Visualizing yield gaps in Australia's wheat cropping zone

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Abstract
Future global food security depends on producing enough nutritious food for a world population expected to peak at over 9 billion by 2050. Achieving this clearly depends, among other things, on realising the highest possible yields on existing farm land. Australian wheat producers have rapidly adopted new and improved crop management practices over the last 20 to 30 years. How much more can they improve their productivity? To answer this question we first need to know the current gap between potential and actual yields. Yet while average farm yield data have been well documented at local to regional scales, until recently there have been few comprehensive assessments of water-limited yield potential of rainfed crops in Australia. This paper describes the methodology used to calculate the gap between actual wheat yields and water limited potential yields in Australia's cropping zone. It then describes the interactive Yield Gap Australia website (www.yieldgapaustralia.com.au) that enables growers, agronomists, research funders and policy makers to visualise and delve into the extent and geographic distribution of the yield gaps. It also enables farmers and their consultants to benchmark their own farm against both average shire (SLA) yields and water limited yield potential adjusted for their soil type. We expect this website to be used for setting research and extension priorities and to inform agricultural policies to ensure a focus on regions with the largest unexploited yield gaps, and greatest potential to close them through sustainable intensification.

Key words
Yield potential, global food security, simulation, wheat, yield map

Introduction

The world's population growth and changing dietary requirements present a future global food security challenge. The FAO has estimated that global grain production will need to increase by at least 60% between 2010 and 2050 (Alexandratos and Bruinsma 2012) whilst growth in global grain production has all but stalled (Grassini *et al.* 2013). This presents a huge challenge for agricultural science and an exciting opportunity for the world's grain producers. One promising pathway to increasing grain production is to close 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). Future global food security clearly depends on achieving the highest possible yields on existing farm land to protect our carbon-rich and bio-diverse forests, wetlands, and grasslands.

Australia contributed 12.1% of global wheat exports in 2005-2012 and has a significant role to play in making up for seasonal fluctuations in other global regions. Wheat is an important crop in Australia, being grown on 55% of the total cropland, which averaged 12.6 million ha between 1998-9 and 2011-12 (ABARES 2012). Overall, yields per hectare have not increased from 1998 to 2011. The first step towards closing the yield gap is to know its size and extent. Here we present the results of a high resolution analysis of yield gaps in Australia's grain belt and demonstrate how this information has been made accessible to Australia's grain growers, their consultants, research funders and policy makers. We discuss how this information might be used and speculate on the next steps in yield gap analysis.

Methods

This analysis is based on adapting, for the whole Australian wheat zone, a yield gap analysis method developed initially for estimating the wheat yield gap the Victoria Mallee region of Australia (Hochman *et al.* 2012). This method attempts to exploit all available soil, climate and crop data in the expectation that more detail will lead to greater accuracy. The first step in calculating the yield gap is to know where a crop is grown. For wheat in Australia, the National Land Use of Australia version 4 (2005-6); (ABARE-BRS 2010) data set provides data for a 'cereals' land use class at approximately 1 km pixel size.

Next we mapped actual annual wheat grain yields obtained by farmers (Ya) onto the land use map. For this we used the national agricultural data collated by the Australian Bureau of Statistics (ABS) at the level of statistical division (SD) annually, and at the finer scale of statistical local area (SLA) every five years when a census is carried out (Walcott *et al.* 2013). SDs are relatively uniform regions with boundaries determined from socioeconomic criteria. SLAs are based on local government areas, and are subdivisions of SDs. SLAs are the smallest administrative unit at which national crop yield data are available; however, since 1996 this has only been the case at five-yearly intervals in census years (1996, 2001 and 2006). For intervening years, only SD level data were available. Data on annual crop harvested area and average yields for the years 1996 to 2010 were sourced from ABS (2012). To derive SLA level estimates for each year, linear regressions were fitted to yield (t/ha) and crop area (ha) data for each of the 259 SLAs that grew more than 5000 ha of wheat from the 17 past census years from 1982 to 2010.

To determine water limited yield potential (Yw; yield that can be achieved under current best practice with well adapted commercial varieties and known technologies) we deployed the APSIM (Version 7.4) wheat model (Keating *et al.* 2003, Holzworth *et al*. 2014) which is well validated for wheat in Australia (e.g. Brown 2014) to simulate wheat grain yields, using 30 years of weather data from 3,913 SILO Patched Point data weather stations (Jeffrey *et al*. 2001) covering the grain zone at a median distance apart of 17 km. We assumed a 20 km radius as the nominal zone of relevance of each weather station and chose up to three dominant soil types per weather station using the ASRIS soil map (Johnston *et al*. 2003) to determine the most relevant soil types covering the cereal land use area in each 20 km radius zone. Typical soil profiles for each soil type were determined by averaging parameters of 434 deep soil profiles characterised in APSoil that had their Australian Soil Classification (ASC) identified. These 'typical soil types' were then used in the wheat simulations to represent the 3 dominant soils in each weather station area. Sowing rules and nitrogen fertiliser rules were used to ensure that yields were only limited by climate and water conditions. Simulations were run from 1981 to 2010 but because starting conditions for soil water were unknown, we only used the years from 1981 to 1995 to allow starting conditions to self calibrate over those years. Yw data from years before 1996 were discarded from the yield gap analysis.

The simulation results (>10,000 weather-soil results per year) were mapped for each year from 1996 to 2010 using local variogram kriging (Haas 1990) which was performed using the VESPER program (Minasny *et al*. 2005) to interpolate the Yw results over the whole cereal land use surface of Australia. These values were then aggregated up to SLA level for comparison with the annual average Ya values available for each SLA. Thus the independently estimated annual Ya and Yw values per SLA could be compared and the yield gap (Yw-Ya) and relative yield (Y% = 100 x Ya/Yw) were calculated and mapped.

The ultimate task was to develop a web based tool to enable users to visualize the spatial and temporal nature of Australia's wheat yield gaps and their components (as expressed by maps of Ya, Yw, Yg and Y%). In order to make these maps available to the public in an accessible and interactive form we adopted a user-centred approach. Following discussions with GRDC managers, CSIRO colleagues and a number of farmers and agronomists, we investigated other map based websites such as the GYGA site; and apps such as SoilMapp to help us develop our ideas about the basic design and functionality of the site. We captured these ideas in a PowerPoint presentation which was a mock up of the key functionality of the website. The PowerPoint mock up was then presented to two reference groups of farmers and advisers. These meetings were audio recorded and feedback was carefully considered in revising the design of the website. Prior to completion, the site was demonstrated to a number of GRDC managers for feedback before it was published online on the 9th February 2015. On that date GRDC panel members were invited to inspect the site and provide their feedback, both as users and based on their intimate knowledge of different parts of the grain zone. This and all subsequent feedback is captured in a spreadsheet which will be maintained as a record of feedback and the actions taken in response.

Results and Discussion

The yield gap of rainfed wheat in Australia in the period between 1996 and 2010 was derived by calculation of average wheat yield (Ya) at 1.74 t/ha, with a water limited yield (Yw) of 3.48 t/ha and a yield gap of 1.74 t/ha. Thus Australia's grain-growers are achieving on average 50% of their water limited yield potential. These average values are subject to large spatial and temporal variability and the interactive Yield Gap Australia website (www.yieldgapaustralia.com.au) now enables growers, agronomists, research funders and policy makers to visualise and delve into the extent, annual variation and geographic distribution of the yield gap. Figure 1 is provided to illustrate how the maps can be interrogated to provide detail at an SLA, Agro Ecological Zone (AEZ) and regional scale by simply pointing at the map. Similar maps and details can be shown for each of yield gap components, for specific years or for any decile year type. To relate this

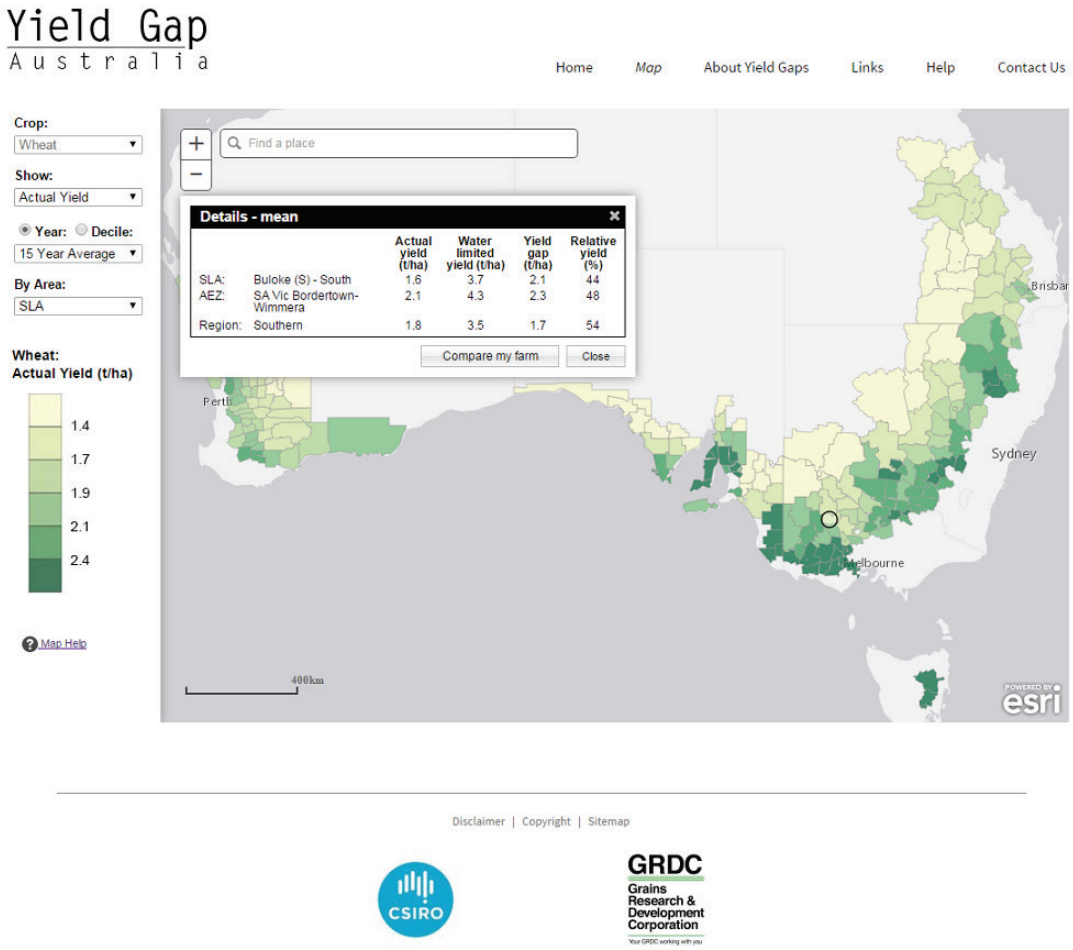

Figure 1. Map of Australia's average actual yields in the 15 years between 1996 and 2010 showing details for the Buloke South SLA (denoted by open circle) in a pop-up window.

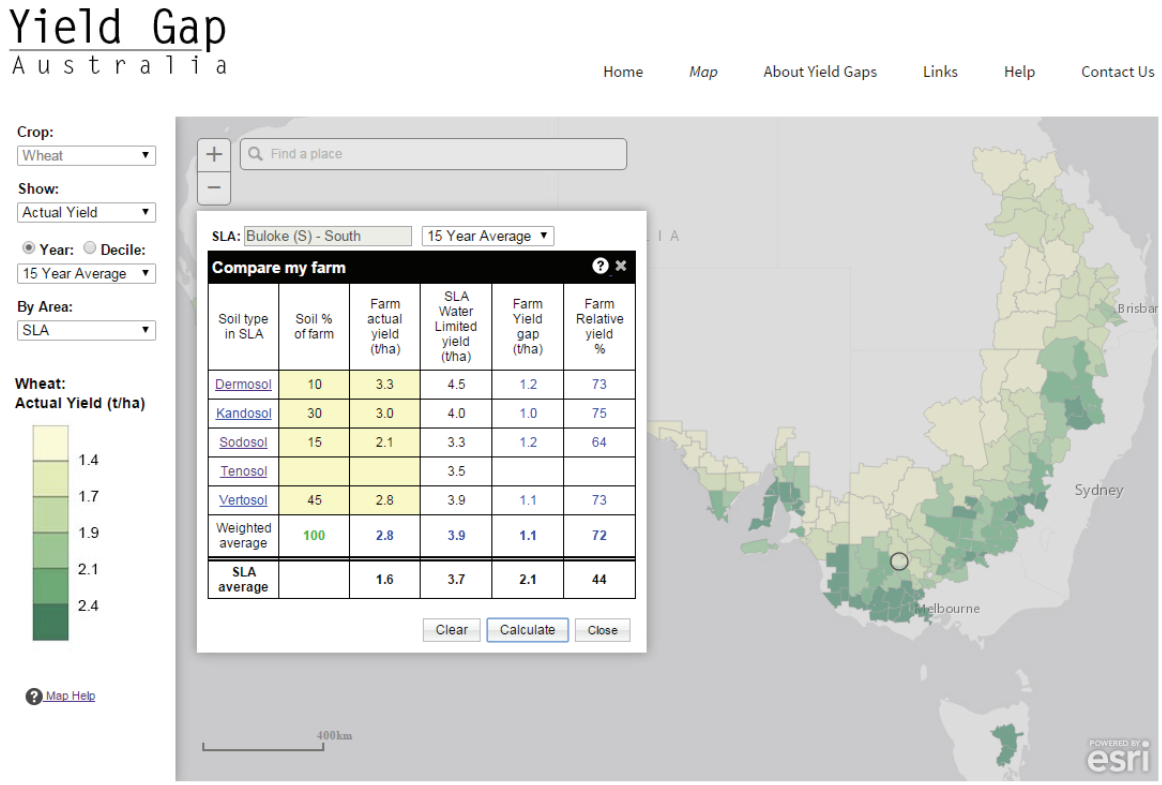

Figure 2. Compare my farm feature for a single farm in the Buloke South SLA that is achieving 72% of Yw.

information more specifically to a particular farm, users can launch the 'compare my farm' tool from the details box and enter farm-specific data that enables the user to benchmark their soil specific yields against both local averages and their water limited potential (Figure 2). In the Figure 2 example this fictitious farm is achieving yields well above the SLA average and at 72% of Yw which is close to the exploitable yield ceiling of 75-80% for rainfed crops.

The 50% yield gap result for Australian wheat is consistent with the results of other studies. At a sub-farm scale, Oliver and Robertson (2013) showed relative yields below 50% on 31% of a farm. At a regional scale, Hochman *et al*. (2012) reported a regional mean of 52.7% for the Wimmera in south eastern Australia over 20 years. A survey of progressive farmers in Australia's northern grain zone, covering 193 crops grown between 2005 and 2008, reported that that yields achieved were 65% of their water and nitrogen limited yield potentials (Hochman *et al*. 2014). Stephens *et al*. (2011) reported mean water use (production) efficiencies of 52.4% (1996-2000) and 51.1 (2003-2008). The highest relative yields reported for Australian wheat farms include a study of leading growers nationally (2004-2008) with relative yields of 77% (Hochman *et al*. 2009), and a study of three leading farmers over 16 to 20 years showed relative yields of 74% to 82% (van Rees *et al*. 2014). Data collated from over 5000 field/years between 1996 and 2010 were used to ground truth these maps. The results (to be published elsewhere) were highly consistent with the annual Ya and Yw values of their SLAs and provide further support for the validity of the yield gap analysis results.

Conclusion

The Yield Gap Australia website is an interactive map-based tool for visualising the extent and geographic distribution of the gap between actual and potential production of rainfed wheat crops in Australia. The website targets grain growers, agronomists, research funders and policy makers. Yield Gap Australia will be updated on an annual basis. It is envisaged that more crops (e.g. Canola) will be added to the website. Data are collected to ground truth Ya and Yw maps. Further work is required on the methodology of yield gap analysis and on utilizing the data produced in this analysis to investigate the causes of yield gaps in Australia. The maps provide an opportunity to investigate the absolute and combined contributions of individual causes of yield gaps such as subsoil constraints, fallow weeds, time of sowing and crop nutrition.

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