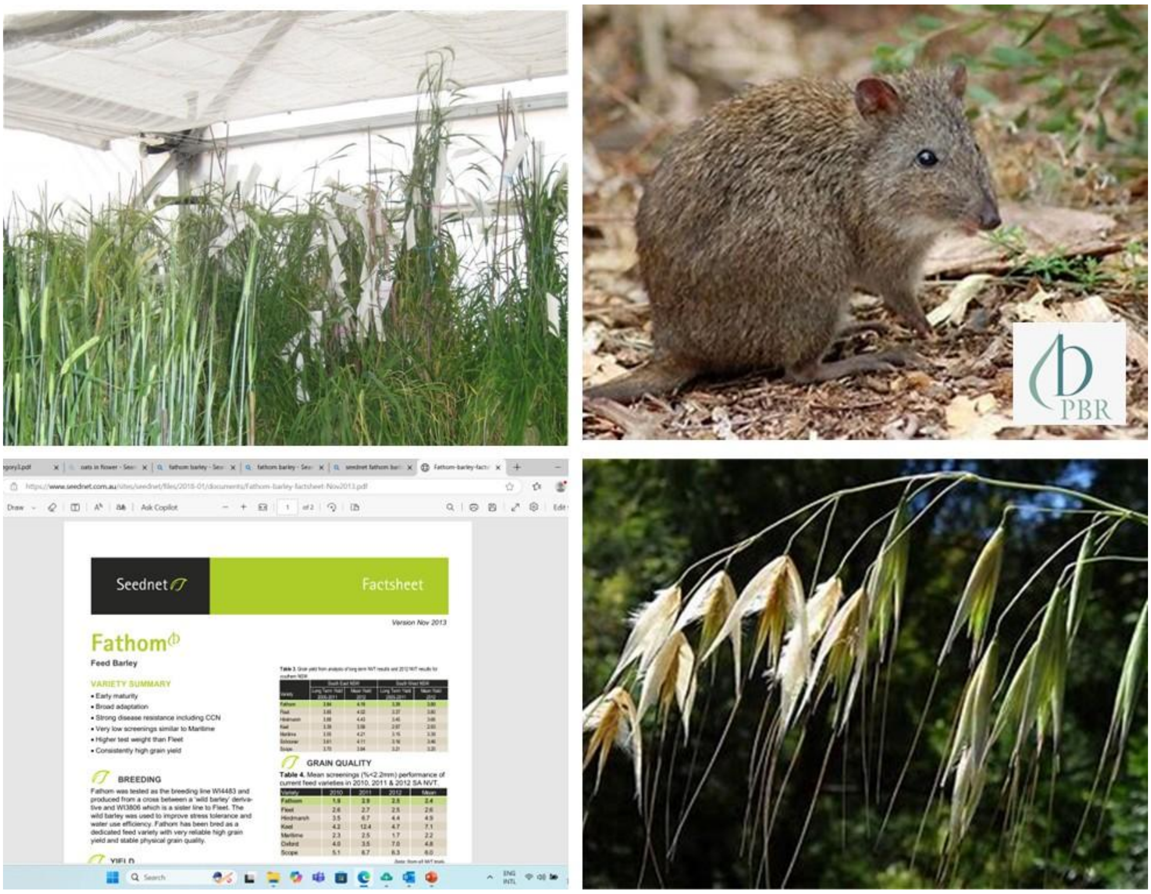


Figure 28 Two examples of using wild germplasm in breeding – in the left hand columns Hordeum spontaneum used to breed the stress tolerant Fathom barley and in the right hand columns Avena sterilis used to breed Potoroo oats resistant to cereal cyst nematode

So, that is the good news! However, there are multiple cases where the breeding work was successful but little commercial value was created....

- **Introgression of high malt quality from Canadian varieties.** In the 1990's, the Australian malting barley industry both admired and coveted the quality profile of Canadian varieties such as Harrington and Manley. All of the Autralian breeding programs worked to introgress these traits with "Hamelin" released from WA and "Flagship" releassed in SA. In the case of Flagship, it had acceptable yield, a good disease package and excellent malt quality. However, one of the key loci conferring high malt quality also conferred a high propensity to sprout. In the first year of release, Flagship suffered from pre harvest sprouting and hence farmers enthusiasm waned quickly. Genes which modify the germination of Flagship types would allow the industry to benefit from this quality type one day ....

- **Herbicide tolerant oats.** The SA oat Program discovered tolerance to the grass herbicide diclofop methyl (Hoegrass®) in 1979 in diploid and hexaploid oats and worked on it for a number of years before presenting findings to Hoechst AG (the patent holder) in Frankfurt in 1985. They were horrified and wanted the effort abandoned IMMEDIATELY because of the risk they saw with wild oats evolving resistance to diclofop after hybridising with cultivated oats and ruining their wheat market. The sequel to this was the discovery of the wild oat *Avena sterilis* ecotype "SAS1" by the Steve Powles group in the late 1980's. This line had a much higher level of tolerance toa wider range of Group 1 herbicides. We crossed this to leading oat varieties like Echidna and Mortlock and found the trait to be highly heritable and provide excellent tolerance to herbicides like haloxfop at rates that would control wild oats, brome grass, barley grass and volunteer cereals (Figure 29). Remarkable after a 20 year lull, four parties have expressed interest in this trait over the past three months!

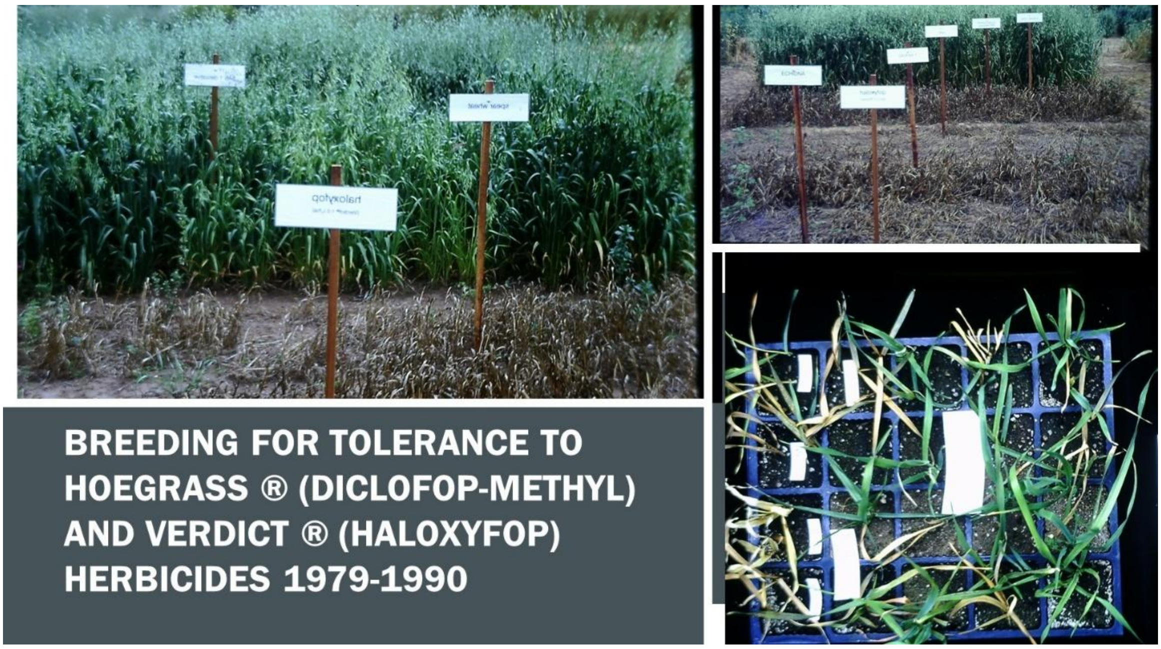


Figure 29; Two field screening trials and a seedling tray of F2 plants from a cross between tolerant wild oats and cultivated oats where the oats were sprayed with haloxyfop

- **Naked (Hull – less) oats.** "Normal" oats have a husk which envelops the seed kernel which can wiegh 25-30% of the total weight which is high in fibre. For human food applications, the husk must be removed (and discarded). While useful in ruminant rations, it severely depresses energy values in rations for monogastrics. The husk can be removed by two genes which prevent the husk from lignifying and hence it is blown away in the harvest process. We imported a Canadian naked oat ("Terra") and spent 12 years crossing the trait into Australian adapted material to the point where a reasonable variety was produced

("Bandicoot") which produced naked grain at a yield level equivalent to hulled oat yield of Echidna. However, the hulless trait exposes silicon impregnated trichomes (hairs) on the kernel which are liberated during harvest to produce the most irritating dust (Figure 30). Farmers (despite having air conditioned cabs), grain handlers and processors found that too much to bear and so naked oats were consigned to history. Thankfully there was no social media in 1990– otherwise we would have been the most unpopular people in southern Australia (due to itchiness of naked oats). One Canadian breeder (Dr Vern Burrows a very talented albeit follicly challenged breeder with a sense of humour!) proposed breeding hulless oats with low trichomes to solve the itchiness problem but thus far nothing commercial is available in Australia.

Figure 30 ; Naked oat montage – clockwise from top left – naked oats; the oat grain showing a kernel with trichomes; Asked CoPilot to draw me a naked oat breeder but it declined; The "Vern Burrows gene" for naked oats with lower hairs on the kernel

- **Naked barley.** Amanda Box within the SA barley program did an excellent job producing naked or hulless barley. This too failed to gain commercial acceptance not because it was itchy, just the market premiums proved insufficient to compensate for lower yield witht the husk removed.
- **Boron tolerant barley.** Steve Jefferies did an excellent PhD thesis mapping the genes for boron tolerance and we crossed the boron tolerant material into our germplasm and selected for tolerance with biossays and molecular markers. This produced agronomically reasonable lines which showed no symptoms of boron toxity at Minnipa when intolerant backcross derived sibs went black with

the lesions associated with boron toxicity. The resulting yield difference ? 0.0%. A staggering result.

In the following case, no genetic variation was found;

- **Frost tolerant barley.** Around 2000, we initiated a project to breed for frost tolerance. This involved designing germplasm search criteria from gene bank collections, developing phenotyping systems, choosing field sites and conducting field trials. This was always a high risk project but with such a big payoff waiting a good result, worth a punt. The result so far? No frost tolerant barley.

The jury is still out on the final two projects;

- **Cold tolerant maize for early spring sowing in southern Australia.** Maize is a huge crop worldwide but is just not adapted to our southern Australian, winter cropping systems. It will not germinate at low soil temperaures and its growth is severely retarded by low temperatures. I imported germplasm from the CIMMYT gene bank chosen with the curator, that might have tolerance to low temperatures, via the Biloela Genebank. I grew these and intercrossed them in 2011 for 3 seasons at Pinery in South Australia (Figure 31). Material was found that would germinate from late August plantings and that would produce reasoable plants and seed set. The best lines and the original material were lost in the Pinery fire of 2015.

Figure 31 ; My Maize selection nursery at Pinery in 2011 when sown "early" into cold soil. Material derived from CIMMYT germplasm. Cobs as harvested with very little supplemental irrigation

- **A toxin free vetch.** Vetch is well adapted to the dry, calcareous regions of southern Australi but its end uses are limited by a neurotoxin which is found in the grain. I am a member of the SA Grain Industry Trust and we have supported a project led by Dr Iain Searle in the University of Adelaide to use CRISPR technology to switch off the gene responsible for toxin production. This would open new uses for vetch grain. The project is in its infancy but is showing promising signs ......

So, what is the conclusion from these epxeriences ....

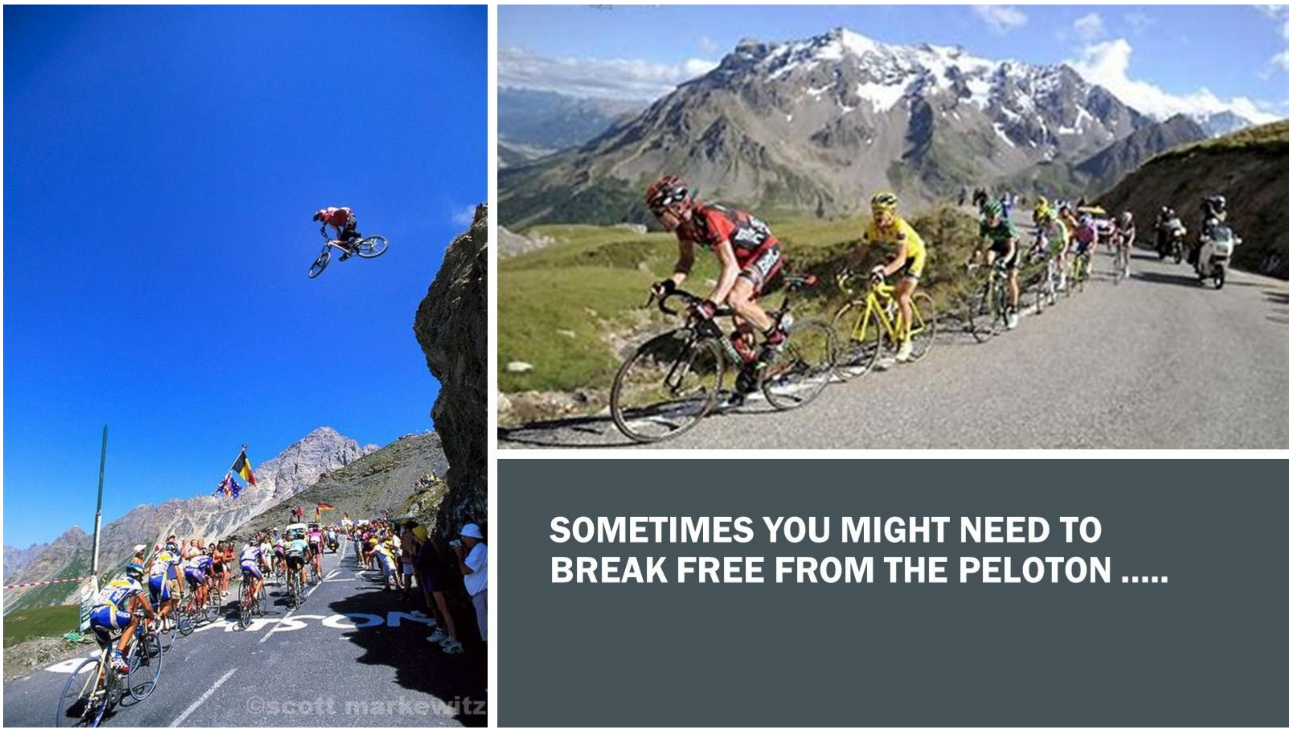


Figure 32 ; Sometimes breaking free of the peloton yields great wins in plant breeding

Thankyou to the following organisations who have employed me and allowed me to have such an interesting and rewarding career;

- SA Department of Agriculture / SARDI
- University of Adelaide
- AGT
- CIMMYT
- GRDC
- SA Grain Industry Trust

List of acronyms

1. AB QTL - Advanced backcross Quantitative Trait Loci breeding system
2. ABTS - Australian Barley Technical Symposium
3. AGROBASE - Agricultural Research Database developed by Agronomix Software, Canada
4. AGT - Australian Grain Technologies P/L
5. BYDV - Barley Yellow Dwarf Virus
6. CCN - Cereal Cyst Nematode
7. CIMMYT - International Maize and Wheat Improvement Center
8. CRISPR - Clustered Regularly Interspaced Short Palindromic Repeats
9. CSIRO - Commonwealth Scientific and Industrial Research Organisation
10. DPI - Department of Primary Industries
11. EPR – End Point Royalty – a system of collecting breeders royalties enabled by changes to the PBR act of 1994 in Australia
12. GM - Genetically Modified (Organism)
13. GRDC - Grains Research and Development Corporation
14. IT - Information Technology
15. MBQIP – The "Malting barley quality improvement program" – a joint venture between University of Adelaide, SARDI, Vitorian DPI, SIRF, Malting and Brewing Companies, GRDC which started in 1992
16. NVT - National Variety Trials funded by GRDC to evaluate field crop varieties across Australia
17. PBYSYS - Plant Breeding System written in Fortran IV implemented on Cyber mainframe by Waite Campus staff of University of Adelaide in late 1960's and early 1970's to design, manage and anlyse plant breeding experiments
18. PBR – Plant Breeders Rights (Australia 1994)
19. PC - Personal Computer
20. POTS - Plastic Tube Screening system for testing varietal resistance to cereal cyst nematodedeveloped by SARDI staff late 1980's/early 1990's
21. PVR - Plant Variety Rights (Australian legislation 1987)

22. QTL - Quantitative Trait Loci
23. SA - South Australia
24. SAGIT - South Australian Grain Industry Trust
25. SARDI - South Australian Research and Development Institute
26. UK - United Kingdom
27. WA - Western Australia

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