Crop simulation for farming systems: from phenotype to farm

Julianne Lilley

CSIRO Agriculture and Food, GPO Box 1700, Canberra ACT 2601, Australia

Abstract

The value of simulation models to assist (i) crop breeding, (ii) agronomic research, and (iii) farm decision-making has been demonstrated in many studies (Holzworth et al. 2014; van Ittersum and Donatelli 2003). In the Australian grains industry several modelling platforms have been developed for a variety of needs, with APSIM (Agricultural Production Systems Simulator) the predominant tool (Robertson et al. 2015). APSIM allows models of crop and pasture production, residue decomposition, soil water and nutrient flow, and erosion to be configured to simulate soil and crop management for various production systems using conditional rules (Holzworth et al. 2014). The model has been well validated in many studies and shown to accurately capture the effects of variability in climate, soil type and management for a range of crops. Linking of APSIM and GRAZPLAN farming systems models (Moore et al. 2007) has also enabled assessment of whole farm issues associated with crop and animal production as well as environmental impacts of a range of practices on mixed farms (Lilley and Moore 2009, Robertson et al. 2009).

In this paper I discuss application of the APSIM model at three scales; (i) the value of individual genetic traits within the context of the farming system, (ii) single or multiple changes to management practices for individual crops over multiple years and locations, and (iii) the effect of a management or genotype change, in the context of multi-year sequences, or multiple paddocks across the whole farm. Case studies at each scale will demonstrate the value of simulation modelling as an integrated tool in modern farming systems research.

Benefits of modified root traits for crop water uptake

Simulation studies offer the opportunity to hypothetically modify genetic characteristics of crops to assess the value of a trait, without modification of other linked traits, effectively testing “virtual isolines” which differ only in the modified trait. Water extracted from deep soil layers (below 1.2 m) can be extremely valuable to grain yield in terminal drought (Kirkegaard et al. 2007; Lilley and Kirkegaard 2007), but evidence of the benefits across variable soils and seasons is required to derive a value-proposition for breeding. Simulation studies were conducted to investigate the benefits of modifying roots to increase the rate and extent of soil exploration and the rate of soil water extraction (Lilley and Kirkegaard 2011, 2016). The study included locations varying in rainfall distribution from equi-seasonal southern NSW, winter-dominant WA, and summer dominant Qld. Maximum root depth varied with location and season. Where soil profiles were wetter (due to wetter seasons, locations, paddock history), rooting depth increased, while the inability of roots to penetrate dry soil restricted rooting depth in dry seasons. Soil exploration could also be modified by changing sowing dates. Later sown fast-developing cultivars had shallow roots, while early-sown long-season cultivars had deeper roots and increased water uptake. In the third study in the series, simulations were set to run continuously without soil resetting to investigate legacy effects (Lilley and Kirkegaard 2016). In essence, the study investigated the long-term benefit of sowing cultivars with more effective root systems in every year. The study showed that at sites with shallower soils, which make up a significant area of the Australian cropping zone, the benefits of more extensive root systems were negligible (Table 1). On deeper soils, more extensive root systems were clearly valuable to acquire resources and increase crop yield, but created a legacy of drier soil for subsequent crops which reduced the average benefit at some locations and created a negative response in some years. In Dalby, Qld, where wheat crops are grown on stored water (due to the summer dominant rainfall), increasing soil water extraction left the soil in a drier state for subsequent crops and long-term average yield decreased. The work showed that cultivars with more extensive root systems provided yield benefits in wetter seasons and locations while benefits were rare in dry environments. On all soil types in Australia’s southern cropping zone, changes in farm management practices to earlier sowing of slower-maturing crops increased water uptake and average yield. Simulations demonstrated that phenotypic differences in root traits *per se* resulted in smaller impacts on soil exploration and potential yield than duration of crop growth (root and shoot) and water uptake, which was determined by sowing date and rate of phenological development of the cultivar.

Table 1. Mean annual rainfall, final rooting depth at maturity and yield of wheat crops (standard cultivar, conventional sowing date) for 100 years of continuous simulations at eight sites. Mean extra water uptake and yield achieved by simulating cultivars with either modified roots or earlier sowing is also shown. Adapted from Lilley and Kirkegaard (2016).

Location	Mean annual rainfall (mm)	Mean final root depth (m)	Extra water extraction (mm)		Baseline mean yield (t ha^{-1})	Mean yield benefit (t ha^{-1})	
			Modified roots	Early sowing		Modified roots	Early sowing
Wongan Hills, WA	369	2.0	17	29	4.01	0.24	0.63
Dalby, QLD	665	1.4	3	14	3.73	-0.03	-0.26
Cootamundra, NSW	619	1.8	16	31	5.66	0.25	0.75
Ardlethan, NSW	471	1.6	10	26	4.90	0.15	0.54
Harden, NSW	605	1.6	7	26	5.60	0.10	0.40
Paskeville, SA	602	1.0	2	22	3.73	0.03	0.08
Esperance, WA	517	1.0	4	26	3.91	0.06	0.34
Birchip, Vic	365	0.7	3	24	3.08	0.05	0.12

Synergies from multiple changes to management

In recent years, increasing farm size, changing seasonal conditions, improved fallow management and seeding equipment, and the availability of new varieties with a wider range of phenological responses have enabled a wider range of sowing date recommendations for wheat and canola in southern Australia (Fletcher et al. 2016, Hunt 2017, Kirkegaard et al. 2016a, Lilley et al. 2019). Kirkegaard and Hunt (2010) used simulation to extrapolate experimental studies which investigated modified farm management practices such as: (i) managing the summer fallow to control weeds and retain stubble; (ii) use of break crops in the crop sequence; (iii) managing in-season water use by sowing earlier using minimum or zero tillage, with cultivars which can emerge from deeper in the soil (Kirkegaard and Hunt 2010, Rebetzke 2007). Their simulation analysis showed that at Kerang in southern Victoria, the long-term average wheat yield was 1.6 t/ha under conventional practices. Analysis of various changes to several individual management practices resulted in an increase in long-term average yields between 0.2 and 0.8 t/ha, depending on the intervention. However the synergistic effects of combining all 6 practices led to a long-term average yield of 4.5 t/ha, a 3-fold improvement in yield. Similar synergistic effects from optimal combinations of cultivar genotype and management strategy were simulated at 9 sites across a range of rainfall zones, with a mean yield increase of 42 % relative to the baseline strategy (Flohr et al 2018). The yield improvement was attributed to increased storage of rainfall in the soil during the summer fallow and more efficient use of available water in most seasons. The pre-experimental modelling was confirmed by five years of experimental work (Kirkegaard et al. (2014) and fallow management practices which maximise water and N and provide earlier sowing opportunities have been widely adopted in the southern Australian cropping zone.

Early sowing increases wheat yields despite recent climate change

Since all paddocks on an Australian farm are not sown on a single date due to logistical limitations, a simulation study was conducted which considered the effect on the average farm yield if sowing the total area of wheat on a farm took 20 days (Hunt et al. 2019). In that context, the study compared sowing of wheat in the "current-practice" sowing window with sowing wheat 3 weeks earlier if the opportunity arose, using a slower developing cultivar which flowered at the same time as a conventional cultivar. The results of the 2 sowing strategies were compared at 23 locations from a diverse range of Australian wheat-growing environments from 1996 to 2015. In the current-practice sowing strategy, only a fast-developing cultivar was sown, commencing when the predicted seedbed moisture was adequate within the appropriate sowing window for the location, usually after mid-May. In the early-sowing strategy, the slow-developing cultivar was sown from 15 March when there was adequate seedbed moisture, and was changed to the fast-developing cultivar once the sowing window for current practice was open. In southern and western Australia, adopting the early sowing system substantially increased the predicted average farm wheat yield at most locations (mean increase 0.8 t/ha or 25%, range 0.1-2.7 t/ha; Figure 1). The yield increase resulted from both the yield advantage of the slow-developing cultivars sown early, and the greater proportion of fields sown at an optimal time with fast developing cultivars over the rest of the farm area. In the northern areas of the cropping zone, early sowing with slower developing cultivars decreased average farm yields. There was significant seasonal variation in the yield response, with yield reductions occurring in some years at all locations. The highest mean yield benefit, and greatest inter-annual variability was recorded for locations with average April to October rainfall greater than 270mm. Spatially interpolating the optimal strategy across the Australian winter cropping areas showed a mean national benefit of 0.54 t/ha (s.d. = 0.38) (Hunt et al. 2019). These and other studies demonstrating the value of early sowing of wheat in southern Australia have led to significant changes in sowing date and plant breeding companies are now developing long season wheat cultivars for commercial release.

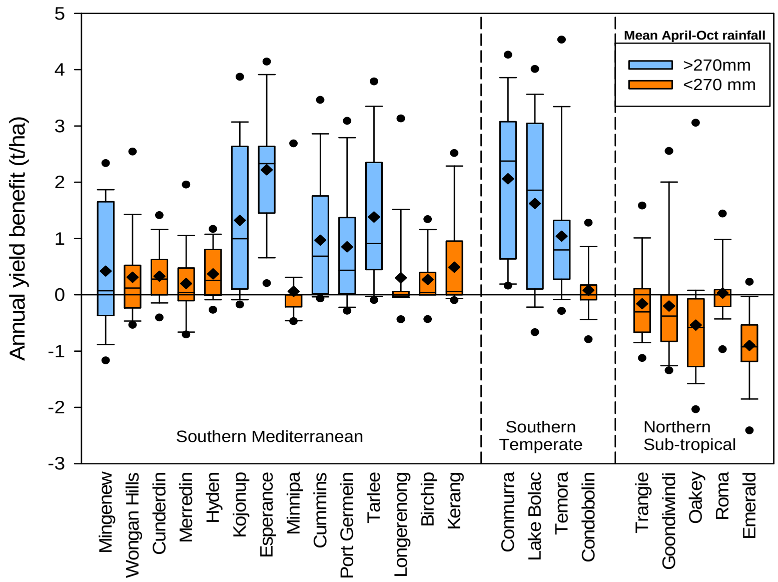

Figure 1. Variability in simulated annual yield benefit (t/ha) achieved by sowing wheat earlier using a novel, slower-developing cultivar when the opportunity arises. Boxes are coloured according to mean April to October rainfall and show median (line), mean (diamond), 25th and 75th (box), 10th and 90th (bars), 5th and 95th percentiles (circles). Adapted from Hunt et al. 2019

Defining the optimal start of flowering in canola

Recent trends in agronomic practice towards earlier sowing systems (Kirkegaard et al. 2016b, Fletcher et al. 2016) highlighted the need to better define the optimal start of flowering for canola. We used simulation analysis to show that the range of optimal start of flowering dates (OSF) to maximise yield, was a period when the combined effects of frost, heat and water stress on yield are minimised. The OSF was defined for 77 locations, covering Australia's cropping zone (Lilley et al. 2019; Figure 2). While APSIM has been used here to integrate abiotic stresses on crop production, consideration of the risk of biotic stress was also critical as infection by blackleg (*Leptosphaeria maculans*) in the upper canopy increased on crops flowering too early (Sprague et al. 2018). The analysis provided recommendations to growers to match sowing dates with varieties of suitable phenology (grdc.com.au/10TipsEarlySownCanola) and is especially important for crops sown earlier in the traditional sowing window (late April to early May). To assist grower decisions on sowing date and cultivar combinations at any location, we are developing an interactive App which incorporates the historical weather record. Validated cultivar parameters are fundamental to the accuracy of the App and we are currently working with breeders and geneticists to better understand genetic control of phenology so that information on cultivar phenological response to the environment is available at the time of cultivar release.

A recent study by Meier et al. (2019) used an APSIM analysis to provide recommendations of canola management decisions beyond sowing date and variety optimised for different rainfall outlooks (below-, average and above-average rainfall) at several locations in the eastern Australian cropping zone. The study included a factorial combination of sowing date, cultivar choice (hybrid or OP; TT or non-TT; fast, medium, or slow rate of phenological development), rate of N application and plant density. Results were considered in the context of the date of a sowing opportunity and the seasonal rainfall outlook and used a regression tree approach to assess economic risk associated with a range of agronomic decisions. The study showed that optimal management varied according to the date of a sowing, and both N rate and phenology type (fast, slow rate of development) had a significant effect on gross margin.

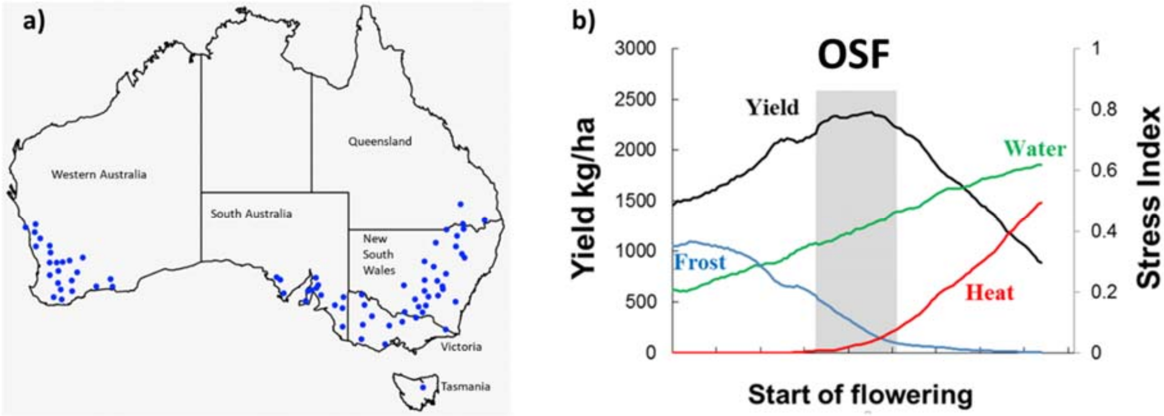

Figure 2. a) The 77 locations across the Australian cropping zone where the optimal start of flowering (OSF) for canola was determined, and b) relationship between start of flowering, and long-term average simulated potential yield (limited by frost and heat; black) frost (blue) and heat (red), and water (green) stress indices. OSF (grey) is the period for the start of canola flowering which achieved ≥ 95% of the long-term average peak yield. Adapted from Lilley et al. (2019).

Yield Gap Analysis

APSIM was used to conduct a comprehensive national assessment of water-limited yield potential for several crops including wheat, canola, barley, sorghum and major pulse crops, and these yield values were compared with current yields on Australian farms (Hochman et al. 2016; Lilley et al. 2016; yieldgapaustralia.com.au). For canola, actual yields achieved by farmers for each year from 1996 to 2017 were aggregated for 164 regions within the cropping zone where canola production covered more than 1000 ha (Lilley et al. 2016). We used APSIM simulations to determine water-limited yield potential at 4,043 weather stations using up to three dominant soil types per weather station, and management rules ensured yield was only limited by climate and water availability. These simulated potential yields were similar to the average yields of elite varieties under experimental conditions at National Variety Trial sites in the period 2005 to 2014 (2.5 to 3.0 t/ha; Kirkegaard et al. 2016b). Within each region, the independently estimated mean annual actual yields were compared to simulated yields as either absolute or relative yield gap. The Yield Gap Australia website is an interactive map-based tool to visualise the extent and geographic distribution of yield gaps and enables growers and advisers to benchmark their own farm against potential and local yields. For canola, the average actual farm yield in Australia from 1996 to 2012 was 1.16 t/ha, while average simulated potential yield was 2.23 t/ha, resulting in a yield gap of 1.07 t/ha. The analysis showed that Australian grain growers typically achieve only half the yield potential of their crops, a shortfall which has been attributed to biophysical, economic and social factors (Hochman et al. 2016).

Dual purpose cropping

On mixed farms, early sown cereal and canola crops can also be grazed during the vegetative period, providing further opportunities to increase farm productivity and profitability and to manage risk (Bell et al. 2015a; Kirkegaard et al. 2008; Dove and Kirkegaard 2014; Sprague et al. 2015). Simulation studies into dual-purpose wheat and canola have demonstrated the economic potential of the grazed fodder as well as the harvestable grain in high and medium rainfall environments (Bell et al. 2015b; Lilley et al. 2015). Season to season variability in grain yield (Fig 3b) was much greater than for fodder production (Fig 3a), and optimal sowing date for maximum fodder and grain production was related to the optimal flowering period defined above (Flohr et al. 2017, Lilley et al. 2019). Early sowing dates enabled production of more biomass during warmer months (Fig 3a), and higher N application significantly increased fodder availability (Fig 3c), as well as grain yield, with the largest benefits for earlier sown winter cultivars. Grazing opportunities increased for earlier sown winter cultivars while fast developing spring cultivars provide small but potentially useful grazing opportunities. The likelihood of receiving an early sowing opportunity varied from <30% of years in parts of Western Australia with more opportunities in eastern Australia (up to 80%; Lilley et al. 2015). Including dual purpose crops into a farm increased whole farm profit around $100 per farm ha when the extra fodder, grain value and benefits to the pasture from spelling while stock grazed crops were taken into account (Bell et al. 2015a). Dual purpose use of canola has now been adopted in every state in Australia.

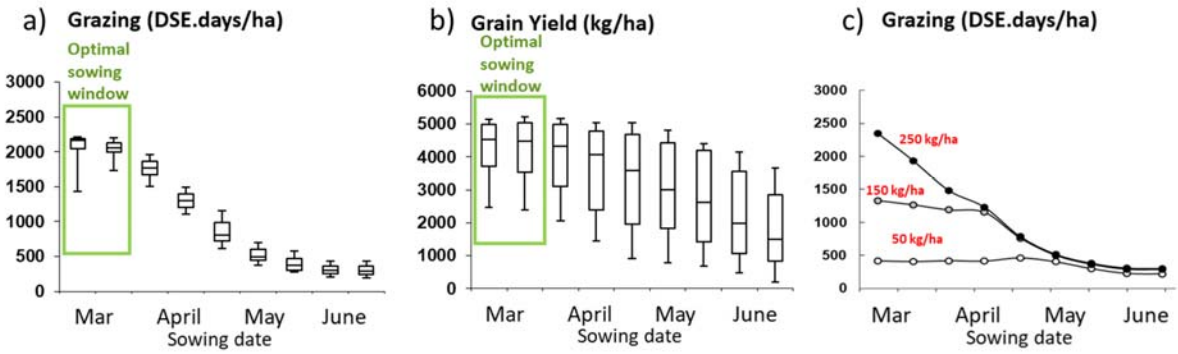

Figure 3. Variability in simulated a) grazing days and b) frost-heat adjusted grain yields in response to sowing date and c) response of average grazing days to N fertiliser application for a winter canola cultivar at Young, New South Wales over a 50-year period. Adapted from Lilley et al. (2015).

Trade-offs between productivity and ground cover in mixed farming systems

Inadequate ground cover because of over-grazing of pastures, fallowing and stubble burning or excessive cultivation exposes land to degradation, yet maintaining cover can constrain productivity. The AusFarm model was used to investigate the impact of modifying stock and crop management practices on the trade-off between farm productivity (grain, meat and wool) and ground cover levels (Lilley and Moore 2009). Management of mixed farms was represented for simulated farms at five locations (426–657 mm mean annual rainfall) in the Murrumbidgee catchment of New South Wales. The impact on ground cover and farm productivity of (1) retention of wheat stubble, (2) altering stocking rate (up to +/-25%) and (3) moving stock elsewhere on the farm when the ground cover fell below a given threshold was examined at each location. Retention of wheat stubble increased long-term mean cover by 1–4%, with little impact on grain yield. Stock management practices that increased minimum cover levels also reduced farm productivity and whole-farm profit. Altering stocking rate had the largest impact on cover at all locations (up to 4%), while confining stock to a 3 ha feeding lot was the most effective strategy to maintain ground cover and minimise financial loss. Seasonal conditions were the dominant effect on the mean farm cover (mean range 64–98%), and cover fell as low as 43–57% in severe droughts, depending on location.

Conclusion

Modelling has provided a tool to quantify long-term impacts of changes in agronomic practice which cannot readily be determined from experiments alone. It can demonstrate productivity, economic risk, and environmental consequences of these interventions within the context of farming systems, giving confidence in the recommendations to Australian growers. Dual purpose cropping of winter wheat and canola can increase farm income by $100/ha and is now practiced in medium and high rainfall areas of all southern states. Higher N rates suggested for early sown winter canola in the high rainfall zones have proven profitable. Canola growers across south-eastern Australia are finishing, rather than starting to sow by 25 April, leading to an average yield increase of 0.3 t/ha (Greg Condon, pers comm). Most growers in southern Australia now practice strict summer fallow weed control to maximise water and N and provide earlier sowing opportunities, and wheat breeding companies are developing slower maturing cultivars with long coleoptiles, specifically adapted to early sowing opportunities. These are clear examples of the significant industry impact that can arise when simulation modelling is embedded with effective farming systems agronomy teams.

References

Bell LW, Dove H, McDonald SE, Kirkegaard JA (2015a) Integrating dualpurpose wheat and canola into high-rainfall livestock systems in southeastern Australia. 3. An extrapolation to whole-farm grazing potential, productivity and profitability. Crop and Pasture Science 66, 390–398.

Bell LW, Lilley JM, Hunt JR, Kirkegaard JA (2015b) Optimising grain yield and grazing potential of crops across Australia’s high-rainfall zone: a simulation analysis. 1. Wheat. Crop Pasture Science 66, 332-348.

Dove H and Kirkegaard JA (2014) Using dual-purpose crops in sheep-grazing systems. J Sci Food Agric 94:1276-1283

Fletcher AL, Lawes R, Weeks C (2016) Crop area increases drive earlier and dry sowing in Western Australia: implications for farming systems. Crop and Pasture Science 67, 1268-1280.

Flohr BM, Hunt JR, Kirkegaard JA, Evans JR (2017) Water and temperature stress define the optimal flowering period for wheat in south-eastern Australia. Field Crops Research 209, 108–119.
Flohr BM, Hunt JR, Kirkegaard JA, Evans JR, Lilley JM (2018) Genotype x management strategies to stabilise the flowering time of wheat in the south-eastern Australian wheatbelt. Crop and Pasture Science 69, 547-560. doi:10.1071/CP18014
Hochman Z, Gobbett D, Horan H, Navarro Garcia J (2016) Data rich yield gap analysis of wheat in Australia. Field Crops Research 197, 97-106. doi:10.1016/j.fcr.2016.08.017.
Holzworth DP, Huth NI, deVoil PG, et al. (2014) APSIM - Evolution towards a new generation of agricultural systems simulation. Environmental Modelling and Software 62, 327–350.
Hunt JR (2017) Winter wheat cultivars in Australian farming systems: a review. Crop and Pasture Science 68, 501-515. doi:10.1071/CP17173
Hunt JR, Lilley JM, Trevaskis B, et al. (2019) Early sowing systems can boost Australian wheat yields despite recent climate change. Nature Climate Change 9, 244–247. doi:10.1038/s41558-019-0417-9.
Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water-limited environments. Journal of Experimental Botany 61, 4129–4143.
Kirkegaard JA, Hunt JR, McBeath TM, Lilley JM, et al. (2014) Improving water productivity in the Australian Grains industry-a nationally coordinated approach. Crop and Pasture Science 65, 583-601.
Kirkegaard JA, Lilley JM, Brill RD, et al. (2016a) Re-evaluating sowing time of spring canola (*Brassica napus* L.) in south-eastern Australia – how early is too early? Crop and Pasture Science, 67, 381-397.
Kirkegaard JA, Lilley JM, Howe GN, Graham JM (2007) Impact of subsoil water use on wheat yield. Australian Journal of Agricultural Research 58, 303-315.
Kirkegaard JA, Lilley JM, Morrison (2016b) Drivers of trends in Australian canola productivity and future prospects. Crop and Pasture Science, 67, i-ix.
Kirkegaard JA, Sprague SJ, Dove H, et al. (2008) Dual-purpose canola – a new opportunity for mixed farming systems. Australian Journal of Agricultural Research 59, 291-302.
Lilley JM, Bell LW, Kirkegaard JA (2015) Optimising grain yield and grazing potential of crops across Australia's high-rainfall zone: a simulation analysis. 2. Canola. Crop and Pasture Science 66, 349-364.
Lilley JM, Flohr BM, Whish JPM, Farre I, Kirkegaard JA (2019) Defining optimal sowing and flowering periods for canola in Australia. Field Crops Research 235, 118–128. doi:10.1016/J.FCR.2019.03.002.
Lilley JM, Hochman Z, Gobbett D, Kirkegaard J, Horan H, Navarro Garcia J (2016) Estimating canola yield gaps in Australia. iCROPM2016. International Crop Modelling Symposium, March 2016, Berlin.
Lilley JM, Kirkegaard JA (2007) Seasonal variation in the value of subsoil water to wheat: simulation studies in southern New South Wales. Australian Journal of Agricultural Research 58, 1115-1128.
Lilley JM, Kirkegaard JA (2011) Benefits of increased soil exploration by wheat roots. Field Crops Research 122,118-130.
Lilley JM, Kirkegaard JA (2016) Farming systems context drives the value of deep wheat roots in semi-arid environments. Journal of Experimental Botany 67, 3665-3681. doi:10.1093/jxb/erw093
Lilley JM, Moore AD (2009) Trade-offs between productivity and ground cover in mixed farming systems in the Murrumbidgee catchment of New South Wales. Animal Production Science 49, 837-851.
Meier E, Lilley JM, Kirkegaard JA, Whish JP, McBeath T (2019) Profitable management packages for canola. Proceedings of the 2019 Agronomy Australia Conference, 25–29 August 2019, Wagga Wagga.
Moore AD, Holzworth DP, Herrmann NI, et al. (2007) The Common Modelling Protocol: a hierarchical framework for simulation of agricultural and environmental systems. Agricultural Systems 95, 37-48.
Rebetzke GJ, Richards RA, Fettell NA, et al. (2007) Genotypic increases in coleoptile length improves stand establishment, vigour and grain yield of deep-sown wheat. Field Crops Research 100, 10–23.
Robertson MJ, Bathgate A, Moore AD, Lawes R, Lilley J (2009) Seeking simultaneous improvements in farm profit and natural resource indicators: a modelling analysis. Animal Prod Science 49, 826–836.
Robertson MJ, Rebetzke GJ, Norton RM (2015) Assessing the place and role of crop simulation modelling in Australia. Crop and Pasture Science 66, 877-893. doi:10.1071/CP16200
Sprague SJ, Graham JM, Brill R, McMaster C (2018). Infection of *Brassica napus* after stem elongation by *Leptosphaeria maculans* (Blackleg): disease progression and yield loss. Proceedings of AusCanola2018.
Sprague SJ, Kirkegaard JA, Graham JM, et al. (2015) Forage and grain yield of diverse canola (*Brassica napus*) maturity types in the high rainfall zone of Australia. Crop and Pasture Science 66, 260-274.
van Ittersum MK, Donatelli M (2003) Modelling cropping systems - highlights of the symposium and preface to the special issues. European Journal of Agronomy 18, 187-197.