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Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia

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ABSTRACT

Closing the yield gap is essential for global food security and for farmers who face increasing costs of production. Recent work showed that Australia's wheat growers are achieving about half their water-limited yield. While quantifying the yield gap is a necessary first step towards closing them, the next step is to understand which factors constrain rainfed grain growers from achieving their water-limited yields. Here we conducted *in silico* experiments over 15 years at 50 weather stations to ascertain the impact on grain yield of suboptimal practices against the 'best management practice' rules that were used to calculate the benchmark water-limited yields. Average national losses per suboptimal practice were: the average N fertiliser application rate – 40%; conventional tillage – 33%; suboptimal weed control during the summer fallow – 26%; low seedling density – 12%; and a two week delay in sowing – 7%. Combining two suboptimal practices does not necessarily lead to an additive effect on yield. Other factors that contribute to the yield gap include biotic stresses such as plant diseases, insects and other pests, in-crop weeds and extreme weather events (e.g. floods, strong winds and hail). In addition to calculating the impact of causes of the yield gap we investigated the opportunity to lift the water-limited yield by adopting an emergent new management practice of sowing on an optimised site specific date that is earlier than the traditional sowing window as described for the currently accepted best practice. We found that this emergent practice, matched with slower maturing varieties and additional N inputs as required, has the potential to increase wheat yields nationally by 30%. Frost and heat stress accounted for losses of 16% to 26% depending on the stress function used. Allowing for the impact of frost and heat stress reduced the yield potential of both the current and emergent water-limited yields yet it did not reduce the advantage of the emergent practice.

1. Introduction

Global food security depends on producing enough nutritiousfood for a world population expected to peak at close to 10 billion by 2050. Achieving this in an environmentally sustainable manner depends on realising the highest possible yields on existing farm land while protecting our carbon-rich and bio-diverse forests, wetlands, and grasslands (Cassman et al., 2003). One promising strategy to increase grain production is to close the yield gap (Yg). Yg is the gap between yields currently achieved on farms and those that can be achieved by using the best adapted crop varieties with the best current crop and land management practices for a given environment (van Ittersum et al., 2013). The first step towards closing the yield gap is to quantify its size and distribution. Once the magnitude and location of the gaps are identified, the next step is to identify those suboptimal management practices that account for the yield gap so that strategies can be developed to target those improvements that can most effectively close the yield gaps (Anderson et al., 2016). Other pathways to future food security, include increasing potential yields (Fischer et al., 2014; Robertson et al., 2016), reducing pressure on food demand, reducing food waste and avoiding losses in current or future production potential (Keating et al., 2014).

Wheat is one of the worlds' most important food crops. Australia has a significant role to play in global food security because, as a significant wheat exporter (Australia contributed 12% of global wheat exports in 2005–2012; ABARES, 2012), it can help compensate for seasonal fluctuations in other regions. Australian grain growers are facing increasing cost of production due to rapidly rising payments on machinery repair and maintenance, interest on bank loans and fertiliser costs, showing an overall 20% increase between 2006 and 2011 (ABARES, 2012). Increasing yield by closing the yield gap and adopting new technologies and improved crop varieties to increase water-limited yield (Yw) has historically been the primary reason for productivity growth in the grains industry (Mullen, 2007; Hughes et al., 2011).

The wheat yield gap has been well described and mapped for the

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world's major producing regions (http://www.yieldgap.org) including Australia (Anderson, 2010; Hochman et al., 2012, 2016; Gobbett et al., 2017; http://www.yieldgapaustralia.com.au). However, only a few studies have attempted to quantify the causes of these yield gaps (Espe et al., 2016; Zhang et al., 2016; An et al., 2018; Mourtzinis et al., 2018) at national or regional scales. These studies were in the USA and China, both countries with much lower crop yield gaps and less variable climates than Australia's. Australia is an interesting case study on causes of yield gaps because it has large yield gaps despite its sophisticated production system and its advanced economic development. Unless we can identify the causes of yield gaps and the ameliorative or adaptive steps that can be taken, current yield gaps may be accepted as inevitable and consequently no action will be taken to close them. We propose that a clearer understanding of the causes of Yg is an essential prerequisite to policy action for accelerating the rate at which growers close it.

Many likely causes of the wheat Yg in Australia have been proposed including: temperature extremes, "agronomic deficiencies" such as 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 (French and Schultz, 1984; Cornish and Murray, 1989; Angus and van Herwaarden, 2001; Beeston et al., 2005; Sadras and Angus, 2006; Hochman et al., 2009a; Kirkegaard and Hunt, 2010; Hunt and Kirkegaard, 2011; Hochman et al., 2014; Kirkegaard and Ryan, 2014; Angus et al., 2015). However, there has been no systematic investigation of the impacts of these factors at a national level.

In this study we first undertake an analysis of the impact, relative to Yw, of the management factors that lend themselves to investigation by simulation modelling using the APSIM model (Keating et al., 2003; Holzworth et al., 2014) namely: seedling density, time of sowing, tillage practices, fallow weed management and nitrogen fertiliser management. To this end we simulated the impact of deviations from the "best management practices" that were used to define Yw of wheat throughout Australia in previous studies (Hochman et al., 2012, 2016; Gobbett et al., 2017; Hochman et al., 2017). Calculating the combined impact on the yield gap of all suboptimal management components was not attempted in the current study as it would require reliable data on the prevalence of each suboptimal practice.

We investigated the following deviations from best practice:

1.1. Nitrogen

Concern about the adequate supply of nitrogen to wheat crops and the decline of soil fertility is a long standing issue (e.g. Hamblin and Kyneur, 1993). The average amount of nitrogenous fertilisers applied to dryland cereals and oilseeds has recently been estimated at 45 kgN/ha (Angus and Grace, 2017), a dramatic increase from the 2–3 kg N/ha estimated almost 3 decades earlier (McDonald, 1998). Even among leading farmers in the Victorian Wimmera and Mallee regions suboptimal N rates limited wheat yields by more than 0.5 t/ha in 15% to 42% of seasons (van Rees et al., 2014). Here we ask what part of the current Australian wheat yield gap can be attributed to the current level of nitrogenous fertiliser inputs and how this varied across the cropping zone.

1.2. Time of sowing and tillage

Evidence of the benefit of earlier sowing across most of the Australian wheat zone is well established (Stephens and Lyons, 1998; Sharma et al., 2008; Fletcher et al., 2015; Lawes et al., 2016; Flohr et al., 2018). This is in contrast to evidence of farmer practice from the Yield Prophet (www.yieldprophet.com.au; Hochman et al., 2009b) database which has captured sowing dates from 11,052 farmers' fields between 2004 and 2016 and has a mean sowing date of 17th May (StDev = 16 days). Here we attempt to quantify the impact of delayed sowing at a national level and to attribute it notionally to either conventional tillage or to other management related delays. While the overall benefits of zero-tillage and stubble retention to Australian crop yields are not clearly defined (Scott et al., 2013; Kirkegaard et al., 2014a; Anderson et al., 2016), the trend towards earlier sowing, observed since the 1980s (Stephens and Lyons, 1998; Sharma et al., 2008; Anderson et al., 2016) was largely made possible by the contemporary progressive introduction of reduced tillage in Australia (Llewellyn et al., 2012). However, delays in sowing may also be due to other management related causes, such as, the logistics of sowing every field on the optimal date on large farms where availability of labour and machinery may be limiting.

1.3. Summer fallow

During the summer fallow (a 5–6 month period between the harvest of last season's winter crop and the sowing of this season's wheat crop) rainfall events in excess of 20–30 mm can infiltrate below the evaporative zone near the soil surface and be stored for subsequent crop growth (Verburg et al., 2012). Yw calculations are based on the assumption that weeds are controlled in the summer fallow period. In a no-till situation this relies on the use of herbicides following each weed germinating rainfall event (e.g. more than 20–30 mm; Hunt et al., 2009). In practice, many farmers tolerate varying degrees of weed infestation which result in loss of stored soil moisture and nitrogen. In mixed farming systems it is common to graze weeds in summer fallows, but total transpiration is unlikely to be reduced through grazing (Moore and Hunt, 2012). The literature on the impact of fallow weeds on Australian crop productivity was summarised by Kirkegaard and Hunt (2010). They found that weed control increased soil water stored at sowing by 6–70 mm depending on weed density and rainfall pattern and that subsequent grain yield loses varied from 0 to 1.3 t/ha depending on fallow rainfall, the amount and distribution of in-crop rainfall, and on soil nitrogen status. Results over a wide range of sites and seasons showed an average soil water saving of 37 mm and 44 kgN/ha from summer weed control (Kirkegaard et al., 2014b). Summer weeds can also form a 'green bridge', hosting root diseases such as root lesion nematodes, take-all, and Rhizoctonia, as well as vectors for viral diseases such as wheat streak mosaic virus which reduce the yield of subsequent crops (Kirkegaard and Hunt, 2010) and as hosts that tend to favour insect pests over beneficial insects (Parry et al., 2015).

In this study we focus on the impact of weeds through their use of soil water and soil mineral nitrogen that might otherwise be accumulated and stored over the summer fallow period (Hunt et al., 2013). The combined impact of water loss and N loss will be investigated in the combined N and summer weeds limitations treatment. However, the acknowledged 'green bridge' effect will be treated in this analysis as a part of the residual yield gap that remains unquantified.

1.4. Seeding rates

Wheat is physiologically well adapted to a wide range of plant densities, as was demonstrated by the pioneering work of Puckridge and Donald (1967) who showed under rainfed conditions that various yield components were able to compensate for lower plant density with no significant difference in yield per m^2 between their 35 plants m^{-2} and 184 plants m^{-2} treatments. Similarly, in a high yielding irrigated experiment there were no yield differences for seedling density treatments between 50 and 200 plants m^{-2} although that result was mitigated by lodging (Stapper and Fischer, 1990). Planting densities of 100 to 150 plant m^{-2} are generally recommended in planting guides for rainfed wheat. The Yield Prophet database has seeding rate data for 6764 fields from 2007 to 2016. These show a mean sowing rate of 145 plants/m^2 (StDev = 26) with only a small number of fields reporting less than 50 plants/m^2. In this study we use simulation to determine the influence of a wide range of plant densities on yield potential across the

grain zone.

1.5. Exploring new productivity frontiers (emergent Yw)

In recognition of the idea that “best management practice” evolves over time we also investigated the prospects for an emerging best management practice to move the production frontier to higher levels of water-limited yield. This emerging practice combines early dry sowing on a date (Fletcher et al., 2015, 2016) with slower maturing varieties (Kirkegaard and Hunt, 2010; Hunt et al., 2012; Kirkegaard et al., 2014b; van Rees et al., 2014; Hunt et al., 2015, 2018). It is based on the idea that the optimum sowing period for any location must strike a balance between minimising the effect of abiotic stresses (e.g. frost at anthesis and heat stress and terminal drought during grainfilling) and using all the available resources such as water and solar radiation (Flohr et al., 2017). These practices are already evident with some leading farmers. While they still require local testing and validation to become accepted best practice, there are no known technological barriers to their implementation.

Here we investigated whether this practice requires more nitrogen fertiliser than allowed by the current best-practice management rules. A major obstacle to adoption of this emergent practice (optimised time of sowing by variety with additional application of N) is the perceived increase in risk of frost at anthesis. We examined that concern by applying a recently developed frost and heat stress function (Bell et al., 2015) to the current and emerging best practice simulations.

2. Methods

The annual actual national average yield (Ya) data were derived from ABARES (2015) and updated to 2016 via http://www.agriculture.gov.au/abares/Documents/agricultural-commodities-report-march-2017.pdf last accessed 08/03/2018). Simulations were created in APSIM Wheat (Version 7.8) to help quantify the national impact of possible causes of wheat yield gaps in Australia. These simulations were variations on the simulations used to calculate Yw in previous yield gap studies (Hochman et al., 2012, 2016; Gobbett et al., 2017) and are based on many conversations with farmers and agronomists and on the authors’ extensive experience in simulating wheat crops in the Australian grain zone. The main difference in the present study is that stubble retention was included in Yw calculations in recognition that it is now an accepted best management practice.

Wheat crops were simulated for 50 weather stations selected to be representative of the grain zone and for the completeness of their observed record (1972–2015) which scored > 0.9 from a possible score of 1.0 for the combined completeness of their rainfall and temperature data; (Supplementary Table 1) using the dominant soil type for the winter cropping land use within a 20 km radius. The highest yielding maturity type was selected for each station by simulating 5 varieties that represent early, mid-early, medium, mid-late and late spring wheat maturity types (Hochman et al., 2017). Where early maturity types have shorter periods from emergence to flowering and later maturity types have longer periods to flowering in a given environment. The average Yw values simulated in this way were previously shown to be highly correlated with the actual national yield from 1990 to 2015 (Hochman et al., 2017). Hence, the 50 weather stations capture the spatial variation in yield potentials that exists in the Australian grain zone.

Initial soil conditions are unknown for any of the 50 locations. To overcome this data limitation, a continuous wheat cropping system was simulated from 1981 to 2000 in order to allow soil water to reach its equilibrium condition by the autumn of 2001 regardless of starting conditions in 1981. The yield data from these years were not used in any subsequent analysis. The fifteen years’ (2001–2015) average yield results at each of the 50 weather stations were then used to compare the effect of treatments on water-limited yield. The fifteen year period was chosen as it was determined to be best suited for yield gap analysis in a variable climate (van Ittersum et al., 2013). The particular years of this study represent a wide range of seasonal conditions from severe drought to excessive rainfall across a wide range of sites.

2.1. Water-limited yield

The benchmark treatment was the fifteen year average Yw which was based on a nutrient unlimited, stubble retained, and zero till cropping system with a cropping intensity of one crop per year. The following management rules were used in APSIM:

2.1.1. The sowing rule

The sowing rule was designed to enable sowing to take place in the conventional sowing window (26th April to 15th July) on the first occasion when there is sufficient soil moisture near the soil surface to enable seeds to germinate. This is expressed by a management rule that varies between the northern and southern parts of the grain zone. All Queensland (QLD) and New South Wales (NSW) sites north of latitude −32.24 (Dubbo, NSW) were classed as northern sites and used the northern sowing rule in which a minimum of 30 mm of Plant Available soil Water (PAW) is required, all other sites used the southern sowing rule.

For Northern sites:

Sow if rain > = 15 mm over 3 days and PAW > = 30 mm from 26 April – 15 July

For Southern sites:

Sow if rain > = 15 mm over 3 days regardless of soil moisture from 26 April – 15 July

Note: Crop is sown on 15 July if criteria is not met during sowing window.

Sowing density = 150 plants/m^2, row spacing = 250 mm, sowing depth = 30 mm

2.1.2. The N fertiliser rule

The N fertiliser rule was designed to minimise the possibility that N supply will limit crop yield while also avoiding the problem of ‘haying off’ – a situation where excessive vegetative growth leads to water stress during grain-filling, and results in lower yields (van Herwaarden et al., 1998). These N application rules, with conditional in-crop application of N, were designed through iterative experimentation to make haying off very unlikely in dry springs while minimising the chance of nitrogen limiting yields in the most favourable springs:

Add 100 kgN/ha minus soil nitrate (NO_3) (kgN/ha) in the 0–60 cm soil layers on April 25.

Check NO_3 - N status in the 0–60 cm soil layers daily. If NO_3 < 80 kg N/ha and PAW > = 30 mm and Zadoks growth stage (Zadoks et al., 1974) > = 10 (emergence) and < = 49 (first awns visible) then add 70 kg N/ha (Max of 1 in-season application per crop). This rule results in variable N application rates and variable dates of N applications according to crop demand for N.

2.1.3. Soil N and soil water settings

Soil N was reset annually at maturity when soil NO_3 was set to 25 kgN/ha for each metre depth of soil, and soil NH_4 set to 5 kg/ha for each metre depth of soil.

Initial soil water was set to 10% of Plant Available Water Capacity (PAWC[1]) at the start of 1981 after which soil water was not reset. Initial surface organic matter was set to 100 kg/ha with a C:N ratio of 80.

[1] PAWC (in millimetres) represents the capacity of a soil to store water that can be extracted by crop roots. It depends on soil physical and chemical properties but also on the depth to which roots can grow and the extent to which they can extract water from the soil.

2.2. Simulation of suboptimal management practices

The various suboptimal management practices were simulated in APSIM according to the following exceptions to the abovementioned rules used to simulate the water-limited yield.

2.2.1. Yield potential restricted by nitrogen application treatments

To quantify the effect of reduced N application on water-limited yield, the following changes were made to the benchmark Yw simulations:

2.2.1.1. N45 treatment. Soil N was set to 124 kg N/ha in 1981, with N distributed through layers of the profile. Each year 45 kg N/ha was applied to the crop at sowing. Soil N and Surface OM were not reset at harvest in subsequent years.

2.2.1.2. N90 treatment. Soil N was set to 124 kg N/ha in 1981, with N distributed through layers of the profile. Each year 90 kg N/ha was applied to the crop at sowing. Soil N and Surface OM were not reset at harvest.

2.2.2. Sowing rules

Sowing rules were selected to reflect two possible causes of delay in the time of sowing compared to current best practice which is based on the appreciation that early sowing tends to optimise yield potential and that zero till/minimum tillage enable producers to sow on a lesser rainfall event than was required under conventional cultivation.

2.2.2.1. Conventional tillage. To simulate the sowing delay and loss of stubble cover associated with conventional tillage we use the following sowing rules:

For northern sites: Sow if rain > = 25 mm over 3 days and PAW > = 30 mm from 26 April–15 July.

For southern sites: Sow if rain > = 25 mm over 3 days regardless of soil moisture from 26 April–15 July

If the sowing criteria is not met by 15 July, sow on 15 July.

To simulate the impact of tillage on stubble retention as well as the sowing delay we also introduced a tillage rule where tillage (using discs) is applied during the summer fallow two weeks after a rain event consisting of at least 25 mm in a seven day period.

2.2.2.2. Late sowing due to low priority given to sowing early. This rule is based on an appreciation that a modest rainfall event, represented by 15 mm of rainfall accumulated over 3 days, represents a sowing opportunity but this event is not exploited immediately due to a number of possible reasons including other priorities, lack of preparation, machinery readiness or other management related factors.

For northern sites: Sow 2 weeks after rain > = 15 mm over 3 days and PAW > = 30 mm from 26 April to 15 July

For southern sites: Sow 2 weeks after rain > = 15 mm over 3 days regardless of soil moisture from 26 April to 15 July

If the sowing criteria are not met by 15 July, sow 2 weeks after 15 July.

2.2.3. Summer weeds

To simulate the effect of weeds during the summer fallow we used the APSIM weeds module to grow grass weeds any time, between harvest and the 25th of April the following year, that there was sufficient rainfall (10 mm in a 3 day period) to germinate weeds. The effect of growing these weeds is to consume soil water and soil nitrogen that would otherwise have been available to the following crop on the 25th of April.

2.2.4. Seedling density

To evaluate the effect of suboptimal seedling density on water-limited yield we simulated 4 plant populations in comparison with the benchmark (Yw) population of 150 plants/m^2. These populations were: 50; 75; 100; and 125 plants/m^2.

2.2.5. Combination of yield-limiting management practices

To evaluate the combined impact of two individually yield-limiting management practices we simulated a treatment that combined the N45 and the practice of not managing weeds during the summer fallow.

2.3. Frost and heat stress (frost and heat)

We applied the frost and heat stress function described in Bell et al. (2015). This function is applied through the APSIM Manager module. It is not part of the simulation process, rather it keeps count of daily stresses and calculates the impact on yield post simulation. For frost we consider 3 levels of stress (mild, moderate and severe) based on daily minimum temperatures and the Zadoks growth stage:

1 Mild Frost: for each day when growth stage is > = Z60 (first flower) and < Z69 (100% flowering), and daily minimum temperature < 2 °C and > = 0 °C, the yield potential is reduced by 10%.
2 Moderate Frost: for each day when growth stage is > = Z60 and < Z75 (mid-milk), and daily minimum temperature < 0 °C and > = −2 °C, the yield potential is reduced by 20%.
3 Severe Frost: for each day when growth stage is > = Z60 and < Z79 (end of grainfilling), and daily minimum temperature < −2 °C, the yield potential is reduced by 90%.

For heat stress we consider 3 levels of stress (mild, moderate and severe) based on daily maximum temperatures when they occur between first flower (Z60) and end of grainfilling (Z79):

1 Mild Heat: for each day when growth stage is > = Z60 and < Z79, and daily maximum temperature > 32 °C and = < 34 °C, the yield potential is reduced by 10%.
2 Moderate Heat: for each day when growth stage is > = Z60 and < Z79, and daily maximum temperature > 34 °C and = < 36 °C, the yield potential is reduced by 20%.
3 Severe Heat: for each day when growth stage is > = Z60 and < Z79, and daily maximum temperature > 36 °C, the yield potential is reduced by 30%.

Frost and Heat 2:

Given that the above frost and heat stress rules have not been thoroughly tested across a wide range of environments we also tested a more conservative version of this rule in which the impact of each of the yield-limiting frost and heat events described above was halved (e.g. instead or reducing yield potential for a day of moderate heat stress by 20% we reduced it by 10%).

2.4. "Emergent best practice rules" for advancing the water-limited yield frontier

Here we examined some emergent management rules based on the idea of early sowing and matching the earlier time of sowing with slower maturing varieties that will best exploit the longer growing season. We also investigated the need for new N fertiliser rules that will allow crops to fully exploit the additional yield potential due to the longer growing season. The treatments that we investigated were:

2.4.1. Sow on the optimal date using the optimal variety (optimal TOS & Var)

Sow on the highest yielding sowing date selected from simulations of crops sown every 7 days from 5 April to 21 June and choosing the highest yielding cultivar (by simulating the 5 varieties that represent early, mid-early, medium, mid-late and late spring wheat maturity

types as per the Yw simulations) and time of sowing combination at each of the 50 sites.

2.4.2. Sow on the optimal date using the optimal variety with the optimised N rule (optimal TOS & Var + N)

Use the 'Optimal TOS & Var' sowing rules with added modifications to the N fertiliser rule such that:

Add 100 kgN/ha NO_3 minus soil nitrate in the 0–60 cm soil layers at sowing.

Check NO_3 status in the 0–60 cm soil layers daily. If $NO_3 < 70$ kg N/ha and PAW > = 40 mm and Zadoks growth stage (Zadoks et al., 1974) > = 10 and < = 49 then add 60 kg N/ha (Max 1 application).

Check 0–60 cm soil layers daily, if $NO_3 < 70$ kg N/ha and PAW > = 30 mm and Zadoks growth stage > = 50 and < = 60 then add 90 kgN/ha (Max 1 application).

The N rates and application thresholds of this new N applications rule were derived by reiteration to ensure that yields were not nitrogen limited given the greater yield potential enabled by the new variety by time of sowing practice.

3. Results

The annual actual national average yield (Ya = 1.71 t/ha; St Dev = 0.42 t/ha; CV = 25%) contained extreme drought years such as 2002 and 2006 as well as near record years such as 2001 and 2011. Ya was consistently well below the water-limited yield of the 50 stations (Yw = 4.28 t/ha; St Dev = 0.51 t/ha; CV = 12%). The year to year variability, at a national (continental) scale, of Ya, Yw and Yg (Yg = 2.57 t/ha; St Dev = 0.34 t/ha; CV = 13%) are illustrated with Fig. 1.

In subsequent analyses, results are summarised as the 15 year average yields per weather station and these are presented as the average, standard deviations (St Dev) and coefficients of variance (CV %) of all stations (Table 1) as well as in probability of exceedence graphs that show the probabilistic distribution of 15 year average yield results across the 50 weather stations (Figs. 2, 4 and 5) where each line interpolates between 50 points that represent the 15 year site mean yield. The benchmark 15 year Yw, averaged over the 50 weather stations, was 4.28 t/ha (StDev = 0.92; CV = 21%).

The impact of yield-limiting practices, as well as the potential for emerging new practices to advance the yield frontier beyond the current Yw, are presented individually and as a combined mix of practices. The relationship between simulated yields and the N treatments (N45,

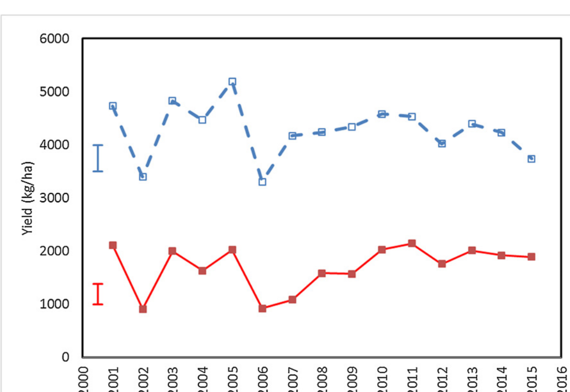

Fig. 1. Temporal variation, from 2001 to 2015, in actual yield (Ya = national yield data; solid lines and squares) and water-limited yields (Yw = water limited yield mean of 50 weather stations; dashed line and empty squares). Vertical lines (I) represent the temporal standard deviations of adjacent Yw and Ya. The difference between the empty and full squares represents the yield gap (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
Impacts, expressed as means, standard deviation (St Dev), coefficient of variation (CV) and relative yields (Y%) of individual and combined management factors that reduce water-limited yield (treatments 2–8) and of individual and combined management factors that improve water-limited yield (treatments 11 and 12). The impacts of frost and heat stress on Yw (treatment 1) is shown in treatments 9 and 10 and on the emergent Yw (treatment 12) is shown in treatment 13.

Treatment Number	Treatment	Mean (t/ha)	St Dev (t/ha)	CV (%)	Y% (%)
1	Yw (water-limited yield)	4.28	0.91	21	100
2	seedling density (50 plants/m^2)	3.78	1.10	29	88
3	Late Sowing (2 week delay)	3.97	1.04	26	93
4	Summer weeds	3.18	1.17	37	74
5	Tillage	2.86	1.08	38	67
6	N fertiliser (45 kgN/ha)	2.57	0.78	30	60
7	N Fertilizer (90 kgN/ha)	3.30	0.96	29	77
8	Combined N Fertilizer (45 kgN/ha) & Summer weeds	2.55	0.92	36	60
9	Frost and Heat	3.15	1.00	32	74
10	Frost and Heat 2 (moderate impact)	3.60	0.95	26	84
11	Optimal TOS & Var	5.06	0.47	9	118
12	Optimal TOS & Var + N	5.58	0.64	12	130
13	Optimal TOS & Var + N with NFH2[a]	4.84	0.79	16	113

[a] Note that treatment 13 should be compared with treatment 10 over which it has a 34% advantage.

N90, Yw and Opt Sow N) for all sites and years is presented in Supplementary Fig. 1. Where a boundary function, and the scatter of data below that function illustrates the dependence of the N response on other factors including total in-crop transpiration and soil mineral N prior to fertiliser application.

3.1. The impact of yield-reducing practices

Reduced seedling density (50 plants/m^2) resulted in an average yield of 3.78 t/ha (StDev = 1.10) and thus reduced the average relative yield (Y%, where Yw = 100 x simulated yield/Yw) to 88%; the effect of delaying the time of sowing by two weeks reduced yield to 3.97 t/ha (St Dev = 1.04) and Y% to 93%; failing to control weeds during the summer fallow period reduced yield to 3.18 t/ha (StDev = 1.17) and Y % to 74%; the partial effect of conventional tillage in incorporating crop residue and delaying the time of sowing until a cumulative rainfall of 25 mm was observed over a 3 day period reduced yield to 2.86 t/ha (St Dev = 1.08) and Y% to 67%; restricting the amount of fertiliser to the national average value of 45 kgN/ha reduced average yield to 2.57 t/ha (StDev = 0.44) and Y% to 60%; even at double the average N fertiliser rate (90 kgN/ha) average yield was reduced to 3.30 t/ha (StDev = 0.96) and Y% to 77% (Table 1).

The impact of frost and heat stress was to reduce potential yields to 3.15 t/ha (StDev = 1.00) and Y% to 74%. The milder version of the Frost and Heat Stress function (FH2) reduced water-limited yield to 3.6 t/ha (StDev = 0.95) and Y% to 84% (Table 1).

The spatial distribution of the impact of the individual and the combined yield-limiting treatments (summer weeds plus N45) is described in Fig. 2 where the annual mean yields of these treatments are compared to the benchmark (Yw) treatment across all sites. The impact of various plant densities on crop yields (Fig. 2a) was quite small for treatments that reduced plant densities from 150 to 100 plants/m^2. More noticeable differences were observed when densities were further reduced to 75 and 50 plants/m^2. These differences tend to be more pronounced around the median than at either extremes of the probability of exceedence curves suggesting that the effect of low plant density is small in the lowest and highest yielding sites and seasons.

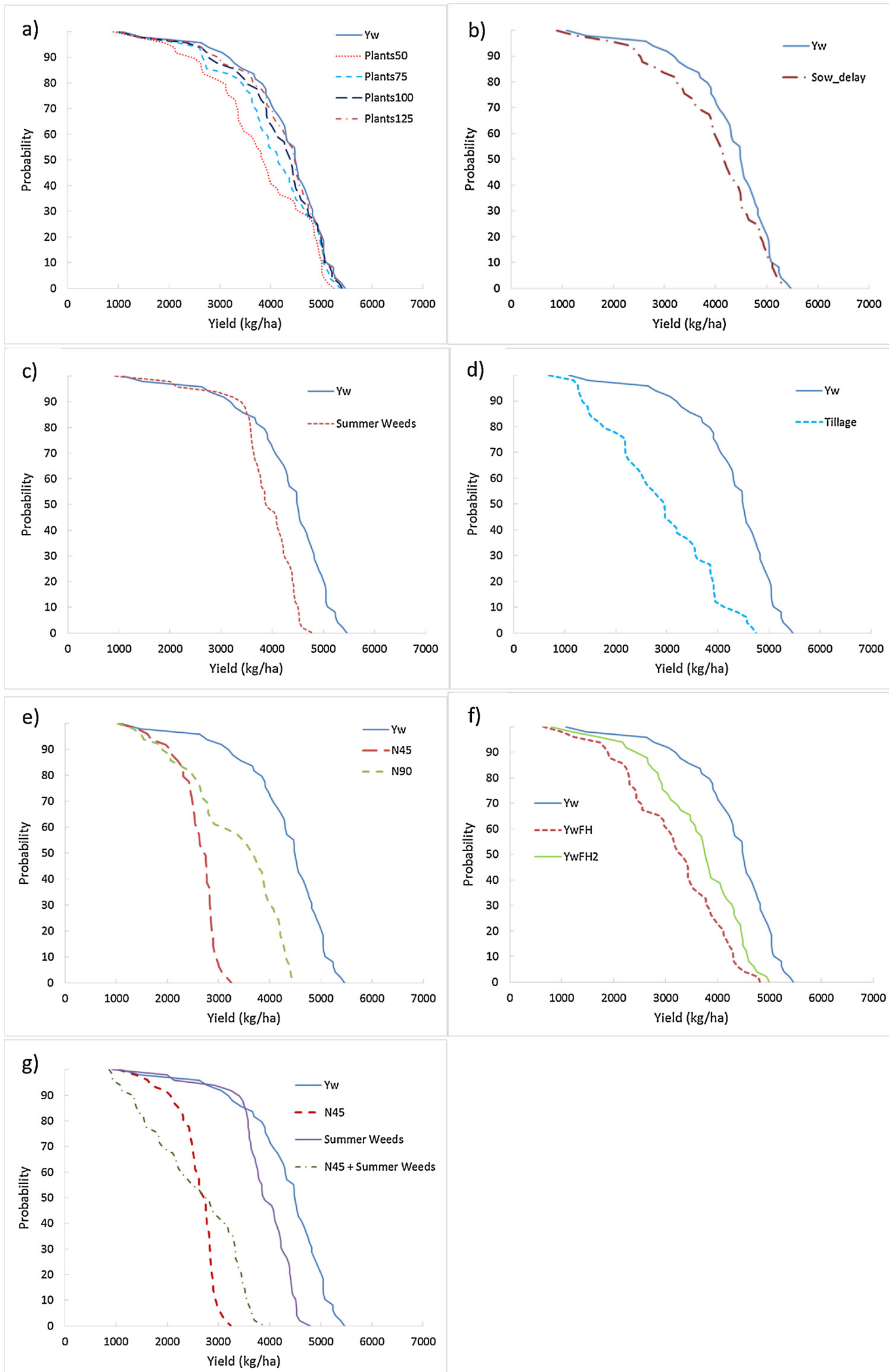

Fig. 2. Identifying causes of yield gaps in wheat: (a) low plant density, (b) delayed sowing, (c) summer fallow weeds, (d) conventional tillage, (e) N Fertiliser, (f) frost and heat stress, (g) N Fertiliser and summer fallow weeds, individual and combined effects. Each line is an interpolation between 50 points that represent the 15 year average of one of the 50 sites simulated.

The impact of sowing being delayed for 2 weeks due to untimely reaction to favourable sowing conditions was more or less evenly distributed in the 90% to 10% probability range and tapered towards the lowest and highest yielding sites and seasons (Fig. 2b).

The impact of failing to control weeds over the summer period, was minimal for sites where Yw was less than 3.5 t/ha but resulted in a yield penalty of about 0.6 t/ha for sites with Yw greater than 3.5 t/ha, indicating that in sites with mean Yw yields of less than 3.5 t/ha, there was less stored water and/or less significant summer rain events and hence less stored water and/or less opportunities for weeds to emerge and exploit the stored soil water (Fig. 2c).

The impact of conventional tillage, due to both the additional amount of rainfall required for sowing and to reduced retention of summer rainfall in the soil by incorporating stubble, was quite large for all but the very lowest yielding sites (Fig. 2d).

The suboptimal application of nitrogenous fertiliser (Fig. 2e)

represented by 45 kgN/ha, reduced yields throughout the probability distribution with yields being more limited the higher the Yw of the sites. This feature of the yield-limiting response is illustrated by the flat distribution of sites with grain yields in the range of 2.4–3.0 t/ha compared to the distribution of site yields in the Yw treatment which demonstrates a near-normal distribution of yields up to over 5 t/ha. The 90 kgN/ha treatment was quite close to the 45 kgN/ha treatment in the 100 to 60% probability range (Yw yields up to 4.2 t/ha) however, at higher yielding sites, the 90 N/ha treatment moves closer to the Yw treatment, though a difference of about 0.8 t/ha is maintained at the higher yielding sites such that for the 90 kgN/ha treatment average yield was restricted to 4.5 t/ha.

The distribution of the impact of frost and heat stress was fairly uniform across most sites except the very lowest and, to a lesser extent, the very highest yielding sites (Fig. 2f).

3.2. Combining two yield-limiting treatments

The average impact on grain yield of combining two yield-limiting treatments (summer weeds + 45 N) was similar to the impact of just limiting N fertiliser to 45 kgN/ha (Table 1). This average result hides a more complex relationship for different sites and seasons. When compared to the summer weeds treatment alone, the combined treatment is much more yield-limiting throughout the yield distribution. However, when compared to the N45 treatment alone, it seems to have a much more severe impact on yields at the top half (lower yields) of the probability of exceedence curve but a lesser impact on yield than N45 alone at the bottom half where yields continue to increase to 3.9 t/ha in the combined treatment compared to 3.2 t/ha for the N45 treatment (Fig. 2g).

To further investigate these counterintuitive results we compared the daily outputs of the amount of N leached (kgN/ha), N uptake (kgN/ha), total above ground dry biomass (kg/ha), final rooting depth (mm), grain yield (kg/ha) and harvest index of crops grown in a wet (2006) and a dry (2005) year at a single site that represents Australia's median Yw yields (Rutherglen, Victoria). In a dry year, the N45 treatment leached 3 kg N/ha while the Yw treatment leached 10 kg N/ha. Summer weeds reduced leaching from the Yw treatment to a level similar to the N45 treatment, while the combined summer weeds and N45 treatment did not leach any N (Fig. 3a). In a wet year the N45 treatment leached 9 kg N/ha while the Yw treatment leached 26 kg N/ha. However, summer weeds only reduced leaching to 25 kgN/ha, a stark contrast with the combined summer weeds and N45 treatment that leached only 3 kg N/ha (Fig. 3b).

In the dry year N Uptake for the N45 treatment was 58 kg N/ha while N uptake from the Yw treatment was 105 kgN/ha. Summer weeds reduced N uptake to 91 kg N/ha, while the combined summer weeds and N45 treatment reduced uptake to 64 kgN/ha which was still 6 kg N/ha more than the N45 treatment alone (Fig. 3c). N Uptake in the wet year for the N45 treatment was 62 kg N/ha while N uptake from the Yw treatment was 118 kg N/ha. Summer weeds slightly reduced N uptake to 107 kg N/ha, while the combined summer weeds and N45 treatment reduced uptake to 93 kg N/ha, still 31 kg N/ha more than the N45 treatment alone (Fig. 3d). Interestingly, in the dry year N uptake peaked in the last week of September for all treatments about 4 weeks after N leaching stopped. Also, while a final rooting depth of 1483 mm was achieved for all treatments in the wet year, a slightly reduced rooting depth of 1456 mm was achieved in the dry year for all treatments except for the combined (summer weeds and N45) treatment which only achieved a final rooting depth of 788 mm (simulated data not shown). This restriction on rooting depth for the combined stress treatment in the dry year occurred during the month of September by the end of which roots had reached their final depth and were unable to utilise any water or mineral N that might be locked up in the subsoil between 788 mm and 1456 mm.

In the dry year, total above ground biomass (DM) for the N45 treatment was 5.9 t/ha while DM from the Yw treatment was 8.5 t/ha. Summer weeds slightly reduced DM to 8.1 t/ha, while the combined summer weeds and N45 treatment reduced DM to 5.2 t/ha which was 0.7 t/ha less than the N45 treatment alone (Fig. 3e). However, in the wet year DM for the N45 treatment was 9.4 t/ha while DM for the Yw treatment was 13.5 t/ha. Summer weeds slightly reduced DM to 13.1 t/ha, while the combined summer weeds and N45 treatment reduced DM to 12.1 t/ha which was still 2.7 t/ha more than the N45 treatment alone (Fig. 3f).

In the dry year, grain yield for the N45 treatment was 1.7 t/ha, with a harvest index (HI) of 0.26 while grain yield from the Yw treatment was 3.2 t/ha with an HI of 0.36. Summer weeds slightly reduced grain yield to 2.7 t/ha with an HI of 0.29, while the combined summer weeds and N45 treatment reduced grain yield to 1.2 t/ha (0.5 t/ha less than the N45 treatment alone) with the HI reduced to 0.20 (Fig. 3g). However, in a wet year grain yield for the N45 treatment was 3.5 t/ha with an HI of 0.33 while grain yield for the Yw treatment was 5.7 t/ha with an HI of 0.38. Summer weeds reduced yield by less than 0.1 t/ha with an HI of 0.36, while the combined summer weeds and N45 treatment reduced yield to 5.4 t/ha (1.9 t/ha more than the N45 treatment alone) with an HI of 0.41 a substantially greater value than 0.33 the HI of the N45 treatment (Fig. 3h).

In summary, when comparing the N45 treatment with and without summer weeds in the wet season summer weeds reduced the amount of N leached (-6 kg N/ha), took up more N (+31 kg N/ha), produced more biomass (+ 2.7 t/ha), had a higher HI value (+0.08) and produced a higher yield (+ 1.9 t/ha). In the dry season, leaching losses (-3 kg N/ha), N uptake (+6 kg N/ha) and biomass difference (-0.7 t/ha) were relatively small while yields were reduced by summer weeds (- 0.5 t/ha) because of their impact on the final rooting depth (−668 mm) and the HI (-0.06) as water and N stored below 788 mm depth became unavailable to the combined summer weeds and N45 treatment in the grainfilling stage.

3.3. Potential to expand the yield frontier

Moving from the current best practice sowing rules to a rule that simultaneously optimises both the time of sowing and the variety maturity type increased the average yield potential to 5.06 t/ha (StDev = 0.47) and the average %Y to 118%. The modified N fertiliser rule together with the optimised sowing and variety rules, allowed the crops to fully realise the yield potential of the optimised time of sowing and variety, increased average yield to 5.58 t/ha (StDev = 0.64) and the average %Y to 130%. The additional yield comes at a cost of higher N fertiliser inputs. While the Yw treatment had an average annual input of 149 kg/ha N (StDev = 3), the new yield frontier had an annual input of 189 kg/ha (StDev = 14).

Introducing the frost and heat stress function reduces the yield potential to 4.48 t/ha (StDev = 0.79) and the average Y% to 113% (Table 1). However, a more sensible comparison for this treatment is not against Yw but against the results of the same Frost and Heat stress applied against Yw. In this comparison the emergent practice has an average yield advantage of 1.24 t/ha and a relative yield of 134%. Surprisingly, this emergent practice, which is predicated on early sowing, is enhanced rather than diminished by the consideration of the impact of frost and heat stress.

The probability of exceedence graphs (Figs. 4 and 5), comparing the impact of the emerging yield-potential-enhancing treatments with the benchmark water-limited yield treatment Yw, revealed that the optimised sowing date and variety maturity adaptation improved yields across the whole yield range but had the most impact between the 90% and the 50% probabilities of exceedence where Yw yields ranged from 3.1 to 4.5 t/ha. The additional benefit of the rule allowing for higher N fertilisation rate was realised over the 0% to 90% of the probability of exceedence curve where Yw yields exceeded 3.1 t/ha. Regardless of whether or not the impacts of frost and heat stress were considered

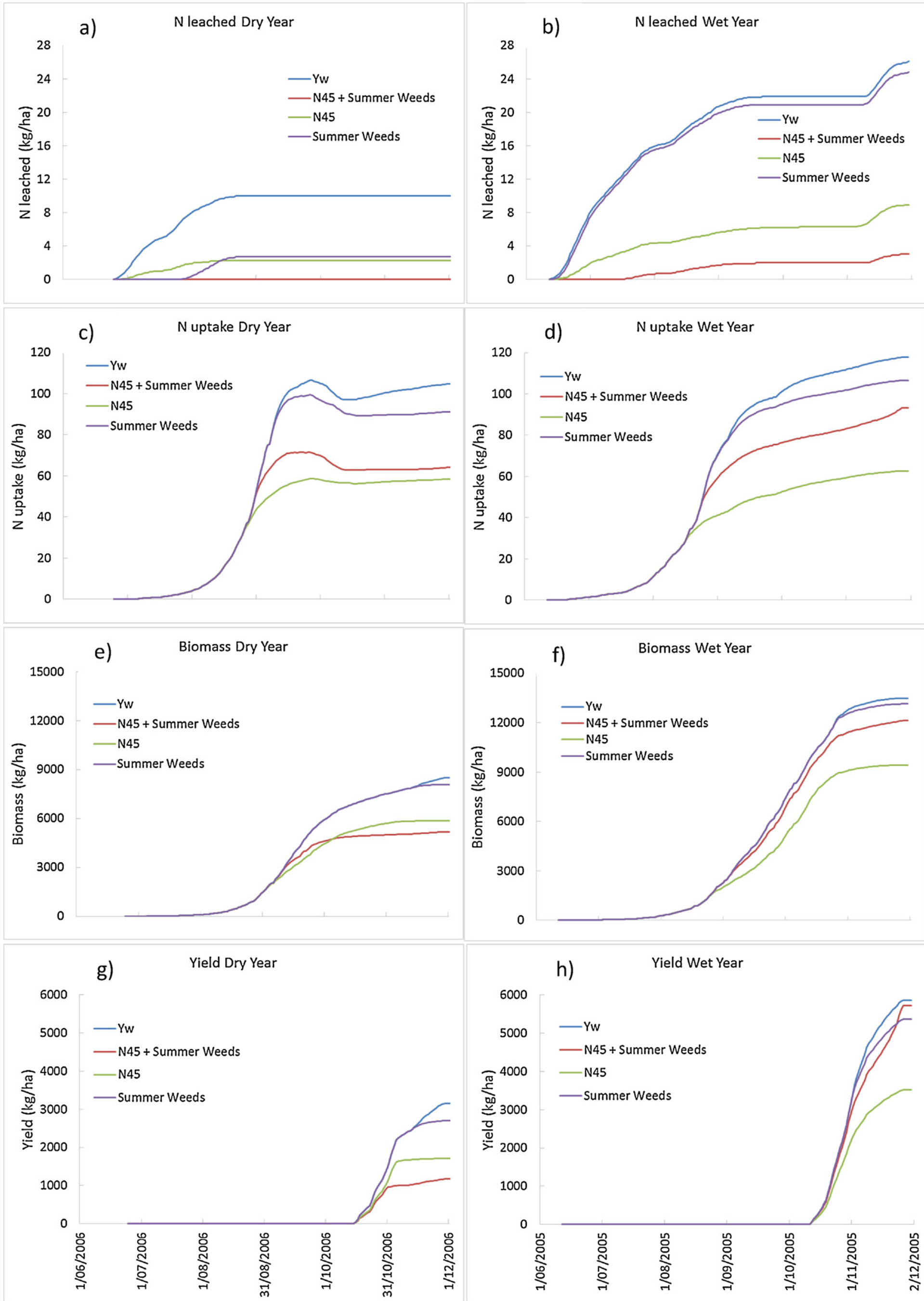

Fig. 3. Comparison of daily cumulative values of N leached (a) and (b), N uptake (c) and (d), total biomass (e) and (f) and grain yield (g) and (h) from sowing to maturity for the Yw, 45 kgN/ha, Summer Weeds and the combined 45 kgN/ha and summer weeds treatments in dry (2006; (a), (c), (e),(g)) and wet (2005; (b) (d), (f), (h)) seasons in Rutherglen, Victoria.

(Fig. 5), yields of the combined (emergent best practice) rules were higher across all environments.

4. Discussion

4.1. Factors that may cause the wheat yield gap

The average amount of nitrogenous fertilisers applied to dryland cereals and oilseeds has recently been estimated at 45 kgN/ha (Angus and Grace, 2017). The current study showed that the impact of using that rate of N fertiliser across 50 sites and 15 years was to reduce %Y to 60% of its water-limited yield (Table 1). In addition to the impact of suboptimal N fertiliser on the yield gap, there is a longer term concern for sustainable cropping. While the total soil nitrogen in the final year of the simulation for Rutherglen remained steady for the Yw treatment, it fell by 14.4 kg/N/ha/yr for the N45 treatment (simulation data not shown). If growers continue to under-fertilise cereal crops such as wheat it is likely that the soil organic nitrogen levels will decline, especially as the area of wheat and other cereal crops grown in sequence with N-fixing pasture legumes continues to decline (Angus and Peoples, 2012).

The average impact of conventional tillage, as simulated through delayed sowing and incorporating stubble, was a 23% reduction in yield potential over the 50 sites and 15 years of this study. However,

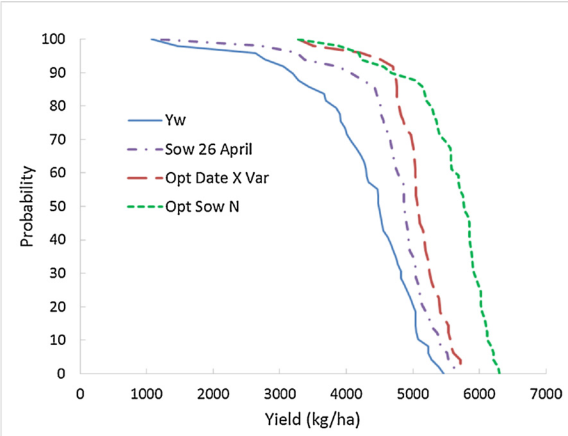

Fig. 4. Impact of emerging management trends on wheat yield potential, where each line interpolates between 50 points that represent the 15 year average of one of the 50 sites simulated. Yw represents the current water-limited yield; Sow 26 April is an emergent practice of sowing into wet or dry soil at the start of the traditional sowing window; Opt Date x Var represents an emergent practice of sowing the optimally maturing variety at the optimal sowing date; and Opt Sow N represents the newly defined optimal N practice required to fully exploit the emerging optimal sowing and variety practice.

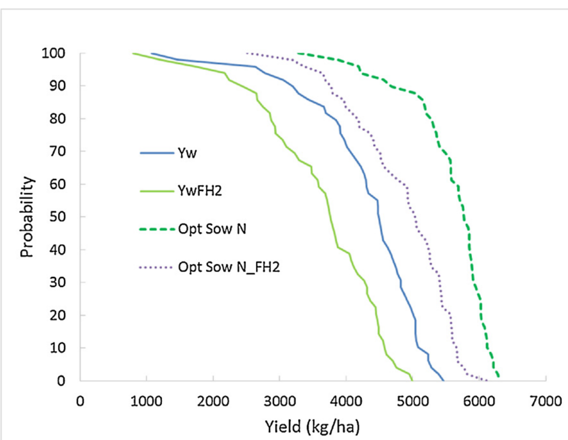

Fig. 5. Impact of frost and heat stress (YwFH2) relative to the current water limited yield potential (Yw) and its impact (Opt Sow N_FH2) on emerging management trend (Opt sow N) where each line interpolates between 50 points that represent the 15 year average of one of the 50 sites simulated.

given the widespread adoption of no-till practices (Llewellyn et al., 2012), this is not likely to be a significant contribution to the current wheat yield gap in Australia. A more likely contributor is the assumed 2 week delay attributed to untimely reaction to favourable conditions due to the need for farmers to balance priorities of different crops, labour and machinery over large cropping areas. The average impact of this delay in time of sowing over the 50 sites and 15 years of this study was a 7% reduction in yield potential. Data from Yield Prophet and from Fletcher et al. (2016) indicate that this 2 week delay is a common event in Australian wheat cropping.

Water-limited yield calculations are based on the assumption that weeds are controlled in the summer fallow period between the harvest of last year's winter crop and the sowing of this season's wheat crop. In practice, many growers tolerate varying degrees of weed infestation which result in loss of stored soil moisture. The average impact of not controlling summer grass weeds over the 50 sites and 15 years of this study was a 26% reduction in yield potential. Given that other studies (Hunt and Kirkegaard, 2011; Hunt et al., 2013; Kirkegaard et al., 2014b) found that weed control increased soil water stored at sowing by up to 70 mm, the results of this study may be an under-estimate of the impact of fallow weeds. Also it should be noted that the impacts of in-crop weeds and particularly of herbicide resistant weeds was not calculated in this study.

Low seedling populations, as represented by the 50 plants/m^2 simulations, had a relatively small impact (12%) on achieving water-limited yield. This result is consistent with the limited experimental literature on this topic (Puckridge and Donald, 1967; Stapper and Fischer, 1990). With the Yield Prophet database indicating a mean sowing rate of 145 plants/m^2 and only a very small proportion of fields reporting less than 50 plants/m^2, it is unlikely that low sowing rates are responsible for a significant portion of Australia's yield gap.

The surprising result that the average yield for the combination of not controlling summer weeds and the 45 kgN/ha treatments is almost equivalent to the average yield from the 45 kgN/ha treatment alone requires some reflection. While it is tempting to see this as an example of Liebig's Law of the minimum, where yield would always be limited to the most limiting factor, in this case the probability distributions of the N45 treatment compared with the combined summer weeds and N45 treatments (Fig. 2g) tells a different story. The combined treatment and the N45 yields have distinct distribution patterns where the N45 yields are clearly higher than the combined treatment yields for sites with lower yield potential (Yw < 4.5 t/ha) but increasingly lower yields for sites with higher yield potential (Yw > 4.5 t/ha). When yield potential is in the range of 2.0–4.5 t/ha, 45 kgN/ha is yield-limiting but summer weeds add to this limitation by reducing PAW and thus further reducing rooting depth, yields and possible N mineralisation. However, for sites with yield potential above 4.5 t/ha the presence of weeds during the summer fallow period improve the yield relative to that of the N45 treatment alone.

This surprising observation may be explained by the Rutherglen site example (Fig. 3) in which daily development of crops was contrasted for a wet and a dry year. Rutherglen was selected as a case study because it is the median yielding site of the 50 sites in the present study. The challenge is to explain why the combined treatment resulted in lower yield than the N45 treatment in a dry year but in a higher yield than the N45 treatment in a wetter year. The simulations showed that both in a wet and in a dry year the N45 treatment leached more N beyond the rooting zone than the combined treatment but the difference was greater in the wet year. In a dry year the combined treatment had a much more limited rooting depth than the N45 treatment and this limited N uptake of the combined treatment to a far greater extent than in the wet year. This effect of restricted rooting depth and N uptake was also reflected in the accumulation of total above ground biomass where the combined treatment fell behind the N45 treatment in the dry year but surged ahead of the N45 treatment in the wet year. The effect on grain yield was even more pronounced due to impact of the harvest index. This reflected a rationing effect of the lower stored moisture at sowing on the use of soil resources (water and more importantly nitrogen in these wetter than average environments) in the early part of the season. This rationing causes the plant to grow more conservatively in the earlier vegetative phase and thus 'save' water and nitrogen for the more critical stages when the grain number and grain weight are determined. Rather than a case of Liebig's Law, this interaction between nitrogen supply and weeds reflects the concept of co-limitations of water and nitrogen as proposed by Sadras et al. (2016).

The practical implication of this analysis is that the biggest single factor required to close the yield gap is to increase the amount of N fertiliser applied to wheat crops in Australia. Conventional tillage, summer weeds, late sowing and low plant density also limit yields but have a lesser impact as single factors and are less prevalent. In the presence of N limitations, the impact of other limiting factors depend on the site yield potential. For sites with lower than average yield potential these factors can be important added limitations and should be corrected. For sites with higher than average yield potential, these management factors may actually be beneficial whilst the N deficiency is

not addressed.

A yield gap of 0.6–1.0 t/ha remains and it may be attributed to a number of biotic causes that were not quantified in this analysis. Accounts of the national impacts of weeds (Llewellyn et al., 2016; https://grdc.com.au/_data/assets/pdf_file/0027/75843/grdc_weeds_review_r8.pdf.pdf), diseases (Brennan and Murray, 1989) and invertebrate pests (Murray et al., 2013; https://grdc.com.au/_data/assets/pdf_file/0026/159281/grdcreportcurrentpotentialcostsinvertebratepests-feb2013pdf.pdf.pdf) collectively suggest yield impacts that are consistent with this gap.

4.2. Potential to expand the yield frontier

Climate trends in the Australian grain zone, particularly increased temperature and declining rainfall during the cropping season (Pook et al., 2009; Cai et al., 2012) together with higher incidence of frost events (Crimp et al., 2016) are reflected in declining water-limited yield and stalled wheat yields since 1990 (Hochman et al., 2017). Closing the yield gap is one way to combat this trend. Another is to use genetic improvement and new management practices to increase the water-limited yield. Several studies have quantified the trend of genetic improvement in wheat at 0.5%/yr (Fischer et al., 2014; Richards et al., 2014). In this paper we provided a quantitative assessment of the potential impact of an emerging (best) practice of sowing on a date that is mostly earlier than the opening of the conventional sowing window using later maturing varieties to take advantage of the potentially expanded growing season. The results of this Australia wide analysis are highly consistent with those of other more regionally constrained studies (Kirkegaard and Hunt, 2010; Hunt et al., 2012; van Rees et al., 2014; Fletcher et al., 2015; Hunt et al., 2015) and more recently also with national studies (Hunt et al., 2018; Flohr et al., 2018). In the present study we found that to take full advantage of this emerging practice it will be necessary to apply more nitrogenous fertiliser. Increasing the national average requirement from 149 kgN/ha to 189 kgN/ha. Implementing this new strategy will require close in-season monitoring of yield potential to ensure that fertiliser is applied only when required to meet the yield potential.

5. Conclusions

This research has produced an estimate that half of the average yield gap of wheat in Australia (i.e. 1.71 t/ha) can be attributed to the low nitrogen fertiliser inputs applied to replace the nitrogen extracted from the soil by crops. Other management practices such as lack of control of weeds during the summer fallow interact with low N by further reducing yield potential in lower yielding sites while improving yield potential in higher yielding sites by sparing crop water use and hence soil nitrogen uptake to the more critical later growth stages. Frost and heat stress (estimated by two alternate functions reflecting uncertainty about their accuracy) may account for between 1.13 t/ha and 0.68 t/ha of the yield gap. A yield gap of 0.6 to 1.0 t/ha remains and this may be attributed to a number of likely causes that were not quantified in this analysis. A quantitative analysis of the impact of suboptimal management of these yield-limiting factors, individually or in combination with each other, remains a challenge worthy of further research.

The yield frontier can be shifted upwards by an average of 30% across the grain zone by adopting an emergent practice that combines three management changes. The first, made possible by new seeding equipment, is to sow early on a site-optimised fixed date. The second is to choose a variety with a maturity type that can take advantage of the longer crop growth period while avoiding increased risk of severe frost damage around anthesis. The third step is to increase the amount of fertiliser N which is applied in the more favoured environments and seasons. Despite the increased frost risk from early sowing, the impact of frost and heat stress reduced the yield potential of both the current and emergent water-limited yields but did not reduce the advantage of the emergent practice.

Closing the current yield gap and shifting the water-limited yield frontier present an opportunity to increase Australia's water and nitrogen-limited wheat yield potential by 3.0 t/ha. That is from 2.6 t/ha, the nitrogen and water-limited yield predicated on current best practice and an average of 45 kgN/ha, to 5.6 t/ha the average water-limited yield predicated on the emergent practice of early time of sowing and later maturity variety choice combined with sustainable, yet non-limiting, nitrogen fertiliser inputs.

The challenge now is to develop strategies that target the growers who are currently well below their current water-limited yield while also supporting those growers who are currently closer to the current yield frontier to realise the potential gains of the emergent best practice technologies.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2018.08.023.

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