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Reprint of "Quantifying yield gaps in rainfed cropping systems: A case study of wheat in Australia"☆

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A R T I C L E   I N F O

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A B S T R A C T

To feed a growing world population in the coming decades, agriculture must strive to reduce the gap between the yields that are currently achieved by farmers (Ya) and those potentially attainable in rainfed farming systems (Yw). The first step towards reducing yield gaps (Yg) is to obtain realistic estimates of their magnitude and their spatial and temporal variability. In this paper we describe a new yield gap assessment framework. The framework uses statistical yield and cropping area data, remotely sensed data, cropping system simulation and GIS mapping to calculate wheat yield gaps at scales from 1.1 km cells to regional. The framework includes ad hoc on-ground testing of the calculated yield gaps. This framework was applied to wheat in the Wimmera region of Victoria, Australia. Estimated Yg over the whole Wimmera region varied annually from 0.63 to 4.12 Mg ha^{-1} with an average of 2.00 Mg ha^{-1}. Expressed as a relative yield ($Y_{\%}$) the range was 26.3–77.9% with an average of 52.7%. Similarly large spatial variability was described in a Wimmera yield gap map. Such maps can be used to show where efforts to bridge the yield gap are likely to have the biggest impacts. Bridging the exploitable yield gap in the Wimmera region by increasing average $Y_{\%}$ to 80% would increase average annual wheat production from 1.09 M tonnes to 1.65 M tonnes. Model estimates of Yw and Yg were compared with data from crop yield contests, experimental variety trials, and on-farm water use and yields. These alternative approaches agreed well with the modelling results, indicating that the proposed framework provided a robust and widely applicable method of determining yield gaps. Its successful implementation requires that: (1) Ya as well as the area and geospatial distribution of wheat cropping are well defined; (2) there is a crop model with proven performance in the local agro-ecological zone; (3) daily weather and soil data (such as PAWC) required by crop models are available throughout the area; and (4) local agronomic best practice is well defined.

1. Introduction

Exploiting the gap between yields currently achieved on farms and those that can be achieved by using the best adapted crop varieties and best crop and land management practices is a key pathway to overcoming the considerable challenge of feeding more than 9 billion people by 2050. Accurate estimates of current exploitable gaps in key crops such as wheat is therefore essential to assess future food production capacity and to help formulate policies and research priorities to ensure local and global food security (van Ittersum and Rabbinge, 1997; Dobermann and Cassman, 2002; Fischer et al., 2009; van Ittersum et al., 2013). A full description of the rational, definitions and assumptions behind yield gap analysis and the need for a yield gap atlas was provided by van Ittersum et al. (2013).

1.1. Yield gap estimation methods for 'data rich' environments

Data rich environments may be characterised as those that have reliable census based statistical data at a regional scale on areas where specific crops are grown and on the annual production of these crops at the same scale. Such data enable us to estimate actual

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farm yields (in Mg ha^{-1}) at this level of aggregation and to upscale these to wider agro-ecological zones and to a national average for targeted crops. Where actual farm yields (Ya) reflect 'farmers' natural resource endowment, their access to technology, and their skill and exposure to real market economics.'

At the smallest unit of data aggregation, there is a great deal of variation in actual yields (Ya) achieved due to differences in soils, local variations in climate and to farmers' management of individual fields. It is therefore important that sufficient data are collected from a representative sample of fields. Consistent collection of such data over periods of 15 or more years can further provide a useful quantification of the volatility of such yields in response to climate variability.

Given that much of the world's cropping areas are rainfed (70% of wheat; Portman et al., 2010), water-limited yield (Yw) is an important concept. Yw can be defined as the yield of an adapted crop variety or hybrid when grown under rainfed conditions without growth limitations from nutrients, pests or diseases. Estimating water limited yield (Yw) at one or two locations, no matter how accurately, cannot be assumed to be representative of Yw for the region or statistical subdivision. The variation in soils and climate inside this area has an influence on Yw so that any method for estimating its value must account for this variation. If geo-referenced and location specific estimates of Yw are made at sites that adequately represent the spatial heterogeneity of the area of interest then Yw estimates can be explored spatially through interpolation and geographical information systems (GIS) techniques.

1.2. Mapping land use and crop areas

For rainfed crops the yield gap (Yg) is the difference between Yw and Ya. The focus of Yg estimates in a geographical region is on current production areas (in this paper region is used to denote a sub state, catchment, or local government area scale in contrast to the geo-political or group of nation-states scale; in Australia, each of the six states has numerous local government entities defined as statistical subdivisions for collection of census information and as shires or catchment regions for local governance purposes). Calculation of both actual and potential yields must be constrained to, and representative of, the specific parts of the region in which the crop of interest is currently being produced. Methods for estimating this area are based on satellite data that match the phenological profile of the crop, combined with data provided by censuses of agricultural producers.

1.3. Quantifying actual yields

Ya is most commonly estimated from statistical data gathered at various levels of spatial detail (Monfreda et al., 2008). Satellite acquired remote sensing data, calibrated against observed field data and a fixed harvest index (Lobell et al., 2010) and data from monitoring of a large number of farmers' fields over a number of seasons (Grassini et al., 2011; van Ittersum et al., 2013; Hochman et al., 2009a) have also been used to estimate Ya.

Precision agriculture and yield mapping technologies currently allow for fine resolution of yield estimates and their variability within a field. However, not enough such data are currently available to provide a robust representation of actual yields over a larger area such as a local statistical area (SLA) or region. More commonly, farmers measure their crop yields on a whole field basis where the area of rainfed wheat fields in the Australian grain zone is typically in the range of 50–300 ha. Average yields calculated from such data are suitable for single point comparisons against measured or calculated potential yields. Data from such fields are collected annually by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) through its Australian Agricultural and Grazing Industries Survey (AAGIS) while the more comprehensive Agricultural Census data are collected every five years by the Australian Bureau of Statistics (ABS, 2009).

1.4. Quantifying water limited yields

Yield contest results (Duvick and Cassman, 1999), the 95th percentile of regional yield statistics (Licker et al., 2010), breeders' trials (Hall et al., 2012), and crop models (Grassini et al., 2011; Hochman et al., 2009a) have all been used to estimate Yw.

Simulation using a locally validated cropping system model can be used to determine Yw at any geospatial location provided that a minimal data set is available including: (1). Daily weather data including minimum and maximum temperatures, rainfall, evaporation and solar radiation; (2) Soil characterisation that matches the local soil type, especially with respect to its water holding capacity; (3) Estimates of soil water status at the time of sowing; (4) A specified best practice that can be consistently applied with regard to time of sowing, sowing density, variety and dates and rates for application of nitrogen fertilizer.

1.5. Quantifying yield gaps

In this paper we propose a framework for realistically estimating Yg by focusing on a case study of rainfed wheat in the Wimmera region (as defined by ABS) of Victoria, Australia. This framework uses various sources of data (local statistical data, satellite data, spatially distributed but site specific historical weather data, soil characterisation data, soil maps) and calculation methods (simulation, GIS mapping) to derive the components of the yield gap. These components (Ya, Yw, cropped area, yield maps) are integrated to achieve spatially and temporally explicit estimates of Yg. The framework includes ad hoc ground testing of Yg and its component parts based on field level monitoring and farmer records.

2. Methods

The proposed framework (Fig. 1) is made up of three layers, a 'data' layer, a 'calculation' layer and a 'ground testing' layer. The role of the data layer is to provide data for input into the other two layers. In the calculation layer, data are used to calculate the yield gap and its distribution in time and space. The ground testing layer uses data and calculation to provide alternative, on-farm or experimental estimates of Ya and Yw where they can be ascertained. Because the yield gap is calculated by the difference of values derived from separate estimation methods, each with its own independent uncertainties, it is difficult to assign an uncertainty value around the calculated yield gap. To partially alleviate this problem, we look for independent, if less systematic, on-ground data that can be used to confirm or refute the values derived in the calculation layer. Considered comparison of the outputs from the calculation layer and the ground testing layer should be used to question the validity of the calculated outputs and to point the way to improvements in the calculation process and if necessary to seek improvement in the input data.

The data layer is divided according to the function for which the data are used. Survey, census and remote sensing data are primarily used in the calculation layer to determine Ya, the area cropped and their spatial distribution. Weather and soil data are used as inputs into cropping system simulation to calculate Yw at multiple geo-referenced points in the region. On-farm data are used in the ground-testing layer to provide alternative (on-ground) sources of assessment of Ya and Yw.

In the calculation layer the area cropped, an aggregated figure for each statistical sub-division is combined with remotely sensed

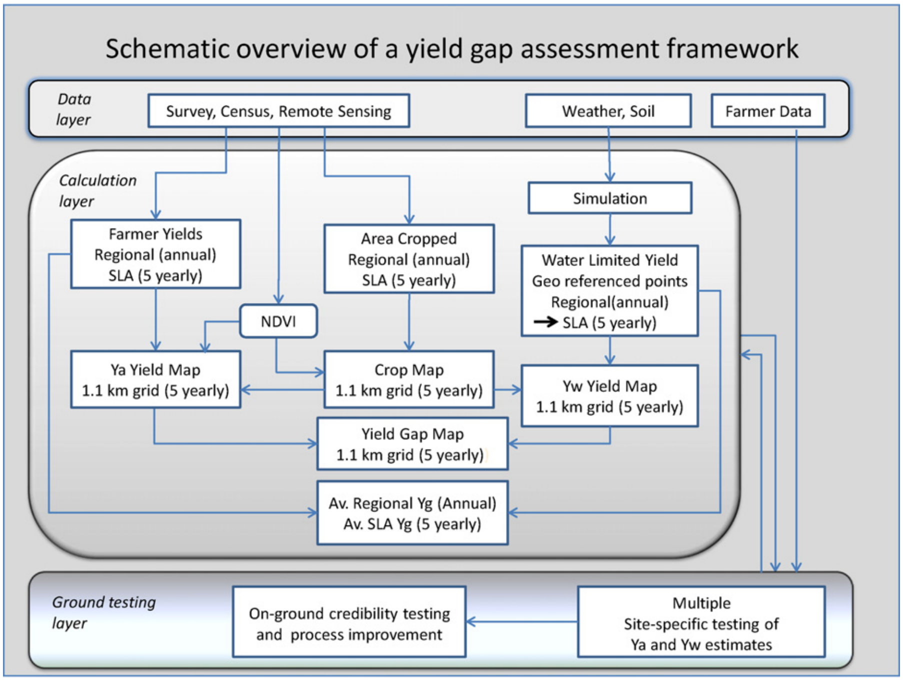

Fig. 1. A systematic framework for Yg assessment.

NDVI to map the area cropped to winter cereals and the crop map is combined with the surveyed Ya data and with NDVI data to produce a Ya yield map. A parallel calculation process is used to combine the crop map with the interpolated simulated Yw estimates to produce a Yw yield map. The calculated Ya and Yw values, at various aggregation levels from 1.1 km cells to SLA to Regional, are then compared and the difference is the yield gap which can also be expressed at a relative yield gap.

The ground testing layer uses data from various sources including on-farm experiments, on-farm crop and soil monitoring data, water-use efficiency frontier data, and crop contest data. Such data are used to calculate Ya and Yw independently of the processes used in the calculation layer. The ground testing results are then considered with regard to their consistency with those derived from the calculation layer.

2.1. The data layer

In this case study the focus is on wheat crops in the Wimmera region in the state of Victoria, Australia. In 2009, the Wimmera produced 922,000 Mg of wheat from 435,000 ha or 4.2% of the Australian wheat harvest from 3.1% of the area sown to wheat (ABS, 2011).

Farmers are surveyed annually by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) through its Australian Agricultural and Grazing Industries Survey (AAGIS). The annual data for wheat are aggregated up from individual farms to SLAs to 11 regions in three ago-climatic zones. The 11 regions in the Australian wheat-sheep zone are viewed by ABARES as the smallest unit for which their annual survey is designed to produce reliable wheat crop estimates (ABS, 2009). These data are available through the Agsurf website (http://abare.gov.au/ame/agsurf/agsurf.asp; last accessed 20 February 2012). The less frequently sampled Agricultural Census data provide reliable crop estimates at the SLA level (there are 7 SLAs in the Wimmera region). At the time of writing the latest agricultural census results were from the 2005/2006 census and as such related to the 2005 wheat crop (ABS, 2008).

Remotely sensed Normalised difference Vegetation Index (NDVI) from the MODIS satellite captures the greenness of a pixel. NDVI data for 2005 were obtained from the MODIS website (http://modis.gsfc.nasa.gov/data/dataprod/dataproducts.php?MOD_NUMBER=13; last accessed 20 February 2012). The weather data used are a subset of a comprehensive archive of Australian climate data (Jeffrey et al., 2001) available through the Silo website (http://www.longpaddock.qld.gov.au/silo/; last accessed 20 February 2012). A map of the plant available water capacity (PAWC) of soils in the region was accessed from a national soils database (Johnston et al., 2003; McKenzie et al., 2005). To represent the range of soils in the region we used soil characterisation data of 5 local soils from a national soils database of over 700 APSIM reference soils in the wheat-sheep zone (Dalgliesh et al., 2009). The soils were selected to represent the range of PAWC values of soils in the Wimmera.

A summary of the various data sources used, the type of data they contain, the scale of data aggregation and the frequency of updates is provided in Table 1.

On-farm data for ground testing were derived from a number of sources:

1. Crop contest yield data from the 2009 Longerenong Cropping Challenge was accessed from the International Plant Research Institute Australia and New Zealand website (http://anz.ipni.net/articles/ANZ0010-EN; last accessed 20 February 2012).
2. Grain yield data from 5 National Variety Trial sites in the Wimmera region in 2009 were accessed through the NVT website (www.nvtonline.com.au; last accessed 20 February 2012).
3. A literature search and personal communication with an experienced local researcher were used to find records of high yielding wheat crops from published reseach station experiments.
4. Thirty subscribers to Yield Prophet (www.yieldprophet.com.au; last accessed 20 February 2012; Hochman et al., 2009b) provided data on their 2007 crop yields as well as on soil types, starting soil water and nitrate to depth, crop management variables such as fertiliser used (dates and rates), wheat variety, time of

Table 1
Varying scale and frequency of data sources used to determine Yg.

No.	Source	Type of data	Scale	Frequency
1	ABARES Survey	Crop area	Farm to region	Annual
2	ABARES Survey	Crop production	Farm to region	Annual
3	ABS Census	Number of farms	Farm to SLA	5 yearly
4	ABS Census	Crop area	Farm to SLA	5 yearly
5	ABS Census	Crop production	Farm to SLA	5 yearly
6	MODIS NDVI	Crop area	1.1 km cells	Every 16 days
7	MODIS NDVI	Peak crop biomass	1.1 km cells	Every 16 days
8	Yield Prophet®	Wheat yields (Ya)	Field	Annual
9	Yield Prophet®	Starting soil water	Field	Annual
10	Yield Prophet®	Actual farm management	Field	Daily
11	APSoil	Soil characterisation	Geo-referenced point	Static
12	ASRIS	Soil PAWC map	Sub-SLA definition	Static
13	Silo patched point	Rainfall	Geo-referenced point	Daily
14	Silo patched point	Temperature (max and min)	Geo-referenced point	Daily
15	Silo patched point	Evaporation	Geo-referenced point	Daily
16	Silo patched point	Radiation	Geo-referenced point	Daily

sowing, seeding rate, etc. These data are associated with a nearby weather station and on-farm rainfall data.

5. One Yield Prophet subscriber supplied additional wheat yield data for the years 1990–2011from a number of fields on his family's farm.

2.2. *The calculation layer*

2.2.1. *Mapping land use and Ya*

A land use map, showing areas most likely to have produced winter cereal crops in the 2005 season, at a spatial resolution of 1.1 km, was generated from ABARE–BRS (2010) dataset. This map is based on SPREAD II (Stewart et al., 2001; Knapp et al., 2006), which uses remotely sensed NDVI data and census information to spatially disaggregate land use within area constraints provided by the agricultural census. The SPREAD II algorithm uses a Bayesian Markov Chain Monte Carlo approach to produce probability surfaces to approximate a maximum likelihood estimate of land use consistent with the area constraints provided by the census. A more detailed explanation of the procedure can be found in Bryan et al. (2009).

Spatially more accurate crop estimates within an SLA can be obtained by intersecting the reported yields with a map (ABARE–BRS, 2010) that shows where individual commodities (in this case wheat) were grown. The reported yields of wheat are then exclusively distributed across pixels that represent wheat crops using a two-step process. First, the reported total production (tons) of wheat within an SLA is divided by the total reported area (ha) sown to wheat. This gives an average value for each wheat pixel within an SLA. A further adjustment of the yield values assigned is then required to account for the spatial variation of wheat yields. We used the peak NDVI value (selected from samples taken every 16 days during the season) for each cell as a proxy of that cell's yield relative to other cells in the SLA. In a second step we therefore produced two surfaces; one that represents the peak NDVI of each pixel and a second layer that represents the average of the peak NDVI values of the full set of wheat pixels within each SLA. Finally, the yield for each pixel was adjusted by multiplying the originally assigned (SLA average) yield value by the ratio of the peak NDVI of each pixel to the average peak NDVI for wheat in the SLA (Marinoni et al., 2012). Using this approach, a detailed Ya map was produced for the Wimmera region for 2005, the last year for which SLA level data was available.

2.2.2. *Calculating and mapping Yw*

To account for the Wimmera region's spatial and temporal variability we used 30 years of weather data from 56 local weather stations in and surrounding the Wimmera. Simulations were set up in APSIM (Keating et al., 2003) a cropping systems simulator that has been previously validated against both research yields (Asseng et al., 1998; Hochman et al., 2007; Wang et al., 2003) and farmer yields (Carberry et al., 2009; Hochman et al., 2009a). Management settings were based on a zero till, stubble retained continuous wheat cropping system and a 'Yield Maximising' management strategy that was shown to achieve an average WUE close to the WUE boundary (and hence grain yields close to Yw) in 334 fields in the Australian wheat zone (Hochman et al., 2009a). This management strategy specifies a sowing density of 150 plants per m^2, sowing date to occur as soon as at least 15 mm of rain accumulates over a consecutive 3-day period after the 24th of April, and 50 kg N ha^{-1} fertiliser to be applied between sowing and anthesis whenever soil nitrate in the root zone falls below 50 kg N ha^{-1}. Because Yitpi was the most commonly used variety in the fields simulated in this study, indicating that it is was the preferred variety among leading farmers in the region, we used it as part of the 'Yield Maximising' strategy.

In the absence of data on soil moisture conditions at the start of the season, we chose 1981 as the starting year and set available soil moisture at the start of the simulation to a modest 10%. We chose 1981 as the starting year because it was a favourable season followed by a severe drought season in 1982. We expected this combination of seasons to correct any errors in the starting condition and we discarded the first five years of Yw outputs to allow the simulations to self correct for any residual errors. The usable simulations provided a factorial combination of 26 years × 56 stations × 5 soils to produce a matrix with 7280 Yw outcomes.

We used the GIS technique of Inverse Distance Weighting (IDW; Shepard, 1968) to interpolate the simulated Yw outcomes for each of the 56 stations and 5 soils to create a grid surface per year from 1986 to 2011 for each soil. The 5 soil specific grids were then mosaiced to match the mapped soil type (Digital Atlas of Australian Soils), and further clipped to the extent of the NDVI derived winter cereals cropping area (described in Section 2.2 above). For 2005, Yw values were aggregated up to SLA and Regional (Wimmera) level for comparison with average farmer yields from the statistical data.

2.2.3. *Yield gap based on the difference between Ya and Yw*

For each year of the study, the yield gap (Yg) was calculated from the difference between the average yields obtained by aggregating the spatially distributed Yw yields to the regional scale and the average regional yield as determined in the ABARES statistical surveys (Ya). Table 2 provides a summary of the various data sources used in estimating each component of Yg, indicating the scale of aggregation and the frequency of measurements of these data.

Table 2
Data sources used in estimation of components of Yg.

Id.	Estimate	Function of (no. in Table 1 or Id. this Table)	Scale	Frequency
A	Land use	4,6	1.1 km	5 yearly
B	Area cropped	1, A	Region	Annual
C		1,2	Region	Annual
D	Ya	3,4,5	SLA[a]	5 yearly
E		3,4,5,6,7	1.1 km	5 yearly
F	Yw – WUE Boundary	9,13	Field	Once
G	Yw – Simulated	B, 11,12, 13,14,15,16	1.1 km	Annual
H	Yg – WUE Boundary	F, 8	Field	Once
I		G,C	Region	Annual
J	Yg – Simulated	G,D	SLA	5 yearly
K		G,E	1.1 km	5 yearly

[a] Statistical Local Area.

The yield gap was also expressed as a relative yield ($Y_{\%}$) calculated by applying Eq. (1):

$$Y_{\%} = \frac{100 \times \text{Ya}}{\text{Yw}} \tag{1}$$

For 2005, Yg was also calculated from the difference between the average yields obtained by aggregating the spatially distributed Yw yields for each SLA and the average Ya values from the 2005/6 ABS census for each SLA. By comparing each cell of the 2005 Ya map with the same cell in the 2005 Yw map we produced a Yg and a $Y_{\%}$ map to show the spatial trends in yield gaps in the Wimmera region.

As a farmer's yields approach Yw, the law of diminishing returns would suggest that further gains will become more difficult and less economically attractive to achieve. Consequently, average farm yields can be expected to peak at 75–85% of Yw. We therefore distinguish between the absolute yield gap (Yg) and the more pragmatic exploitable yield gap. For rainfed wheat we define exploitable yield gap as Yw × 0.80 – Ya.

2.3. The ground testing layer

2.3.1. Crop contest data for estimating Yw

Crop contests have fallen out of favour in Australia over the past two decades or so. However, in 2009 the Longerenong College held a contest called the Longerenong Cropping Challenge, in which 14 teams made up of local agronomists, consultants, farmers, college staff and students attempted to grow the most profitable crop in the same field.[1] Treatments were all applied by college staff but varied in fertiliser applied, variety, sowing date, etc. We review the results of this contest as an example of an on-ground estimate of Yw in a single season and a single location in the Wimmera region.

2.3.2. National variety trials (NVT) and experiment station data for determining Yw

Wheat variety testing is conducted annually at the Grain Research and Development's (GRDC) NVT trial network of around 100 trial sites throughout the wheat zone. Current and recently released varieties are compared in replicated small plot trials conducted either on farms or on research stations. In 2009 there were 6 such sites in the Wimmera region. We investigated the results of these trials as a possible source of on ground data for confirming predicted Yw.

The Wimmera region has a significant agricultural research facility. The Grains Innovation Park Horsham was established in the 1960s. We investigated the published yield data from this Victorian Department of Primary Industries centre to ascertain evidence of high yields.

2.3.3. Farmer data (Ya) from 30 individual fields in 2007

The grain yield data from 30 individual commercial fields in the Wimmera were supplied by subscribers to Yield Prophet. The mean Ya values from these fields and their standard deviations were compared to the regional Ya values in the region for the 2007 crop.

2.3.4. Yw based on the WUE of Yield Prophet fields

Data for calculating WUE were available for the 30 Yield Prophet fields of Section 2.3.3. We explored the yields that could have been achieved on these fields at the WUE boundary as calculated by using Sadras and Angus (2006) WUE function:

$$\text{Yw} = (\text{water use} - 60) \times 22 \tag{2}$$

where: water use is estimated by adding plant available soil water at sowing to in-crop rainfall. In this analysis the pre-sowing plant available soil water was measured gravimetrically in the field. This use of measured soil water data is a point of difference from previous Australian broad-scale WUE studies (e.g. Stevens et al., 2011).

2.3.5. A farmer's 16 year Yg history

In addition to applying a subjective plausibility test, based on expert knowledge of the region, to the Yw maps we sought to ground test the maps at a specific location by comparing the interpolated Yw outcomes against an elite farmer's wheat yield records. For each year from 1996 to 2011 we compared Ya from the farmer's best yielding wheat fields, in a high yield potential area between Horsham and Stawell, against the interpolated Yw for the same location and years.

3. Results

3.1. Calculation layer results

3.1.1. Estimating and mapping farmers' yields (Ya)

The Wimmera study region, its SLAs and the towns in and around it are shown with the location of the Wimmera region outlined on an inserted map of the Australian continent (Fig. 2a). The area cropped to winter cereals, the location of weather stations and a map of the estimated soil PAWC values in the Wimmera region are indicated in Fig. 2b and c. AgSurf data for the 20 years from 1990 to 2009 (Table 3) show that both the area sown per farm unit (average = 120 ha) and the average yield per hectare (2.21 Mg ha^{-1}) varied considerably from year to year with respective standard deviations (Sd) of 38 ha and 0.84 Mg ha^{-1}. These results illustrate the impact of climate variability on actual yields. The impact of the drought period from 2002 to 2008 masks any yield increases from technology improvements that might have otherwise been expected over the 20-year period.

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[1] While the contest aimed to reward the most profitable crop, the highest yielding crop in the contest was not the most profitable. Here we focus on the production data.

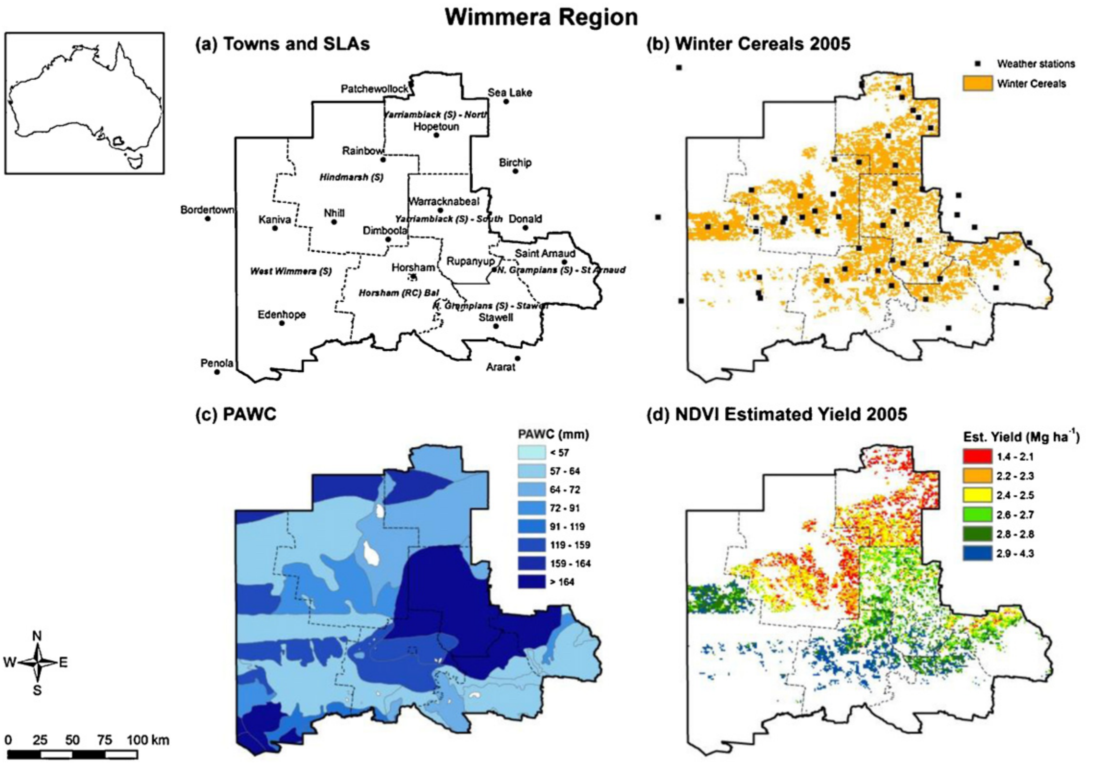

Fig. 2. Maps of the Wimmera region with (a) Statistical Local Areas (SLAs) and towns, (b) location of cereal cropping areas and weather stations, (c) soil plant available water characteristics, and (d) spatial distribution of farm yields in the 2005 season.

A more detailed estimate of the spatial distribution of wheat grain yields for 2005, when the latest available Agricultural Census data provided crop estimates at the SLA level, is provided in Table 4. Mean SLA yields ranged between 2.10 Mg ha^{-1} in Yarriambiack – North and 3.02 Mg ha^{-1} in N. Grampians – St Arnaud. Further disaggregating the 2005 yield values by using the remotely sensed NDVI data resulted in a detailed spatial map of Ya in the Wimmera region (Fig. 2d).

Table 3
Average wheat production per farm in the Wimmera region.

Year	Wheat area sown (ha)	Wheat produced (Mg)	Yield (Mg ha^{-1})
1990	100	203	2.03
1991	71	177	2.49
1992	85	255	3.00
1993	103	313	3.04
1994	96	126	1.31
1995	109	315	2.89
1996	71	215	3.03
1997	97	167	1.72
1998	80	159	1.99
1999	107	285	2.66
2000	118	364	3.08
2001	116	366	3.16
2002	133	50	0.38
2003	156	433	2.78
2004	126	227	1.80
2005	223	582	2.61
2006	142	83	0.58
2007	172	267	1.55
2008	145	213	1.47
2009	153	406	2.65
Mean	120	260	2.21
Sd	38	128	0.84

Source: ABARES Agsurf website.

Table 4
Average wheat production per Statistical Local Area in the Wimmera region in 2005.

SLA	Area (ha)	Wheat produced (Mg)	Yield (Mg ha^{-1})
Hindmarsh	75,149	168,967	2.25
Horsham	40,255	117,733	2.92
N. Grampians – St Arnaud	18,650	45,043	2.42
N. Grampians – Stawell	11,487	34,693	3.02
West Wimmera	42,646	124,684	2.92
Yarriambiack – North	157,005	329,526	2.10
Yarriambiack – South	149,032	379,041	2.54
Wimmera region	494,257	1,199,703	2.43

Source: ABS (2008).

3.1.2. *Estimating and mapping water limited yield potential (Yw)*

Statistical analysis of the results of simulation of 56 weather stations by 5 soil types over 26 years (Table 5) showed significant effects ($p < 0.001$) of location (station), season (year) and soil type (PAWC). There are also significant interactions ($p < 0.001$) between location and season, between location and soil type and between

Table 5
Analysis of variance of results of simulated grain yield; response to location (weather station), season (Year) and soil PAWC.

	Df	Sum Sq	Mean Sq	*F* value	Pr (>*F*)
PAWC	4	1550.7	387.67	321.13	<0.001
Station	55	8422.6	153.14	126.85	<0.001
Year	25	12706.7	508.27	421.03	<0.001
Residuals	7325	8842.8	1.21		
Year × Station	1375	6584.9	4.79	7.487	<0.001
Residuals	5954	3808.5	0.64		
PAWC × Station	220	224.9	1.02	0.3417	NS
Residuals	7130	21324.6	2.99		
PAWC × Year	100	782.8	7.83	3.4575	<0.001
Residuals	7280	16482.5	2.26		

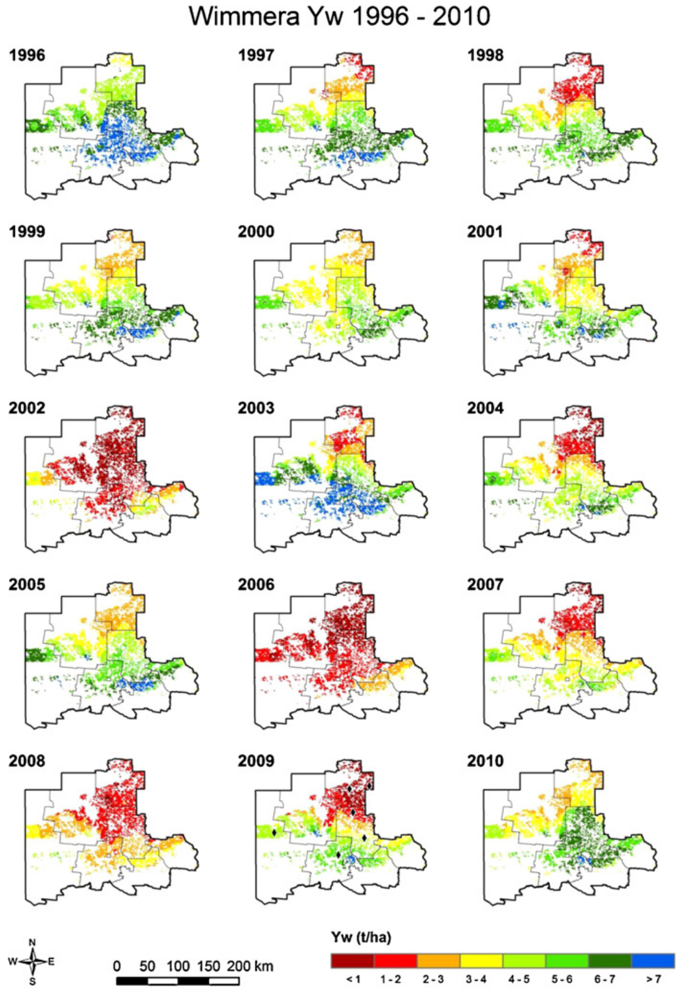

Fig. 3. Annual variation and spatial distribution of Yw in the Wimmera, 1996–2010. Values were simulated using 56 weather stations and corresponding PAWC map values and spatially distributed onto "winter cereal" cells of the 2005 land use map (Black diamond symbols represent location of NVT sites in 2009 map).

soil type and season. This analysis demonstrates that Yw is sensitive to these three variables in a complex way that requires adequate representation of these factors in the region. A map representing simulated potential yields, taking into account location, soil PAWC and seasons (Fig. 3) illustrates the spatial and temporal variation in Yw in the Wimmera for the years 1996–2010.

Table 6
Annual yield gap estimates based comparison of spatially aggregated simulated Yw and statistically determined Ya (Source ABARES Agsurf website) for the Wimmera region of Victoria.

YEAR	Yw (Mg ha^{-1})	Ya (Mg ha^{-1})	Yg (Mg ha^{-1})	$Y_{\%}$ (% of =Yw)
1990	3.73	2.03	1.70	54.4
1991	5.06	2.49	2.57	49.2
1992	7.12	3.00	4.12	42.1
1993	6.51	3.04	3.47	46.7
1994	2.95	1.31	1.64	44.4
1995	5.30	2.89	2.41	54.5
1996	6.17	3.03	3.14	49.1
1997	4.95	1.72	3.23	34.7
1998	4.25	1.99	2.26	46.9
1999	4.75	2.66	2.09	56.0
2000	4.21	3.08	1.13	73.1
2001	4.45	3.16	1.29	70.9
2002	1.45	0.38	1.07	26.3
2003	5.32	2.78	2.54	52.2
2004	3.54	1.80	1.74	50.8
2005	4.65	2.61	2.04	56.1
2006	1.24	0.58	0.66	46.8
2007	3.04	1.55	1.49	50.9
2008	2.10	1.47	0.63	69.9
2009	3.40	2.65	0.75	77.9
Mean	4.21	2.21	2.00	52.7
Std	1.57	0.84	0.98	12.7

3.1.3. *Estimating and mapping of Yg and $Y_{\%}$*

Next we calculated annual Yw for the whole region by aggregating all individual cell values to produce a spatially weighted Yw and compared it to the region's statistical Ya for each year from 1996 to 2009 to calculate Yg and $Y_{\%}$ (Table 6). Annually estimated yield gaps ranged from 0.66 Mg ha^{-1} in 2006 to 4.12 Mg ha^{-1} in 1992 with an average Yg of 2.00 Mg ha^{-1} (Std = 0.98). $Y_{\%}$ ranged from 26.3% in 2002 to 77.9% in 2009 with an average $Y_{\%}$ of 52.7% (Std = 12.7%). On average an exploitable yield gap was observed every year for the region as a whole.

Given that Ya data for the 2005 season were available at the finer SLA resolution we were able to estimate Yg and $Y_{\%}$ at the SLA level (Table 7). Yg was largest for N. Grampians – Stawell (4.41 Mg ha^{-1}) and least for Yarriambiack – North (0.60 Mg ha^{-1}). Similarly, $Y_{\%}$ was highest (77.7%) at Yarriambiack – North and lowest (35.5%) at N. Grampians – Stawell. The spatial variability that we found for Ya and Yw was echoed in the spatial variability of Yg and $Y_{\%}$. By combining the data from Figs. 2(d) and 3 (2005 map), Yg and $Y_{\%}$ can be calculated for each 1.1 km cell for the year 2005 (Figs. 4 and 5, respectively) to show in greater detail where the largest gaps are likely to exist.

3.2. *Ground testing layer results*

3.2.1. *Crop contests as a basis for determining Yw*

The amount of growing season rainfall in Longerenong for the 2009 'Longerenong Challenge' was in the top 20 percent of historical records with yield potential being limited by unusually hot conditions that prevailed during grain filling. The calculated Yw at this location in 2009 was 5.23 Mg ha^{-1}. The 14 yield outcomes in this competition ranged from 0.95 to 4.93 Mg ha^{-1} with a mean of 3.67 mg ha^{-1}. The winning yield of 4.93 Mg ha^{-1} (followed closely by a 4.82 Mg ha^{-1} yield) was close to Yw and thus confirms Yw for this grid cell in 2009.

3.2.2. *National Variety Trials (NVT) and experiment station data for determining Yw*

Fig. 6 shows the distribution of yields at six NVT sites in 2009. If one could always pick the best variety, the average yield across the five sites would be 2.67 Mg ha^{-1}. If by contrast, variety choice is completely random, then yields across the sites would be 2.14 Mg ha^{-1}. If the top 30% of yields represent managers with good knowledge of variety choice for their field then yields for such farmers would be 2.58 Mg ha^{-1}. Given this range of outcomes, it seems that the NVT trial results for 2009 were close to the regional

Table 7
Yield gap estimates based on comparison of spatially aggregated simulated Yw and statistically determined Ya (Source ABS, 2008) for the seven Statistical Local Areas of the Wimmera region of Victoria in 2005.

SLA	Yw (Mg ha^{-1})	Ya (Mg ha^{-1})	Yg (Mg ha^{-1})	$Y_{\%}$ (% of =Yw)
Horsham	5.82	2.25	3.57	38.7
N. Grampians – St Arnaud	5.76	2.92	2.84	50.7
N. Grampians – Stawell	6.83	2.42	4.41	35.5
West Wimmera	6.23	3.02	3.21	48.5
Hindmarsh	3.88	2.92	0.96	75.2
Yarriambiack – North	2.70	2.10	0.60	77.7
Yarriambiack – South	4.74	2.54	2.20	53.6
Wimmera region	4.65	2.43	2.22	52.3

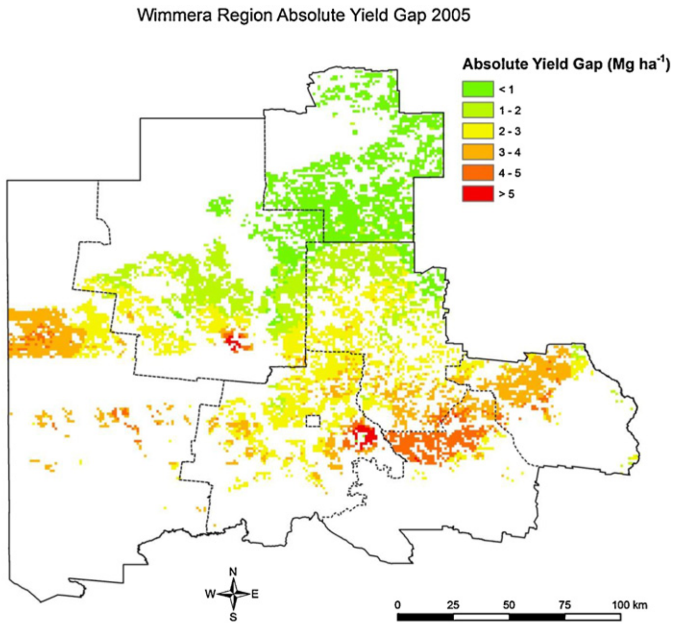

Fig. 4. Spatial distribution of Yg in the Wimmera in the 2005 season. Each cell value was derived by subtracting Ya from Yw for each "winter cereal" cell.

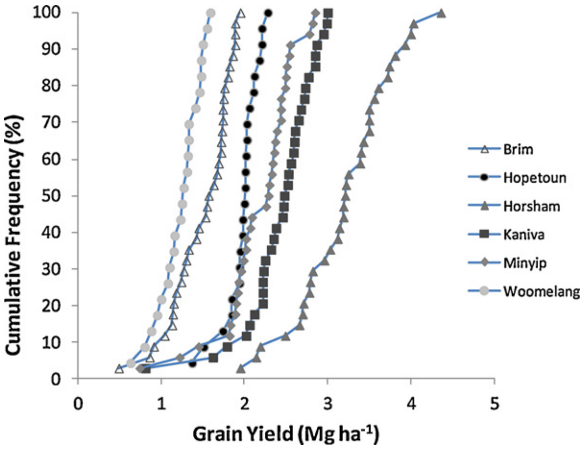

Fig. 6. Grain Yield distribution at six National Variety Trials (NVT) sites in the Wimmera in 2009. Each line represents a site and each point in a line represents a wheat variety.

Ya average (2.65 Mg ha^{-1}) and well below Yw. NVT site yields (top 30%) showed a high correlation (R^2 = 0.86) with Yw of cells within two kilometres of the sites. However, while they yielded above Yw at low yielding sites, at sites with yields above 3 Mg ha^{-1} Yw yields were considerably higher (data not shown). These observations are consistent with the management regimes (e.g. mid season sowing dates, no fungicides, and sub-optimal fertilisers) that were implemented at these trials in past years. Another issue might be that the other four NVT sites over-represented lower yielding parts of the Wimmera region (as indicated on 2009 map in Fig. 3).

A search of the literature from the Grains Innovation Park Horsham (backed up by personal communication with Gary O'Leary) revealed few examples of yields above 5 Mg ha^{-1}. The highest yield found was 5.72 Mg ha^{-1} at zero water content or 6.5 Mg ha^{-1} at 12% water content, recorded in 1981 (Cantero-Martinez et al., 1995). While these results may appear to suggest caution with regards to the simulated Yw values in this study, evidence from comparable research stations in the Australian grain zone suggest that on average WUE is about 15–16 kg grain ha^{-1} mm (Cornish and Murray, 1989; Siddique et al., 1990) compared with the WUE boundary value of 22 kg grain ha^{-1} mm, suggesting that research station yields may be about 30% below water limited yields. Indirect support for higher Yw comes from irrigated wheat experiments elsewhere in South Eastern Australia (Stapper and Fischer, 1990; Steiner et al., 1985). Given that in some seasons parts of the Wimmera are not limited by available water such experiments provide evidence in support of yields in excess of 8 Mg ha^{-1} for the most favourable combinations of season and location.

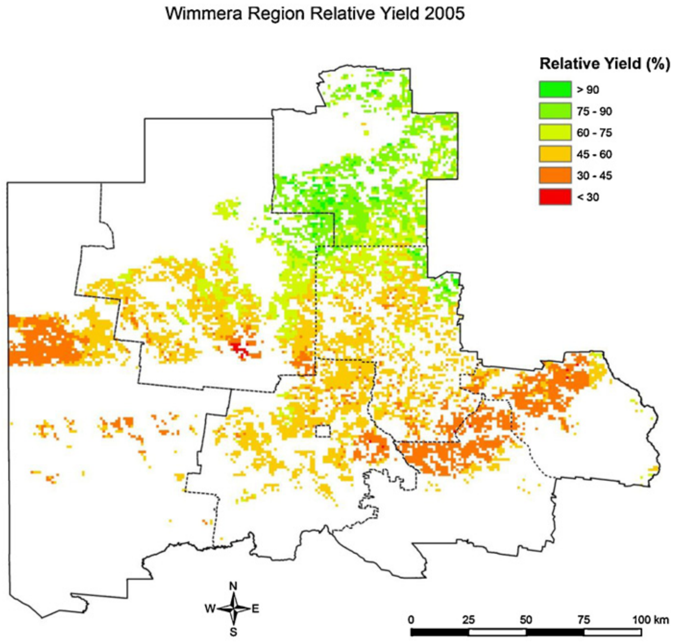

Fig. 5. Spatial distribution of $Y_{\%}$ in the Wimmera in the 2005 season. Each cell value was derived by expressing Ya as a percent of Yw for each "winter cereal" cell.

3.2.3. Yield gap based on the WUE of Yield Prophet Fields

For the 30 fields monitored for WUE in 2007, Table 8 showed that available water averaged at 234 mm (Sd = 52) and grain yields (Ya) averaged 1.98 Mg ha^{-1} (Sd = 0.77). The average Yw, based on the WUE boundary formula was 3.5 Mg ha^{-1} (Sd = 1.44). The average gap between Ya and Yw yields was 1.51 Mg ha^{-1} (Sd = 0.79).

The average result produced by this on-ground yield gap assessment was close to the calculated Yg value derived for the whole region in 2007 from the calculation layer methods (1.49 Mg ha^{-1}). As such the WUE frontier method of estimating Yg provided strong on-ground support for the simulation based calculation method, at least in a particular year.

An average $Y_{\%}$ of 57.7% (Sd = 16.1%) derived from the WUE frontier method indicates that an exploitable yield gap exists for Wimmera farmers who subscribe to Yield Prophet even though these farmers are regarded as elite farmers. The yield results also illustrate the considerable spatial variability in Ya and Yw among Yield Prophet fields in the region. The extent to which these farms can be considered to be representative of the region is unclear given that Ya for these farms in 2007 averaged at 1.98 Mg ha^{-1} compared with the regional statistical Ya average of 1.55 Mg ha^{-1} for the same year. The difference between these fields and the regional average in $Y_{\%}$ (57.7% compared with 50.9%) suggests that these farmers are more proficient while the similarity in absolute Yg values suggests that they are also fortunate to be located in better than average environments.

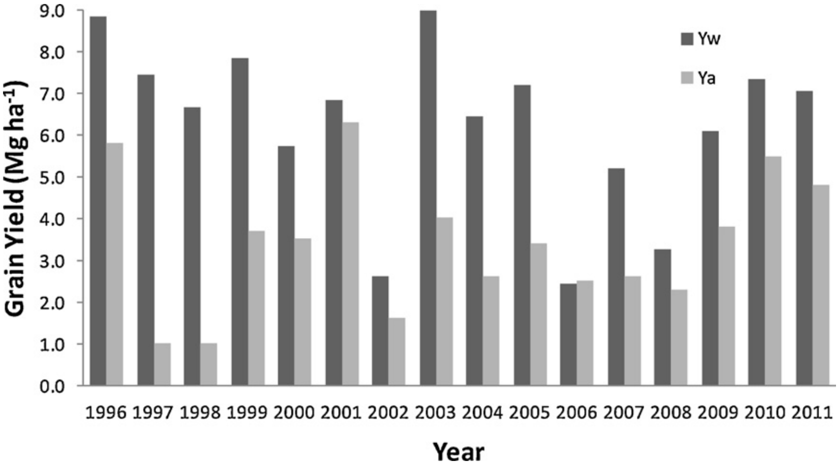

Fig. 7. Comparison of Ya based on records of a single farmer's field and Yw based on crop simulation at the matching geo-referenced cell location over 15 years (1996–2011).

3.2.4. One farmer's Yg history

Ya of this farm's best yielding fields 1996–2011 (mean Ya = 3.4 Mg ha^{-1}) were well below the interpolated Yw (mean Yw = 6.3 Mg ha^{-1}) for the same years (Fig. 7). The resulting mean Yg value on this farm was 2.4 Mg ha^{-1} and the mean $Y_{\%}$ was 54%. The largest yield gaps on this farm occurred in 1997 and 1998. In 1997 the yield was severely reduced by a hail storm and the insurance company's loss adjuster assessed damages at 3.5–4 Mg ha^{-1} for various fields. In 1998 a severe stem frost caused widespread damages to crops over a large area in the Wimmera including this farm. In 2001 and 2006 Ya was close to Yw and in 2010 an experiment on canopy management (controlling pests and diseases and experimenting with timing and amounts of N fertiliser) yielded 7.7 Mg ha^{-1} (Nick Poole, unpublished data) providing further support for the simulated Yw values. After excluding 1997 and 1998 data from the analysis, the average Yg value was 2.4 Mg ha^{-1} and $Y_{\%}$ was 63%. These results suggest that while this farm is achieving above average yields, notwithstanding its favourable location, there is still an exploitable yield gap, especially in more favourable seasons. Simulation of yields based on the farmer's inputs including nitrogen fertiliser, sowing dates, seeding rates and variety choice resulted in a mean yield of 3.3 Mg ha^{-1} compared with the observed mean of 3.4 Mg ha^{-1}. The simulated yields exceeded observed yields only in 1997 and 1998 (data not shown). Given that the farmer always applied high seeding rates and timely sowing dates, it is likely that the main factor contributing to the gap between Ya and Yw on this farm was the amount of nitrogen applied, especially in years with Yw greater than 4 Mg ha^{-1}.

Table 8
Water use efficiency based yield gap estimates of 30 Yield Prophet fields in the Wimmera region in 2007.

Field number	Available water[a] (mm)	Ya (Mg ha^{-1})	Yw (Mg ha^{-1})	WUE Yg (Mg ha^{-1})	$Y_{\%}$ (%)
1	274	2.33	4.37	2.04	53.3
2	273	2.70	4.37	1.67	61.8
3	273	2.40	4.37	1.97	54.9
4	273	2.70	4.37	1.67	61.8
5	309	2.49	5.14	2.65	48.4
6	312	3.70	5.21	1.51	71.0
7	226	2.20	3.33	1.13	66.1
8	281	3.20	4.54	1.34	70.5
9	207	1.48	2.91	1.43	50.9
10	210	1.48	2.96	1.48	50.0
11	269	3.20	4.27	1.07	74.9
12	183	1.20	2.38	1.18	50.4
13	286	2.30	4.63	2.33	49.7
14	215	2.30	3.09	0.79	74.4
15	168	0.90	2.04	1.14	44.1
16	162	1.10	1.91	0.81	57.6
17	191	1.20	2.54	1.34	47.2
18	253	0.90	3.92	3.02	23.0
19	262	2.00	4.11	2.11	48.7
20	184	1.70	2.40	0.70	70.8
21	227	1.70	3.34	1.64	50.9
22	220	1.95	3.20	1.25	60.9
23	248	2.60	3.80	1.20	68.4
24	199	0.65	2.72	2.07	23.9
25	164	1.85	1.96	0.11	94.4
26	162	1.38	1.90	0.52	72.6
27	183	2.10	2.38	0.28	88.2
28	330	1.93	5.61	3.68	34.4
29	162	1.00	1.92	0.92	52.1
30	310	2.90	5.16	2.26	56.2
Mean	234	1.98	3.50	1.51	57.7
Sd	52	0.77	1.14	0.79	16.1

[a] Available water includes available water at sowing plus in-crop rainfall.

The comparison in Fig. 7 illustrates that the high Yw values calculated in this study are realistic. However it also shows that APSIM (in common with other models of its kind) does not account for rare and extreme events such as severe frosts and hail storms and may consequentially be overly optimistic about Yw in some seasons and some locations (2 out of 16 seasons at this location). The risk that such events pose certainly accounts for many farmers' risk averse tendencies.

While acknowledging that caution is required when interpreting the evaluation of data for one of 7991 geo spatial grid cells on a map, the value of such ground testing is both indicative of the difficulty of 'validating' yield gaps and illustrative of the desirability of triangulation of methodologies to provide a compelling quantitative case regarding the likely size of the yield gap.

4. Discussion

4.1. Reflecting on methods

The focus of yield gap estimation is to establish the size of the gap that is caused by suboptimal management of pests and diseases, nutrient supply, time of sowing, crop density, and variety choice. This case study has consistently illustrated that, at a regional scale, Ya, Yw and Yp are subject to large spatial (Figs. 2–6 and Tables 4, 5, 7 and 8) and temporal (Figs. 3, 4, 5 and 7, and Tables 3, 5, 6 and 8) variability of a magnitude that, if not properly accounted for, could lead to large errors in estimating the yield gap due to management. The implication of this is that, at the regional level, Yg must be determined at a sufficient number of locations to adequately represent the regions' spatial variability (both soil and climate related) and over a number of years that adequately represent climatic seasonal variability. The proposed framework of Fig. 1 provides a method that is well equipped to represent this variability.

Despite this case study having the luxury of access to a relatively rich set of data, we must remain mindful that the data were not collected for the purpose of determining yield gaps their suitability for this purpose is uneven. Table 1 illustrates the different scales and frequency of data observations that were used in this study. In estimating the various components of the yield gap (Table 2) there is a need to integrate data of different scale and frequency. The need to use mixed sources in this way reduces the accuracy with which the yield gap can be determined.

Allocating Ya values to the 1.1 km land use cells is a case in point. Land use is allocated probabilistically to each cell. NDVI values were used to allocate a yield value to the whole of each cell with a designated land use of "winter cereals". This process does not account for the fact that some cells cover more than one field and may contain a mix of crop or land use types or that part of the cell may be in fallow. Consequently, some error in estimating yields of individual cells is inevitable. However, the extent of this problem is reduced in situations such as the Australian cropping zone since wheat crops tend to dominate the landscape. Furthermore, since the calculation method incorporates the Ya value over the whole SLA, the errors in individual cells must average out within each SLA. Higher resolution land use mapping would reduce this error.

There are a number of sources of error in determining Ya. These include the error in the yield and land area data collected by the ABS and ABARES, the allocation of land use to cells, the assumption of uniform land use within cells, and the use of NDVI as an indicator of relative grain yield. Estimating uncertainty in Yw is also subject to sources of error including in the quality of weather and soil data, model errors and model parameter errors. Defining uncertainty in estimating yield gaps is likely to be a major challenge requiring further research.

The mismatch in data for Ya and Yw means that Yg can best be determined by estimating each separately at many sites and over many years to determine if a robust estimate of the difference between the two values emerges. In Australia, on farm experiments, crop contests and national variety testing are not numerous enough to provide a reliable estimate of either Ya or Yw at a regional scale in their own right. However they can provide valuable data for ground testing Yg and as such they make a valuable contribution to the overall framework. Consideration should be given to establishing strategically located reference sites to provide a more reliable ground testing data set for simulated Yw values. Agreed management and measurement protocols applied to designated farmers' fields would ensure a uniform benchmark Ya is available for comparison with simulated yields at these locations.

4.2. Reflecting on the yield gap in the Wimmera region

The full spatial and temporal simulation analysis of the whole Wimmera region over 26 years (Table 6) resulted in annually estimated yield gaps of 0.66–4.12 Mg ha^{-1} with an average Yg of 2.00 Mg ha^{-1}. On ground testing of this estimate through a yield contest, WUE boundary analysis of 30 farms and a farmer's long term wheat grain yield record produced results that were consistent with this range of values. We propose that there is a compelling case for the framework of Fig. 1 and the resultant assessment of the magnitude of the yield gap in the Wimmera region.

Given that a relative yield of 80% is the exploitable yield for rainfed crops in a variable climate, that the area of the Wimmera cropped to wheat in 2005 was 494,257 ha and that the average Ya between 1990 and 2009 was 2.21 Mg ha^{-1}, we can calculate that exploiting the yield gap by increasing relative yields from 53% to 80% will increase wheat produced in the Wimmera region from an average of 1,092,308 tonnes to 1,648,767 tonnes per annum.

The more detailed spatial analysis of the yield gap indicated which SLAs within the region are already close to achieving the exploitable yield (Yarriambiack – North and Hindmarsh) and which SLAs (e.g. N. Grampians – Stawell and Horsham) have the greatest potential for yield improvements. The results indicate that the yield gap is wider where Yw is higher and narrower where Yw is lower. This pattern is likely to reflect a need for farmers in the more marginal areas to invest the necessary inputs to ensure that they don't miss the opportunity to maximise production in a good season, while farmers in the higher Yw areas are profitable in most years even at lower than optimal input levels and are therefore more risk averse due to their concern with downside risk in case of extreme events such as frost of hail damage to their crops. Investigation of the difference in management practices (time of sowing, fertility levels, weed and disease control, and others) between fields in the contrasting SLAs is likely to reveal which management factors should be most effectively targeted to close the yield gap.

The more detailed maps of Figs. 4 and 5 showed that important differences occur within some SLAs. Information provided at such a relatively fine scale is likely to be highly valued by agronomic advisers working directly with farmers as it can provide a benchmark against which farmers can gauge the performance of their fields on an annual basis.

5. Conclusions

The yield gap assessment framework proposed in this paper and demonstrated in the Wimmera case study should be applicable to a significant proportion of the world's rainfed crop production regions. The range of its suitability is limited to the more developed countries where quality input data are available at a spatial resolution that can capture local spatial variability. Locally measured long term climate data, soil characterisation data and maps and a reliable record of statistical production data are required. Specifically the framework requires that a number of conditions can be satisfied: (1) Ya as well as the area and geospatial distribution of wheat cropping must be well defined; (2) there is good coverage throughout the area of daily weather data and of soil properties data (such as PAWC) required by crop models; (3) local agronomic best practice is well defined; and (4) there is a crop model with proven performance in the local agro-ecological zone.

Alternative methods must be developed for countries where such data are still scarce. Another limitation of this method is that it assumes annual winter (or summer) crops with a cropping intensity of one crop per year. In regions where both summer and winter crops are grown and where long fallows are routinely practiced, this method would need to be modified.

We anticipate that future improvements in the accuracy of yield gap assessment, and of the level of uncertainty around these estimates, would require improvements in input data quality, improved cropping systems models, improvement in remote sensing technology and the setting up of instrumented geo-referenced validation sites for a monitoring and evaluation program required to inform a continuous improvement cycle for yield gap assessment. More comprehensive survey data, more weather stations measuring more weather parameters such as daily solar radiation, better soil characterisation data and soil characterisation maps, improvements in remote sensing technology and its interpretation would each provide more accurate inputs into estimates of Ya and Yw. Parallel improvements in crop growth models and their embodied crop and soil science would improve their predictive power. Establishing strategically placed ground testing sites for validation of Yw values predicted from modelling and for validation of Ya values predicted from remotely sensed data is necessary for monitoring, evaluation and improvement of the Yg assessment framework.

In the Wimmera case study we estimated that farmers in this region can increase the average annual wheat produced in the region from 1.09 M tonnes to 1.65 M tonnes. This scale of increase in grain production, in a region that represents rainfed cropping in a variable climate, supports claims that bridging the exploitable yield gap is an important pathway to future global food security.

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