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RESEARCH ARTICLE

Socio-psychological and management drivers explain farm level wheat yield gaps in Australia

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Abstract

Achieving sustainable global food security for a rapidly growing world population is one of the greatest challenges of our time. Producing more food efficiently by closing the yield gaps is regarded as a promising solution to address this challenge without further expanding farming land. However, there is limited understanding of the causes contributing to yield gaps. The present study aimed to comprehensively examine three dimensions of the causes for the wheat yield gaps in Australia: farm management practices, farm characteristics and grower characteristics. Computer-assisted telephone interviews of 232 wheat producers from 14 contrasting local areas were conducted. The data collected on these three dimensions were used to develop a comprehensive framework to understand causes of yield gaps. Results reveal significant differences between farms with smaller yield gaps and those with greater yield gaps in relation to farming management as well as farm and grower characteristics. Findings further underline that farms with smaller yield gaps are likely to be smaller holdings growing less wheat on more favourable soil types, are more likely to apply more N fertiliser, to have a greater crop diversity, to soil-test a greater proportion of their fields, to have fewer resistant weeds, to adopt new technologies, and are less likely to grow wheat following either cereal crops or a pasture. They are more likely to use and trust a fee-for-service agronomist, and have a university education. The dynamic relationships between grower characteristics and farm management practices in causing yield gaps are further highlighted through a path analysis. This study is the first to demonstrate that yield gaps are the result of the intertwined dynamics between biophysical factors, grower socio-psychological characteristics and farm management practices. Socio-psychological factors not only directly contribute to yield gaps, but they also influence farm management practices that in turn contribute to yield gaps. Our findings suggest that, to close wheat yield gaps, it is important to develop integrated strategies that address both socio-psychological and farm management dimensions.

Keywords Crop management · Nitrogen fertiliser · Soil type · Wheat · Consulting services · Crop rotation · Technology adoption

1 Introduction

Sustainably producing enough nutritious food for a rapidly growing world population is imperative for future global food security. Increasing crop yields is regarded as a vital pathway to address this challenge while protecting valuable forests, wetlands and grasslands (Cassman et al. 2003; Godfray et al. 2010; Zhang et al. 2016). Indeed, research has shown that, across various crops, significant gaps exist between yields currently achieved on farms and yields that could be potentially achieved by using the best adapted crop varieties with the best current crop and land management practices for a given environment (Fischer 2015; van Ittersum et al. 2013). For example, research at a global scale has found that, by closing yield gaps, worldwide crop production could be increased by 45 to 70% for most major crops (Mueller et al. 2012). Similarly, in Australia, Hochman et al. (2016) found that, from 1996 to 2012, the average wheat yields for dryland cropping (i.e. water-limited cropping) relative to water-limited yield potential was only 50%. Hence, closing such remarkable yield gaps would make a great contribution to global food security without further expanding farming land.

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Fig. 1 Wheat harvest on an Australian family farm. The harvesters were operated by the father and son, while the chaser bin was operated by a permanent farm employee. (Source: Robyn Ferrier)

Closing the yield gap requires not only quantifying its magnitude and location but also identifying the suboptimal management practices and socio-psychological drivers that account for these yield gaps (Anderson et al. 2016; Hochman and Horan 2018). Currently, there is limited understanding of the causes for the gaps, hindering efforts to close them (Anderson et al. 2016). After reviewing the latest research on yield gaps, Beza et al. (2017) argued that, to explain yield gaps, comprehensive information about farm characteristics, farm management, and socio-psychological conditions is required. Unfortunately, published individual studies so far have only focused on particular aspects of the potential contributing factors such as application of nitrogen fertiliser and suboptimal cropping sequences. The present research aims to incorporate the biophysical, management practices and the grower characteristics into an analytical framework to examine the causes of wheat yield gaps at farm level in Australia (Fig. 1). Such an approach can develop a comprehensive framework to identify the underlying drivers of yield gaps. In the present paper, we first outline the key explanatory factors in management, biophysical and socio-psychological attributes proposed by previous research which are reflected through farm management practice, grower characteristics and farm characteristics. We then describe the methodology used to survey grain growers and present the results based on statistical analysis of the survey data, and conclude with a discussion of these results.

1.1 Farm management practice

Management factors have been the most researched in examining yield gaps. For example, application of nitrogen fertiliser, land preparation and soil fertility are found to be significant contributors to yield gaps by most studies (Beza et al. 2017). However, the overall findings suggest that factors explaining yield gaps vary between regions and crops.

Many likely causes of the wheat yield gap in Australia have been proposed. These include temperature extremes, late sowing, low seedling density, insufficient nitrogen and phosphorus nutrition, tillage practices, fallow weeds, lack of control of pests and diseases, and suboptimal cropping sequences (Angus et al. 2015; Angus and van Herwaarden 2001; Beeston et al. 2005; Cornish and Murray 1989; French and Schultz 1984; Hochman et al. 2009, 2014; Hunt and Kirkegaard 2011; Kirkegaard and Hunt 2010; Monjardino et al. 2015; Monjardino et al. 2013; Sadras and Angus 2006; van Rees et al. 2014). More recently, a simulation analysis undertook a systematic investigation of the impacts of these factors at a national level (Hochman and Horan 2018). That study found that, on average, yield gaps expressed as a percentage of water-limited yield (Yw) were 40% due to the average N fertiliser application rate of 45 kg N/ha, 33% due to conventional tillage (where it is still practiced), 26% due to a loss of stored soil moisture as a consequence of suboptimal weed control during the fallow, 12% due to low seedling density and 7% due to a 2-week delay in sowing. A combination of these suboptimal practices is not always additive. Moreover, additional losses of 16 to 26% can be attributed to frost and heat stresses. The remaining yield gap may be explained by uncontrolled biotic stresses such as plant diseases, insects and other pests, in-crop weeds, deficient soil nutrients other than nitrogen, and extreme weather events such as hail, strong winds and floods (Hochman and Horan 2018).

1.2 Grower characteristics

The contribution of grower characteristics to the yield gap has, so far, only been scarcely explored, especially in the developed world (Anderson et al. 2016; Beza et al. 2017). The question of how growers' socio-psychological characteristics contribute to yield gaps is, to our knowledge, yet to be examined. Research on land management has demonstrated that a number of factors influence growers' attitudes and

behaviours, but a clear link between these attitudes and behaviours as well as their effect on yield gaps has not directly been established. For example, a sense of being in control, often referred to as locus of control, has been shown to be a strong predictor of farmers adopting improved land management practices (Leviston et al. 2011; Price and Leviston 2014). A positive self-concept of being an agricultural leader is another variable being explored in relation to farmers adopting sustainable land management practice (Price and Leviston 2014; Quinn and Burbach 2008).

In addition, growers' trusted information sources have been shown to be an important predictor of their attitudes and behaviour, as well as their inclination to adopt agricultural innovation (Arbuckle et al. 2015; Carolan 2006; Price and Leviston 2014). For example, research on growers' support for climatic adaptation showed that the extent to which growers supported adaptive responses to climate change was strongly associated with who they trusted as their information sources (Arbuckle et al. 2015). In Australia, state governments no longer fund farm advisers. There are currently two types of agronomic advisers: fee-for-service or private agronomists who provide advice to their grower clients on a fee for service basis; and agribusiness or retail agronomists who are employed by agribusiness companies who provide advice (mostly without direct charge) to clients who purchase inputs from their employer's company.

Risk perception is another key variable examined in growers' attitudes and behaviour. Uncertainty and risk is an inherent feature of farming. Risk management may reflect growers' sense of personal control over agricultural production. Farmers tend to invest financially to avoid some risk or uncertainty (Khuu and Juerg Weber 2013; Marra et al. 2003). For example, insurance against various unpredictable events such as hail are often taken to protect farm income. A World Bank survey revealed that 50% of Australian farmers purchased a crop insurance policy in 2007 (Mahul and Stutley 2010). Similarly, farm diversification through crop-livestock balance or through growing a diverse range of crops is regarded as important adaptations (Kingwell and Pannell 2005).

Previous research has also explored the role of other demographic characteristics such as age, years of farming and education in technology adoption. While age and years of farming experience are not usually considered to be reliable predictors of technology adoption, there is some evidence suggesting that managers with a university education are more likely to adopt new technologies (D'Emden et al. 2008).

1.3 Farm characteristics

Larger farms are generally considered to benefit from economies of scale leading to higher output per hectare. Family-owned and -operated farms are predominant in the Australian grains sector. While there is a growing trend towards joint venture or corporate farm ownership structures (Lynch et al. 2017), it is unclear if and how this trend is likely to impact farm productivity.

Soil types have been shown to be a key contributor for yield in general. For example, favourable soil orders such as Vertosols and Dermosols are generally less susceptible to physical and nutrient constraints, and thus are able to produce greater yield for all regions in Australia (Isbell et al. 1997). Even though the effect of soil types on yield is already incorporated in water-limited yield modelling (Hochman et al. 2012, 2016), it is not clear whether soil types also contribute indirectly to yield gaps by influencing growers' confidence to invest sufficiently in inputs required to exploit their yield potential.

1.4 The present study

We aim to examine the factors that contribute to the water-limited yield gaps for wheat in Australia. We propose that a clearer understanding of management practices as well as grower and biophysical characteristics underlying the yield gaps will help develop targeted strategies to close them. Unless we can drill down to the causes of yield gaps and identify what ameliorative or adaptive steps can be taken, the risk is that the current situation may be accepted as inevitable and, consequently, no action will be taken.

We hypothesised that differences in yield gaps between different farms are largely determined by differences in farm management practices, as well as farm and grower characteristics. In addition, grower characteristics may influence how farm practices are managed which, in turn, contribute to the yield gap. Factors such as farm size, the proportion of farmland that is cropped, managers' age, experience, and level of education, sources of trusted information, adoption of new technologies, satisfaction with current yields and the degree of perceived control over yield outcomes may impact the yield gaps observed at farm level.

2 Materials and methods

A research survey company that specialises in the Australian grains industry was engaged to conduct a computer-assisted telephone interview of wheat growers. To be eligible, participants had to be the decision-makers of their farms with a minimum cropping land of 200 ha, and their wheat crops were rainfed. In the context of Australian grain growing, less than 200 ha is considered to be 'lifestyle farms' and these growers are not considered to be production oriented.

2.1 Survey regions

Potential participants in this survey were sampled from the Grains Research and Development Corporation's (GRDC)

Customer Relationship Management database. They were drawn from seven subregions (one in Queensland, one in New South Wales, one in Victoria, three in South Australia and one in Western Australia). This strategy was designed to maximise the likelihood of sampling growers with contrasting relative yield (based on the Yield Gap Australia website www.yieldgapaustralia.com.au; Hochman et al. 2016) as well as sampling from a wide range of agro-ecological zones (see Fig. 2). As a result, two neighbouring SA2s (i.e. statistical subdivisions roughly equivalent to shires) with contrasting relative yields ($Y\% = 100 \times$ [15-year average farmer yields / 15-year water-limited yield]; Hochman et al. 2016) were selected per subregion. Note that a high relative yield denotes a low yield gap and vice versa. We attempted to sample up to 20 growers per SA2.

2.2 Farm management practices

The aspects of farm management practice included sowing start and finish date, preceding crops and N fertiliser application, and other crop management practices.

Sowing start date and *finish date* were collected and converted into day of year (e.g. 26 April is day 117). The duration of the sowing window was calculated by the difference between start and finish dates.

Preceding crops and N fertiliser application were assessed by asking participants to indicate, for their wheat crops planted last season, whether these wheat crops followed a cereal crop, a canola or another oilseed crop, a pulse crop, a pasture phase where legumes were dominant (e.g. clover, lucerne), or any other crop types. They were then asked the amount of nitrogen (N) fertiliser per hectare applied to each of these wheat crops. Participants were further asked to indicate how they determined their N fertiliser rate by choosing one of the four statements: ‘You target your estimated crop yield potential when determining nitrogen fertiliser rates’, ‘You set your total fertiliser budget at the start of the season and stick to it’, ‘The nitrogen fertiliser rates are based on your grain protein target’ and ‘You monitor your crop through the season and make decisions on applying nitrogen based on soil moisture, crop growth stage and shoot number’.

Other crop management practices Participants were asked what other crops they grew last season, the proportion of their wheat crop which had a weed problem that they could not control well enough to prevent yield loss, what percentage of their wheat area was soil tested, and whether they had a crop yield map from any of their fields. If they had yield maps, participants were then asked to indicate the extent to which (on a 1 to 5 scale) they agreed with the statement: ‘Crop yield mapping has helped you make management decisions including on fertiliser rates’.

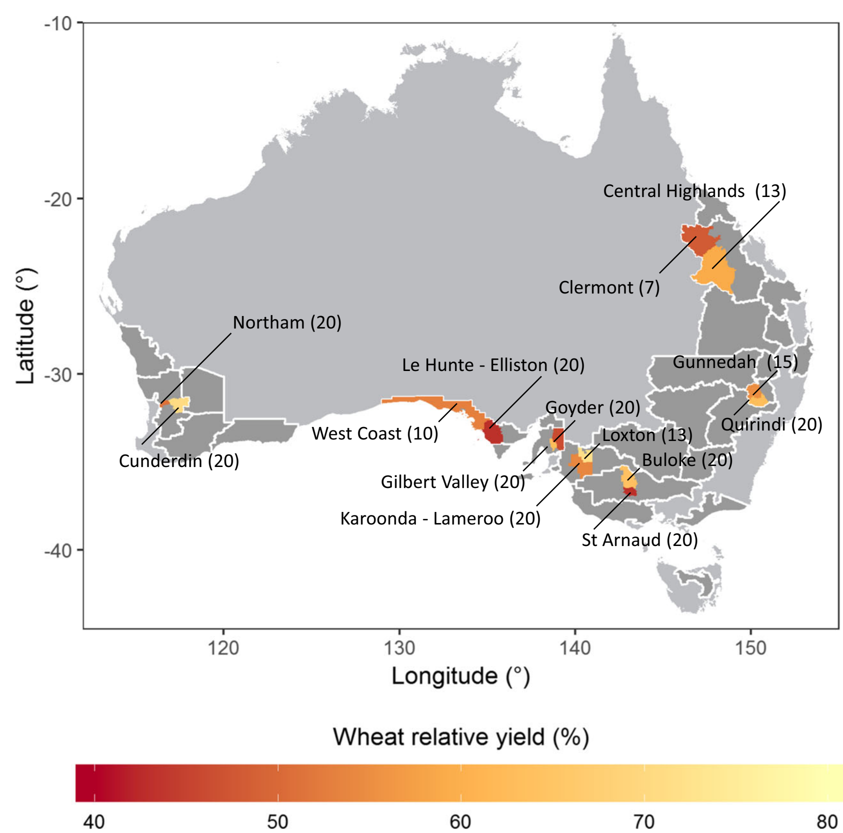

Fig. 2 Locations of surveyed SA2s with contrasting average relative yields and the number of participants in brackets. Note that the relative yield of wheat is indicated by the red-yellow colour gradient. The white borders show the GRDC subregions of the Australian grain zone

2.3 Grower characteristics

Participants were asked for their age, gender, and years of experience in growing crops. Participants were also asked to list the sources of information they used for crop management and planning decisions. They were then asked to indicate their three most *trusted* information sources from a predefined list. In addition, participants were asked to list the *top three practices* which were essential for achieving a good wheat yield according to their experiences.

Risk taking was measured in a number of ways. First, *risk taking in adopting new technology* was measured by participants indicating the extent to which (on a 1 to 5 scale) they agreed with the statement: 'You are always one of the first farmers in your area to adopt new technology'. Second, *risk management* was measured by participants indicating the extent to which they agreed with the statement 'it is important to have livestock on the farm as it allows you to better manage risk' and whether they leased land or machinery to better manage business risk. Third, *risk taking as reflected in crop insurance* was measured by asking whether participants currently purchased insurance for hail or frost; and whether they had, or had considered purchasing, multi-peril or similar insurance for their crops (which was a relatively new product on the crop insurance market at the time of the survey). Fourth, due to Australia's temporally and spatially variable climate, a geographical spread of land under management may be viewed as a risk mitigation strategy. Hence, *risk taking* via *diversification* was measured by asking participants whether they owned or managed farms in locations more than 50 km apart.

Locus of control was measured by asking participants to indicate the extent to which (on a 1 to 5 scale) they agreed with 'You often feel that you have little influence over how the crops perform'. This question is reverse coded so that higher scores indicate stronger sense of control. *Positive self-concept* and *satisfaction with yield* was measured by asking participants to indicate the extent to which (on a 1 to 5 scale) they agreed with 'Other farmers often come to you for agricultural advice', and 'You are satisfied with the wheat yield you have achieved over the past five years', respectively.

Finally, participants were asked to indicate whether they or anyone else involved with management decisions for the farm had ever undertaken a formal university degree course. Participants were also asked whether they used a fee-for-service or private agronomist.

2.4 Farm characteristics

Participants were asked to provide information on the proportion of farm income that they derived from dryland cropping and the average tonnes per hectare harvested from a typical wheat paddock over the past 5 years, the land area for each crop planted last season and whether the farm was a family farm or a corporate farm.

Participants were also asked to provide descriptive information on three main soil types (i.e. the most/the second most/the third most common soil types) in their cropping paddocks by describing the colour (e.g. black, brown, red, yellow), soil texture (e.g. clay, clay loam, sandy loam, sand) and other features (e.g. alkaline, acidic, uniform, deep, shallow), or simply by naming the soil order if they knew it by name. Using the grower soil descriptions and previously documented local soil information (Johnston et al. 2003), the soil types were coded into the following soil orders: Vertosols, Dermosols, Sodosols, Calcarosols, Chromosols, Kandosols, and Ferrosols (Isbell 1996). From herein, these soil orders are referred to as the soil types identified in the study.

2.5 Relative wheat yield

The dependent variable for this study is the relative wheat yield achieved in 2016. This value was calculated by dividing the actual yield by the water-limited yield in 2016 ($Y\% = 100 \times$ [2016 grower reported farm yield / 2016 water-limited yield]). Water-limited yield is defined as the yield of a crop when grown with nutrients non-limiting and biotic stress effectively controlled. It is calculated for optimum or recommended sowing dates, planting density, and cultivar maturity. Growth is also limited by soil type especially rooting depth and water-holding capacity, as these influence availability of water to crops. Water-limited yield is best determined by a locally validated crop simulation model (van Ittersum et al. 2013). A higher relative yield is, therefore, indicative of a lower yield gap. The actual yield was reported by participants for the 2016 season in the survey. The water-limited yield was updated from previous estimations across the Australian grain zone, using the APSIM simulation model (Holzworth et al. 2014) which is well validated for wheat in Australia (e.g. Brown et al. 2014) at about 4000 weather stations and up to three soil types per weather station (Hochman et al. 2016). This method provides a continuously mapped surface of water-limited yield, which can be applied to any map location in the Australian grain zone. For the present study, the water-limited yield is calculated as the average water-limited yield of the area defined by the farm postcode and the performance of each of the farm's three soil types within that postcode. We assumed a weighting of 60% for the dominant soil type, 30% for the next most dominant soil type and 10% for the third soil type.

2.6 Analysis

Two analytical approaches were taken to develop in-depth insights into yield gaps from the survey data. First, to achieve a comprehensive understanding of the differences between

participants with larger yield gaps and those with smaller yield gaps, we split the participants into a high relative yield group and a low relative yield group using the median relative yield for the whole sample population. We then compared them on the three measured dimensions (i.e. farm management practices, grower characteristics and farm characteristics). The comparison analyses between the two groups were conducted using independent samples *t* tests for quantitative responses and chi-square tests for categorical responses (Field 2009).

Second, to examine the interactive relationships between grower characteristics and farm management practice in predicting relative yield, path analyses were conducted (Byrne 2001). Potential paths were developed based on the reviewed literature and the results of the comparison analyses between high and low relative yield groups. The goodness of fit of the model was assessed using the chi-square test, the comparative fit index (CFI), Tucker-Lewis index (TLI) and root mean square error of approximation (RMSEA). A satisfactory fit is suggested by a non-significant chi-square test, CFI ≥ 0.95, TLI ≥ 0.95 and RMSEA ≤ 0.06 (Hu and Bentler 1999; Kenny and McCoach 2003).

3 Results and discussion

Participants were identified from the matched subregions as shown in Fig. 2. In total, 406 growers were successfully contacted. Of these, 238 grain producers participated in the survey (59%), 94 growers declined to be interviewed (23%) and 74 growers were ruled out because they had less than 200 ha cropped (18%). Of the 238 participants, six were excluded on the grounds that we suspected they may not have provided valid or usable data (2.5%).

The average participants' age was 51 years old (SD = 11, ranging from 20 to 89 years in age), with an average of 31 years (SD = 13) of experience in growing crops. Among the participants, there were only 10 female producers (4%). Seventeen farms (7%) were identified as corporate owned, while the rest identified as family farms. Thirty-three participants (14%) owned or managed other farms in locations more than 50 km apart. Only two of these were corporate farms. The average cropping land area was 2149 ha (SD = 2073). The total cropped area of participants was 0.5 million ha, or about 2% of Australia's cropped area.

3.1 Relative yields achieved

The overall average *Y%* achieved by the 232 participants was 72% (SD = 29%). This is higher than the expected 50% based on results of Hochman et al. (2016). A close examination of the results revealed that 20% of participants reported a higher than 100% relative yield, thus skewing the average *Y%* upwards. The occurrence of higher than 100% relative yield is due to the fact that the simulation model by Hochman et al. (2016) did not include the emergent best practices such as early sowing with later maturing wheat varieties (Hochman and Horan 2018). Participants were split into a high relative yield group and a low relative yield group using the median relative yield for the whole sample population. An independent samples *t* test indicated that participants in the high relative yield group ($M = 96\%$, SD = 20%) reported significantly higher relative yield compared to their counterparts from the low relative yield group ($M = 47\%$, SD = 12%), $p < .001$.

This observation provides strong supporting evidence for the existence of a large yield gap for wheat in Australia. With almost 20% of participants reporting a yield greater than Yw, these data support the findings of an emergent best practice based on early sowing, slower maturing wheat varieties and high levels of N fertiliser, which has the potential to increase Yw at a national scale by a further 30% (Hochman and Horan 2018). The high relative yield group also reported higher 5-year average yields from a typical wheat field ($M = 3.12$ t ha^{-1}, SD = 1.15 t ha^{-1}) than the low relative yield group ($M = 2.07$ t ha^{-1}, SD = 0.76 t ha^{-1}), $p < 0.001$. This result indicated that the differences observed in 2016 between the high relative yield group and the low relative yield group were consistently observed over a longer time period.

The following analyses focus on the comparisons of the measured variables between the high relative yield group and the low relative yield group.

3.2 Farm management practices

3.2.1 Sowing date and sowing window

The average start of the sowing window was 9 May (SD = 18 days; ranging from 1 April to 30 July), with 24% of farms starting their sowing program before the 26th of April. It took participants an average of 21 days (SD = 14 days; ranging from 2 to 85 days) to complete their sowing programs. Against expectations, the high relative yield group had marginally significantly later sowing dates (day 131.98 vs. day 127.51, $p = .065$). This was partially driven by the high representation in the high relative yield group from the Liverpool Plains subregion (Quirindi and Gunnedah Region SA2s) where late sowing is the norm. When these two SA2s were excluded from the analysis, the order was reversed but the difference was nonsignificant (123.69 vs. 126.04, $p = .222$). In relation to the length of the sowing window in 2016, there was no significant difference between the high relative yield group ($M = 20.20$ days, SD = 12.76) and the low relative yield group ($M = 22.58$ days, SD = 13.56).

3.2.2 N fertiliser application and preceding crops

Table 1 presents the percentage of surveyed farms that planted their wheat crop following various crops and the average

Table 1 Preceding crops before wheat crop and average nitrogen applied

	% of farms		Nitrogen application	
	High relative yield group (%)	Low relative yield group (%)	High relative yield group M (SD) (kg N ha^{-1})	Low relative yield group M (SD) (kg N ha^{-1})
A cereal crop	37***	65***	79 (*51*)*	57 (*42*)*
A canola crop	44	48	116 (*146*)**	58 (*45*)**
A pulse crop	62	53	75 (*61*)***	42 (*34*)***
A pasture phase	22***	44***	64 (*58*)**	30 (*33*)**

The asterisk symbol indicates the statistical significance level of the differences between high and low relative yield groups: *$p < .05$, **$p < .01$, ***$p < .001$

nitrogen rate applied to wheat crops following each of these crop types last season. The results revealed that farms in the high relative yield group were less likely to plant a wheat crop following a cereal crop or a pasture phase. However, there were no differences in the percentage of farms planting wheat following a canola crop or a pulse crop between the high and low relative yield groups. In addition, farms in the high relative yield group applied significantly more nitrogen following all crop types in comparison to those from the low relative yield group. In particular, the rate of N applied to wheat crops following a canola crop by high relative yield growers doubled that applied by low relative yield growers.

Regarding the principles used for determining N fertiliser rate, despite the clear difference in the amount of N applied between the high and low relative yield groups (see Table 1), there were no significant differences in relation to the principles used to determine their N fertiliser rates (Pearson chi-square $p = .235$). Results suggest that the majority of participants in both groups (high relative yield 67% vs. low relative yield 61%) monitored their crop through the season and made decisions on applying nitrogen based on soil moisture, crop growth stage and shoot numbers. Less participants from both groups used the other three principles: crop yield potential (high relative yield 17% vs. low relative yield 13%), set fertiliser budget at start (high relative yield 12% vs. low relative yield 22%) or grain protein target (high relative yield 3% vs. low relative yield 4%).

3.2.3 Soil testing and yield mapping

Farms from the high relative yield group had a significantly higher percentage of their wheat area soil tested ($M = 24\%$, $SD = 34\%$) than those from the low relative yield group ($M = 15\%$, $SD = 28\%$), $p = .03$. It should be noted that, for both high and low relative yield groups, the standard deviations were large, suggesting that soil testing practices varied widely within each group.

The adoption rates of yield mapping between the high (52%) and low (43%) relative yield groups were not statistically significant, $p = .189$. Moreover, for those who had a yield map, participants from both the high ($M = 3.4$, $SD = 1.4$) and low ($M = 3.8$, $SD = 1.5$) relative yield groups reported equally positive evaluations of its helpfulness in making management decisions including decisions about fertiliser rates.

3.2.4 Crop diversity, wheat area cropped and weed problem

Farms with high relative yield ($M = 3.84$, $SD = 1.02$) were more likely to have a greater variety of crops last season compared to farms with low relative yields ($M = 3.56$, $SD = 1.07$), $p = .045$; their wheat crop land area in hectare (high relative yield: $M = 742.6$, $SD = 880.4$ vs. low relative yield: $M = 1171.1$, $SD = 1111.2$; $p = .001$) and the proportion of crop land area being planted to wheat (high relative yield: $M = 40.8\%$, $SD = 18.4$ vs. low relative yield: $M = 49.3\%$, $SD = 23.6$; $p = .003$) last season were all significantly smaller for farms with high relative yields than farms with low relative yields. The proportion of wheat crops with a weed population that they could not control well enough to prevent yield loss was reasonably small for both groups. However, farms with low relative yield ($M = 5.93$, $SD = 14.10$) appeared more likely to have weed problems compared to their counterparts ($M = 3.06$, $SD = 8.67$), $p = .064$.

3.3 Grower characteristics

There were no significant differences in age, gender and the number of years of experience in growing crops between the high and low relative yield groups. However, farms in the high relative yield group were more likely to have someone involved in farm management decisions who had undertaken a formal university degree course (43%), in comparison to the low relative yield group (32%), Pearson chi-square $p = .078$.

There was no difference in the number of times someone involved in farm management decisions attended cropping extension events such as field days, seminars, workshops, GRDC updates or short courses in the last 12 months (high relative yield: $M = 3.0$, $SD = 3.1$, vs. low relative yield: $M = 3.1$, $SD = 2.8$), indicating that ongoing learning was equally, yet, variably distributed in both groups (as indicated by the large SD).

3.3.1 Trusted sources for crop management information and planning decisions

The three most trusted sources for crop management information and planning decisions reported by participants were accumulated and presented as the percentage of participants who used each source for the high and low relative yield groups, respectively. The results indicated that both fee-for-service and agribusiness/retail agronomists were most widely regarded as trusted sources. In particular, fee-for-service agronomists were more popular with participants from the high relative yield group (60%) than the low relative yield group (39%, $p = .002$), while agribusiness/retail agronomists were more popular with participants from the low relative yield group (46%) than with their counterparts (28%, $p < .004$). Both groups reported similar levels of usage of other sources: GRDC (high relative yield 21% vs. low relative yield 24%), own knowledge or records (high relative yield 24% vs. low relative yield 18%), other farmers (high relative yield 15% vs. low relative yield 15%), farmer groups (high relative yield 11% vs. low relative yield 8%), decisions support tools (high relative yield 5% vs. low relative yield 12%) and family members (high relative yield 1% vs. low relative yield 2%).

The preference of fee-for-service agronomists by participants from the high relative yield group was further corroborated by answers to the question asking whether they were using a fee-for-service agronomist: 71% of participants from the high relative yield group used a fee-for-service agronomist in comparison to 52% from the low relative yield group ($p = .003$).

3.3.2 Top practices essential for achieving a good wheat yield

The three top practices that participants reported as essential for achieving a good wheat yield were accumulated and presented as the percentage of participants who nominated each practice for the high and low relative yield groups, respectively. The results indicated that weed control, fertilising and sowing at the right time were regarded as important practices by the majority of participants in both groups, but with different magnitudes and order. Both groups nominated weed control (high relative yield 72% vs. low relative yield 84%, $p < .039$) as the most important practice, while the high relative yield group placed fertilising (63%) second and sowing at the right time (53%) third, whereas the low relative yield group placed timely sowing second (60%) and fertilising (56%) third. Both groups had crop rotation as the fourth ranked practice, though this was rated more frequently by the higher relative yield group (high relative yield 30% vs. low relative yield 20%). Variety choice (high relative yield 4% vs. low relative yield 7%), disease control (high relative yield 3% vs. low relative yield 8%), zero tillage (high relative yield 6% vs. low relative yield 9%), seedling management (high relative yield 4% vs. low relative yield 3%) and pest control (high relative yield 0% vs. low relative yield 1%) were all given a lower ranking by both groups.

3.3.3 Risk taking

Overall, there were few differences between the two relative yield groups in relation to their response to questions designed to probe their attitude towards risk. Participants from the high relative yield group were slightly more likely to take the risk of adopting new technology ($M = 3.3$, SD = 1.3) compared to those from the low relative yield group ($M = 3.0$, SD = 1.3; $p = .090$). A very high percentage of participants from both groups (high relative yield 79% vs. low relative yield 87%) took insurance for hail and/or frost damage, which was much higher than the 50% reported in 2007 (Mahul and Stutley 2010). However, participants from the high relative yield group were more likely to either already have or were considering multi-peril insurance cover for their crops (high relative yield 42% vs. low relative yield 28%, $p = .058$).

About 15% of growers in each group reported that they owned or managed another farm more than 50 km away. There was no significant difference in the percentages of farms leasing land or machinery to better manage business risks between the two groups, with a majority in both group using this strategy (high relative yield 61% vs. low relative yield 53%). Both groups also agreed that it was important to have livestock on the farm to better manage risk (high relative yield $M = 3.9$, SD = 1.5 vs. low relative yield $M = 4.0$, SD = 1.4).

3.3.4 Locus of control, positive self-concept, and satisfaction with yield

Overall, there were no significant differences between the two relative yield groups on agency and satisfaction with yield. In particular, participants from both groups reported equally moderate levels of sense of control (high relative yield: $M = 3.4$, SD = 1.4 vs. low relative yield: $M = 3.2$, SD = 1.4). That is, they felt a certain degree of control over how their crops performed. In addition, participants from both groups tended to agree that other farmers often sought their advice on agriculture (high relative yield: $M = 3.2$, SD = 1.2 vs. low relative yield: $M = 3.2$, SD = 1.2).

Interestingly, although participants from the low relative yield group reported significantly lower average wheat yields over the past 5 years ($M = 2.1$, SD = .8) in comparison to those from high relative yield group ($M = 3.1$, SD = 1.1), participants from both groups reported similarly moderate levels of satisfaction with their wheat yield (high relative yield: $M = 3.6$, SD = 1.3 vs. low relative yield: $M = 3.4$, SD = 1.4).

3.4 Farm characteristics

There was no significant difference between the high (M = 74.1%, SD = 23.8) and low (M = 76.8%, SD = 21.5) relative yield groups in the proportion of farm income from dryland cropping compared to livestock. There were also no significant differences in the proportion of corporate and family farms between the high and low relative yield groups, although this is not surprising given the small number of corporate farms. The total crop land area in hectare (high relative yield: M = 1886.0, SD = 1993.0 vs. low relative yield: M = 2394.7, SD = 2127.4; p = .061) was less for higher relative yield farms.

Table 2 presents the proportion of each soil type being named as the first, second and third most common soil types on farm. Results suggest that farms with high relative yields were more likely to have Vertosols and Dermosols as their most common soil types. On the other hand, farms with low relative yield were more likely to have Chromosols and Kandosols. This finding is consistent with Vertosols and Dermosols being superior cropping soils to Chromosols which are often structurally degraded, have hard-setting surfaces and impeded internal drainage, and Kandosols which mostly have low fertility and are usually restricted to grazing of native pastures in the arid and semi-arid interior (van Gool 2016).

3.5 A comprehensive framework explaining wheat yield gap in Australia

Summarising the findings from the factors examined above, a comprehensive framework was constructed to explain wheat yield gaps at farm level in Australia (see Fig. 3). The framework highlights the major differences and similarities between farms with high yield gaps and with low yield gaps.

Six key factors from the farming management aspect have been identified as contributing to the yield gaps: quantity of N fertiliser applied, type of crops preceding wheat, the area of land that was soil-tested, crop diversity, wheat area cropped (i.e. the proportion of crop land area being planted to wheat) and weed problem. In comparison to growers with lower yield gaps, growers with higher yield gaps had applied considerably less N fertiliser, were more likely to plant a wheat crop following a cereal crop (65% vs. 37%) or a pasture phase (44% vs. 22%), and had less of their crop area soil tested. Noticeably, although both groups regarded fertilising as an important practice, and both tended to use information on soil moisture, crop growth and shoot number to guide their fertiliser decisions, they still differed substantially in the amount of N applied. These results highlight the importance of nitrogen fertiliser (Anderson et al. 2016; Angus and Grace 2017; Hochman and Horan 2018) and cropping sequences (Angus et al. 2015; Hochman et al. 2014; Kirkegaard et al. 2014) as key factors related to achieving water-limited yield. It is important to note that the comparatively higher N application reported by growers with low yield gaps is not excessive, and the amount of N used is flexible and responsive to yield potential. Only excess use of N results in detrimental environmental consequences and this was shown to be rare in Australian cropping (Carberry et al. 2013).

A number of grower characteristics are associated with the yield gap. Farms with lower yield gaps were more likely to trust a private agronomist as a source for their crop management information and planning decisions (59% vs. 39%), while farms with high yield gap were more likely to trust

Table 2 Percentage of each soil type being named as top three most common soil types by high and low relative yield groups

Soil type	Yield status	The most common soil type	Second most common soil type	Third most common soil type
Vertosols[a]	High relative yield	48.3%	21.6%	16.4%
	Low relative yield	11.2%	7.8%	8.6%
Dermosols[a]	High relative yield	10.3%	13.8%	1.7%
	Low relative yield	4.3%	6.9%	4.3%
Sodosols	High relative yield	19.0%	20.7%	26.7%
	Low relative yield	24.1%	22.4%	25.9%
Calcarosols	High relative yield	6.0%	9.5%	15.5%
	Low relative yield	9.5%	14.7%	13.8%
Chromosols	High relative yield	10.3%	17.2%	15.5%
	Low relative yield	27.6%	24.1%	13.8%
Kandosols	High relative yield	3.5%	7.8%	5.2%
	Low relative yield	14.7%	12.1%	10.3%
Ferrosols	High relative yield	0.9%	3.5%	7.8%
	Low relative yield	0.0%	0.0%	0.0%

[a] Favourable soil types for all regions (Isbell et al. 1997)

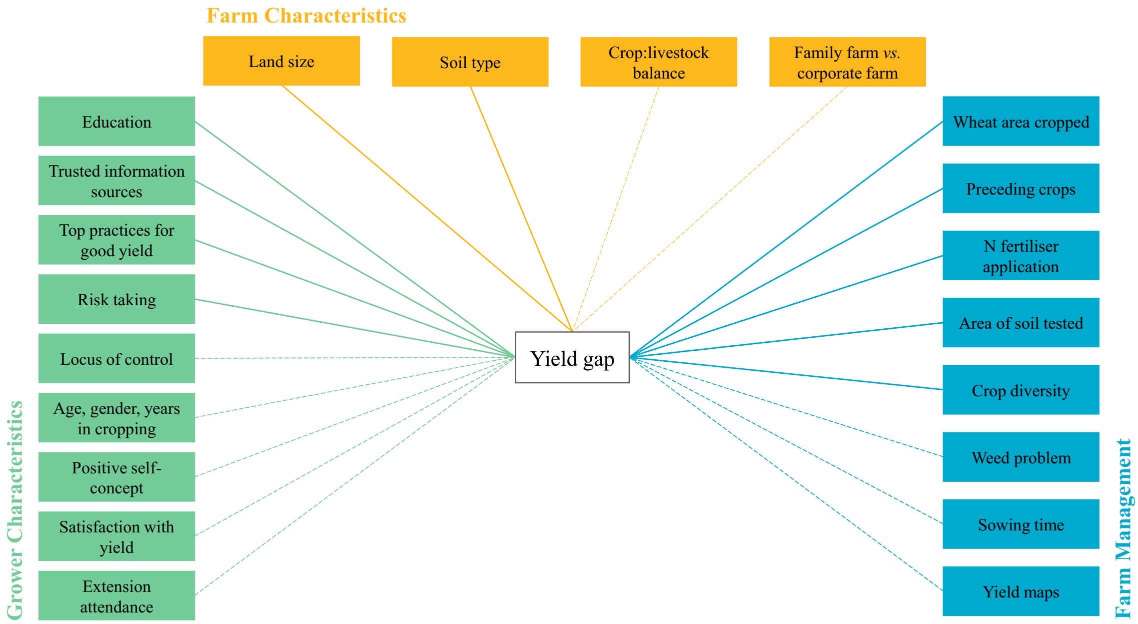

Fig. 3 A comprehensive framework for explaining wheat yield gaps in Australia. Solid lines indicate characteristics with differences between high- and low-yield-gap farms; dashed lines indicate characteristics that were not significantly different between these farm groups

agribusiness or retail agronomists (44% vs. 28%). Given that agribusiness or retail agronomists are the more likely trusted sources of advice for the high yield gap group, these agronomists should be better supported to provide the relevant advice. Similarly, GRDC is in a good position to influence this group.

In relation to the top practices for achieving a good wheat yield, participants from both groups nominated weed control, fertilisation and time of sowing as the most essential practices. However, comparatively, growers with high yield gaps seemed more likely to regard weed control as important (84% vs. 72%), and growers with low yield gaps were more likely to regard crop rotation as important (30% vs. 20%). In addition, growers with low yield gaps were marginally more willing to take risks in adopting new technologies compared to those with high yield gaps. There were few differences in other aspects of risk taking between the two groups.

In relation to farm characteristics, the results revealed that growers with low yield gap tended to have comparatively smaller crop land area. This finding suggests that consolidation of cropping farms in Australia may be associated with inefficient production practices. This is consistent with the suggestion that productivity improvement among smaller farms can be made through increasing their ability to access advanced technologies, rather than simply expanding their scale (Sheng et al. 2015). Larger farms may need to simplify their operations, which may be at the expense of crop diversity in their rotations.

Interestingly, although soil type is already factored in the calculation of water-limited yield, it appeared that farms with low yield gaps were more likely to have favourable soil types. Hence, this finding indicates that superior soils may provide a productivity advantage which goes beyond their simulated biophysical attributes. The prevalence of poorer soil types on farms may be a disincentive to investing in adequate N fertiliser, which in turn may make it difficult for these growers to close their yield gaps.

3.6 A path model for predicting relative yield

To investigate the dynamic relationships between grower characteristics and farm management practices in predicting yield gaps, we conducted a number of potential path models with the measured continuous variables and binary categorical variables. To effectively present the significant interactions between measured variables, the exploration of potential models was guided to achieve the most parsimonious analysis. A best fitted model was achieved, and the findings are presented in Fig. 4. The model provided excellent fit for the survey data, with a non-significant chi-square value (χ^2[28df] = 20.31, p = .85), suggesting that the hypothesised model covariance matrix did not differ from the actual covariance matrix. Other model fit indices supported this evaluation of the model as very good: CFI = 1.00, TLI = 1.15 and RMSEA ≤ .001. The standardised parameter estimates are presented in Fig. 4.

This model suggests that grower characteristics were associated with relative yield through four major paths. First, stronger sense of control over how crops perform (i.e. locus of control) was positively linked to risk taking as reflected in more likely having or considering purchasing a relatively new type of crop insurance (i.e. multi-peril or similar insurance), which was in turn positively associated with relative yield.

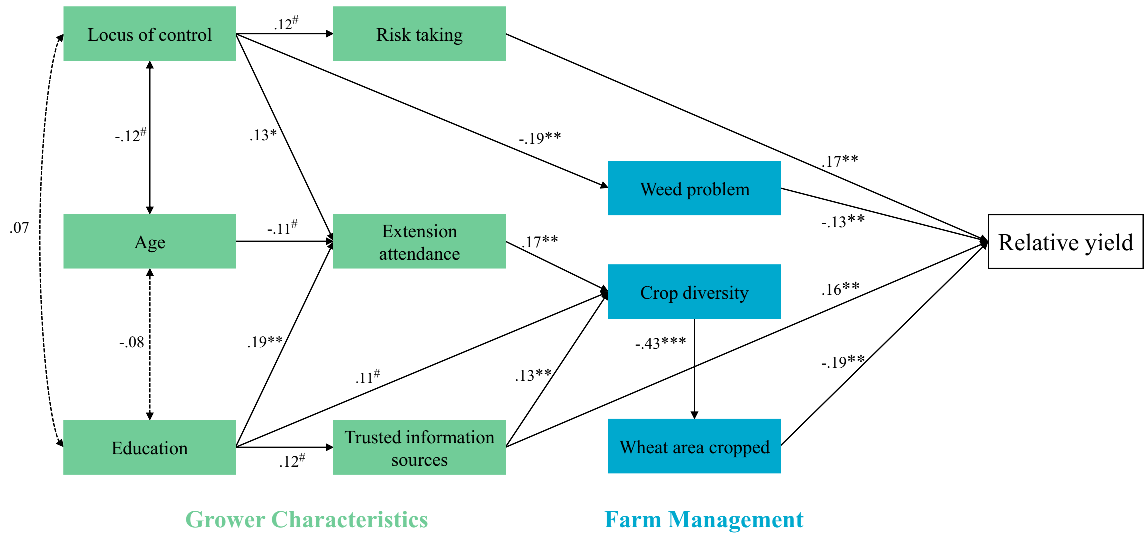

Fig. 4 A path model for predicting relative yield. $\#p < .10$; $*p < .05$; $**p \leq .01$; $***p \leq .001$. Solid lines denote statistically significant relationships; dashed lines indicate statistically nonsignificant relationships. The value next to each line is the standardised regression coefficient and represents the strength of relationship between variables, with positive numbers indicating positive relationships and vice versa

This finding indicates that growers with a greater sense of control may take more proactive measures in managing their crops. Second, a stronger sense of control was negatively associated with having a bigger weed problem, which was in turn negatively linked to relative yield. This finding suggested that growers with a greater sense of control may put more effort into managing and controlling problem weeds, supporting the results of the first path that those growers took more proactive measures in crop management.

Third, a stronger sense of control and a university degree were positively associated with extension attendance, while age was negatively associated with extension attendance. Extension attendance was positively linked to more types of crops planted (i.e. crop diversity), which led to smaller proportion of crop land area being planted to wheat. Additionally, the proportion of wheat planted was negatively associated with relative yield, such that the smaller the wheat area proportion, the greater the relative yield. The forth path is also through more crop diversity and a smaller proportion of wheat planted. But, it is through having someone in management with a university degree that led to more likely use a fee-for-service or private agronomist, which was in turn positively associated with crop diversity.

Finally, having someone in management with a university degree was directly linked to more crop diversity, which indicates that higher level of education enabled a better understanding of the benefits of crop diversity. Moreover, using a fee-for-service or private agronomist was directly linked to greater relative yield. This suggests that private agronomy services would have other influence on crop management, which contributed to higher yield.

While the path analysis suggested that locus of control was a key grower characteristic contributing indirectly to the yield gap through influencing other factors such as risk taking, it is worthwhile to note that, in the high and low relative yield comparison analysis, there was no statistically significant difference in locus of control between high and low relative yield groups (see Fig. 3). This difference in findings is likely caused by the considerable variability of variable 'locus of control' that may be subsumed within each group in the between-group comparison analysis (Altman and Royston 2006). Though grouping farms into high and low relative yield groups helps identify the distinctive differences in farm management and characteristics between the two groups, it may also have limitations as noted here.

4 Conclusion

The present study is the first to comprehensively examine farm management practices, farm and grower characteristics associated with wheat yield gaps in Australia. In particular, the findings have informed the development of a comprehensive framework highlighting the key differences in farming management practices, farm and grower characteristics between farms with smaller yield gaps and farms with greater yield gaps. The contrasting profiles of farms with smaller vs. greater yield gaps emphasise that no single factor is the panacea to a better yield. Instead, it is the combination of all three aspects that contributes to the existing yield gaps. The present study has further revealed that socio-psychological factors of growers play an important role in yield gaps through influencing farm management practice. The findings underscore that, to close wheat yield gaps in Australia, it is important to address both socio-psychological and management pathways. More importantly, it appears that the differences between the

two groups in farm and grower characteristics are not so strong as to suggest that the higher yield gap group cannot emulate the achievements of the low yield gap group. This observation has implications for the likely success of well-targeted interventions to close the yield gap.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Altman DG, Royston P (2006) The cost of dichotomising continuous variables. BMJ 332:1080. https://doi.org/10.1136/bmj.332.7549.1080

Anderson W, Johansen C, Siddique KHM (2016) Addressing the yield gap in rainfed crops: a review. Agron Sustain Dev 36(1). https://doi.org/10.1007/s13593-015-0341-y

Angus JF, Grace PR (2017) Nitrogen balance in Australia and nitrogen use efficiency on Australian farms. Soil Res 55:435–450. https://doi.org/10.1071/SR16325

Angus JF, van Herwaarden AF (2001) Increasing water use and water use efficiency in dryland wheat. Agron J 93:290–298. https://doi.org/10.2134/agronj2001.932290x

Angus JF, Kirkegaard JA, Hunt JR, Ryan MH, Ohlander L, Peoples MB (2015) Break crops and rotations for wheat. Crop Pasture Sci 66: 523–552. https://doi.org/10.1071/CP14252

Arbuckle JG, Moeton LW, Hobbs J (2015) Understanding farmer perspectives on climate change adaptation and mitigation: the roles of trust in sources of climate information, climate change beliefs, and perceived risk. Environ Behav 47(2):205–234. https://doi.org/10.1177/0013916513503832

Beeston G, Stephens D, Nunweek M, Walcott J, Ranatunga K (2005) GRDC strategic planning for investment based on agro-ecological zones. Final report to GRDC, June 2005. Commonwealth of Australia, Canberra

Beza E, Silva JV, Kooistra L, Reidsma P (2017) Review of yield gap explaining factors and opportunities for alternative data collection approaches. Eur J Agron 82:206–222. https://doi.org/10.1016/j.eja.2016.06.016

Brown HE, Huth NI, Holzworth DP, Teixeira EI, Zyskowski RF, Hargreaves JNG, Moot DJ (2014) Plant modelling framework: software for building and running crop models on the APSIM platform. Environ Model Softw 62:385–398

Byrne BM (2001) Structural equation modeling with AMOS: basic concpets, applications, and programming. Lawrence Erlbaum Associates, Mahwah

Carberry PS, Liang W, Twomlow S, Holzworth DP, Dimes JP, McClelland T, Huth NI, Chen F, Hochman Z, Keating BA (2013) Scope for improved eco-efficiency varies among diverse cropping systems. Proc Natl Acad Sci U S A 110(8381–8386):8381–8386. https://doi.org/10.1073/pnas.1208050110

Carolan MS (2006) Social change and the adoption and adaptation of knowledge claims: whose truth do you trust in regard to sustainavle agriculture. Agric Hum Values 23:325–339. https://doi.org/10.1007/s10460-006-9006-4

Cassman KG, Dobermann A, Walters DT, Yang H (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. Annu Rev Environ Resour 28:315–358. https://doi.org/10.1146/annurev.energy.28.040202.122858

Cornish PS, Murray GM (1989) Low rainfall rarely limits the yield of wheat in southern NSW. Aust J Exp Agric 29(2):77–83. https://doi.org/10.1071/EA9890077

D'Emden FH, Llewellyn RS, Burton MP (2008) Factors influencing adoption of conservation tillage in Australian cropping regions. Aust J Agric Resour Econ 52(2):169–182. https://doi.org/10.1111/j.1467-8489.2008.00409.x

Field A (2009) Discovering statistics using SPSS, 3rd edn. SAGE Publications Ltd, London

Fischer RA (2015) Definitions and determination of crop yield, yield gaps, and of rates of change. Field Crop Res 182:9–18. https://doi.org/10.1016/j.fcr.2014.12.006

French RJ, Schultz JE (1984) Water use efficiency of wheat in a Mediterranean type environment. I. The relation between yield, water use and climate. Aust J Agric Res 35:743–764. https://doi.org/10.1071/AR9840743

Godfray HC, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327(5967):812–818. https://doi.org/10.1126/science.1185383

Hochman Z, Horan H (2018) Causes of wheat yield gaps and opportunities to advance the eater-limited yield frontier in Australia. Field Crop Res 228:20–30. https://doi.org/10.1016/j.fcr.2018.08.023

Hochman Z, Holzworth D, Hunt JR (2009) Potential to improve on-farm wheat yield and WUE in Australia. Crop Pasture Sci 60:708–716. https://doi.org/10.1071/CP09064

Hochman Z, Prestwidge D, Carberry PS (2014) Crop sequences in Australia's northern grain zone are less agronomically efficient than implied by the sum of their parts. Agric Syst 129:124–132. https://doi.org/10.1016/j.agsy.2014.06.001

Hochman Z, Gobbett D, Horan H, Navarro Garcia J (2016) Data rich yield gap analysis of wheat in Australia. Field Crop Res 197:97–106. https://doi.org/10.1016/j.fcr.2016.08.017

Holzworth DP, Huth NI, deVoil PG, Zurcher EJ, Herrmann NI, McLean G, Chenu K, van Oosterom EJ, Snow V, Murphy C, Moore AD, Brown H, Whish JPM, Verrall S, Fainges J, Bell LW, Peake AS, Poulton PL, Hochman Z, Thorburn PJ, Gaydon DS, Dalgliesh NP, Rodriguez D, Cox H, Chapman S, Doherty A, Teixeira E, Sharp J, Cichota R, Vogeler I, Li FY, Wang E, Hammer GL, Robertson MJ, Dimes JP, Whitbread AM, Hunt J, van Rees H, McClelland T, Carberry PS, Hargreaves JNG, MacLeod N, McDonald C, Harsdorf J, Wedgwood S, Keating BA (2014) APSIM—evolution towards a new generation of agricultural systems simulation. Environ Model Softw 62:327–350

Hu L, Bentler PM (1999) Cutoff criteria for fit indexes in covariance structure analysis: conventional criteria versus new alternatives. Struct Equ Model 6:1–55. https://doi.org/10.1080/10705519909540118

Hunt JR, Kirkegaard JA (2011) Re-evaluating the contribution of summer fallow rain to wheat yield in southern Australia. Crop Pasture Sci 62: 915–929. https://doi.org/10.1071/CP11268

Isbell RF (1996) The Australian soil classification. CSIRO Publishing, Collingwood, Victoria

Isbell RF, McDonald WS, Ashton LJ (1997) Concepts and rationale of the Australian soil classification. CSIRO land and water, Canberra

Johnston RM, Barry SJ, Bleys E, Bui EN, Moran CJ, Simon DAP, Carlile P, McKenzie NJ, Henderson BL, Chapman G, Imhoff M, Maschmedt D, Howe D, Grose C, Schoknecht N, Powell B, Grundy M (2003) ASRIS: the database. Soil Res 41:1021–1036

Kenny DA, McCoach DB (2003) Effect of the number of variables on measures of fit in structural equation modeling. Struct Equ Model 10:333–351. https://doi.org/10.1207/S15328007SEM1003_1

Khuu A, Juerg Weber E (2013) How Australian farmers deal with risk. Agric Finance Rev 73(2):345–357. https://doi.org/10.1108/afr-10-2012-0054

Kingwell R, Pannell D (2005) Economic trends and drivers affecting the Wheatbelt of Western Australia to 2030. Aust J Agric Res 56(6): 553. https://doi.org/10.1071/ar04196

Kirkegaard JA, Hunt JR (2010) Increasing productivity by matching farming system management and genotype in water limited environments. J Exp Bot 61:4129–4143

Kirkegaard JA, Conyers MK, Hunt JR, Kirkby CA, Watt M, Rebetzke GJ (2014) Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. Agric Ecosyst Environ 187:133–145. https://doi.org/10.1016/j.agee.2013.08.011

Leviston Z, Price JC, Bates LE (2011) Key influence on the adoption of improved land management practice in rural Australia: the role of attitudes, values and situation. Rural Soc 20:142–159

Lynch B, Llewellyn R, Umberger W, Kragt ME (2017) Farmer interest in joint venture structures in the Australian broadacre grains sector. Agribusiness 34:472–491. https://doi.org/10.1002/agr.21525

Mahul O, Stutley CJ (2010) Government support to agricultural insurance: challenges and options for developing countries. World Bank, Washington DC

Marra M, Pannell DJ, Ghadim AA (2003) The economics of risk, uncertainty and learning in the adoption of new agricultural technologies: where are we on the learning curve? Agric Syst 75:215–234

Monjardino M, McBeath TM, Brennan L, Llewellyn RS (2013) Are farmers in low-rainfall cropping regions under-fertilising with nitrogen? A risk analysis. Agric Syst 116:37–51. https://doi.org/10.1016/j.agsy.2012.12.007

Monjardino M, McBeath T, Ouzman J, Llewellyn R, Jones B (2015) Farmer risk-aversion limits closure of yield and profit gaps: a study of nitrogen management in the southern Australian wheatbelt. Agric Syst 137:108–118. https://doi.org/10.1016/j.agsy.2015.04.006

Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, Foley JA (2012) Closing yield gaps through nutrient and water management. Nature 490(7419):254–257. https://doi.org/10.1038/nature11420

Price JC, Leviston Z (2014) Predicting pro-environmental agricultural practices: the social, psychological and contextual influences on land management. J Rural Stud 34:65–78

Quinn CE, Burbach ME (2008) Personal characteristics preceding pro-environmental behaviors that improve surface water quality. Great Plains Res 18:103–114

Sadras VO, Angus JF (2006) Benchmarking water use efficiency of rainfed wheat crops in dry mega-environments. Aust J Agric Res 57:847–856

Sheng Y, Zhao S, Nossal K, Zhang D (2015) Productivity and farm size in Australian agriculture: reinvestigating the returns to scale. Aust J Agric Resour Econ 59:16–38

van Gool D (2016) Identifying soil constraints that limit wheat yield in South-West Western Australia. Resource management technical report 399. Department of Agriculture and Food, Western Australia, Perth

van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z (2013) Yield gap analysis with local to global relevance—a review. Field Crop Res 143:4–17. https://doi.org/10.1016/j.fcr.2012.09.009

van Rees H, McClelland T, Hochman Z, Carberry P, Hunt J, Huth N, Holzworth D (2014) Leading farmers in South East Australia have closed the exploitable wheat yield gap: prospects for further improvement. Field Crop Res 164:1–11. https://doi.org/10.1016/j.fcr.2014.04.018

Zhang W, Cao G, Li X, Zhang H, Wang C, Liu Q, Chen X, Cui Z, Shen J, Jiang R, Mi G, Miao Y, Zhang F, Dou Z (2016) Closing yield gaps in China by empowering smallholder farmers. Nature 537(7622):671–674. https://doi.org/10.1038/nature19368