Bridging the Yield Gap : Diagnosing poor performing patches from paddock to farm scale

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Abstract
We have developed a method that combines yield maps from multiple seasons, farmer-derived soil maps, routine near-surface soil tests, and daily rainfall records to generate paddock or whole-farm maps of farm yield, potential yield, the yield gap and an estimate of the feasible interventions to close that gap. Our aim was to develop an approach that could be used by farmers and their advisors using readily available data. This method has potential applicability to a large number of grain growers.

On a case study farm in Bodallin, the low rainfall zone of WA, the average farm yield ranged from 0.47-1.97 t/ha over the 2004-2009 seasons. The yield gap ranged from 0.6 t/ha in the dry year of 2007 to 1.5 t/ha in the high yielding year of 2005. Relative yield potential (RYP) calculated as the actual yield divided by the yield potential (estimated by an adaption of the French and Schultz (1984) method using the closest rainfall station) was used to determine areas of below-average performance (<50% RYP), average performance (50-75% RYP), and above-average performance (>75% RYP). Over the farm, 31% was below-average performing (20-49%) in the "normal" seasons (2004, 2005, 2008, 2009) and 70% was below-average performing (63-77%) in dry seasons of 2006 and 2007. Across the six seasons 11-34% of the farm was performing near yield potential.

Combining the RYP, soil maps and soil analysis, the below-average performing areas were associated with the gravel, loamy earth and shallow sandy duplex loamy soils, which had intractable soil constraints. The average performing areas were often associated with the deep yellow sand/acid sand and the shallow loamy duplex soil types. Overall, 16% of the farm was poor performing due to soil acidity, 10% due to poor soil structure, 3% due to unmanageable soil characteristics such as coarse texture or shallow profile depth, 5% due to the influence of tree-lines and trees within paddocks, and 3% to other non-defined factors. The results of this analysis and maps lead to discussion with the farmer about improvement of soil maps, prioritising inputs and gaining of more information through targeted soil testing before ameliorating the constraint.

Key Words
potential yield, yield maps, soil maps

Introduction
With the imperative to identify pathways for continued improvements in crop yield there has been considerable focus in recent publications on understanding the potential yield of a crop and the gap between potential and actual yield (Lobell et al, 2009, Dang et al, 2011). In rainfed environments, the yield potential (Yp) is limited by rainfall and defined as the yield of an adapted cultivar when grown with the best management and without natural hazards such as hail, frost, lodging, nutrient, or biotic stress limitations. Actual yield (Ya) is defined as the yields farmers actually produce. For individual farmers, quantifying the yield gap at the farm or field level is often constrained by the lack of necessary data to both quantify Ya and Yp. This is even more the case on large farms, with fields that contain considerable spatial variation in Ya and presumably Yp.

In this paper we generate whole-farm maps of Ya, Yp, the relative yield potential (Ya/Yp, RYP) and an estimate of the causes of the yield gap. To do this we combined yield maps over multiple seasons, farmer-derived soil maps, routine near-surface soil tests, daily rainfall records and farmer knowledge. The approach can be used by advisors and farmers to assess the proportion of the farm that reaches Yp, and gives advisors a tool to target regions within the farm that fail to reach Yp. A secondary aim is to quantify the size and distribution of the yield gap for a large case study farm, which is located in the low rainfall cropping zone of the Western Australian grain-belt and is typical of many low rainfall grain production systems.

Methods

Case study farm

The case-study farm is located near the township of Bodallin (−31.266 S, 118.942 E), in the low rainfall zone (<325mm annual rainfall) of Western Australia's cropping belt with 75–86% of annual rain falling in April–October, the winter growing season months. The farm produces grain crops and livestock, with spring wheat (*Triticum aestivum* L.) the dominant crop. The farm, and each paddock, has a collection of soils that range from deep well drained yellow sands, to red loamy sands and duplex sands with a clay layer at depth (Schoknecht 2002). Soils possess a number of soil constraints such as acidity, and poor water infiltration and the farmer has been applying lime and gypsum, respectively, to ameliorate these constraints.

Yield data were collected for 32 paddocks totalling 4466 ha under cereal production for the 2004-2009 seasons. The yield was monitored on the harvester, logged using the John Deere APEX software package and positional information was recorded using a JDGPS. These positional and yield data were exported into ARCGIS v9.3 and the data kriged using an exponential variogram onto a 25 m grid. The farm has a network of five rainfall stations from which daily rainfall was recorded and there was significant variability in rainfall between the stations. The farmer had maps of the soils over the whole farm which we adjusted and revised together, after we identified discrepancies in descriptions and discontinuities across paddock boundaries. The farmer-described soil types were translated to taxonomic soil groups (Schoknecht 2002). A farm-wide program of GPS-referenced soil testing for soil nutrients and physical properties collected in 2009 by the farmer from the 0-10 cm soil layer was used to cross-check the farmer-derived soil maps and assign a typical range for soil attributes to each soil type. Deep soil cores to 1.5 m were also taken by us on 3 paddocks (at 12 locations) on the farm with soil chemical properties collected for the 0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.6, 0.6-0.9, 0.9-1.2, 1.2-1.5 m layers.

Determining the yield gap

Each 25 m^2 yield pixel measured by the yield monitor was ranked and summed to produce a cumulative frequency distribution for farm yield as a function of cumulative area cropped. To compare the performance of the farm across seasons, the area cropped in each year was normalised to a value of 1.0. Then, the yields were divided by the yield potential to give relative yield potential (RYP) using the following methods:
(1) The maximum yield recorded on the farm in that year - the yield corresponding to the 98^{th} percentile of the yield-area cumulative frequency distribution
(2) An estimate of water-limited potential yield adapted from French and Schultz (FS) (1984) with water-use estimated by growing season rainfall (May to October) plus 30% of summer fallow rainfall (November to April). An intercept (minimum evaporation) of 110 mm and a transpiration efficiency for grain production of 20 kg/ha/mm were assumed. Rainfall used was

A) the rainfall station located in the centre of the farm and

B) the closest of the five rainfall stations to each yield pixel.

(3) Water-limited potential yield as simulated by APSIM (Keating et al. 2003). A sowing date was used for the whole farm similar to the observed average for the whole farm, with wheat cultivar Wyalkatchem sown at 100 plants/m^2. The soil used had a plant available water capacity (105 mm) typical of the highest yielding soil type on the farm (sandy earth) with nitrogen non-limiting. APSIM was also validated on a number of soils on the farm over the 2008-2009 period (data not shown).

Results

Growing season rainfall varied from 130 mm (2007) to 262 mm (2008) and the average wheat yield over the farm ranged correspondingly from 0.47 t/ha in 2007 to 1.97 t/ha in 2008 (Table 1). The area of the farm cropped to wheat varied from 32 to 65% of the total 4466 ha (Table 1). The farm maximum yield (98^{th} percentile) varied from 1.37 to 3.53 t/ha across the six seasons (Table 1). Due to the rainfall variation across the farm, there was on average a 0.6 t/ha difference in Yp (range 0.25-0.74 t/ha), calculated with FS, across the farm (Table 1).

The Yp calculated from FS and wettest rain gauge was 1.15-3.41 t/ha and within 0.2 t/ha of the maximum yield measured on the farm in 2005, 2007, 2008. In 2006 both the FS and APSIM yields were higher than farm maximum (0.7, 1.1 t/ha respectively) but this was explained by poor summer weed control (identified by the farmer). FS yield potential with the wettest rain gauge was 0.5 t/ha higher than farm maximum in 2004 and 2009, however APSIM and FS Yp with the central rain gauge were similar, confirming that the FS highest yield potential as possible.

Table 1: Summary values for each seasons (2004-09) for rainfall, yield potential and relative yield performance

	Season					
	2004	2005	2006	2007	2008	2009
Growing season (May-Oct) rainfall (mm)	227	249	132	130	262	196
Preceding summer (Nov-April) rainfall (mm)	119	57	208	91	103	92
Percent farm in wheat	50	33	32	41	45	65
Farm mean yield (t/ha)	1.33	1.60	0.80	0.47	1.97	1.36
	Yield potential (t/ha)					
Farm maximum	2.37	2.87	1.77	1.37	3.53	2.38
French and Shultz						
- Central rainfall gauge	2.43	2.32	1.90	0.77	2.67	2.23
- Wettest rainfall gauge	2.96	2.87	2.22	1.15	3.41	2.86
- Driest rainfall gauge	2.26	2.25	1.96	0.77	2.67	2.23
APSIM	2.48	3.09	2.92	1.13	2.56	2.23
	Relative yield performance (RYP)					
% Farm < 50% of Yp	49	36	77	63	25	20
% Farm between 50 and 75% Yp	40	42	19	22	50	46
% Farm > 75% of Yp	11	22	4	15	25	34

Areas of the farm were defined as performing close to the potential (>75% RYP), around average (50-75%RYP), and below-average (<50%RYP) using the Yp calculated using FS with closest rainfall station. Over the farm, 31% was below average performing (20-49%) in the "normal" seasons (2004, 2005, 2008, 2009) and 70% was below-average performing (63-77%) in dry seasons of 2006 and 2007 (Table 1, Fig1a). Across the six seasons 11-34% of the farm was performing near yield potential and 15% of the farm when averaged over the "normal" seasons. The yield gap ranged from 0.6 t/ha in the dry year of 2007 to 1.5 t/ha in the high yielding year of 2005. A similar yield gap of 0.41-1.66 t/ha was found by Anderson, 2010 for Merredin (a nearby town in WA) over 1997-2006 using shire yields and yield potential estimated using French and Schultz (1984) method.

Overlaying the farmer soil map with the maps of performance (Fig 1 b) we calculated median, 25th and 75th percentile of the RYP for each soil type to determine the ranking and variation of the RYP of each soil. The best performing soils were the sandy earth and deep loamy duplex which comprise 40% of the farm. These soils had a median RYP of 0.61-0.66, with 25% of this soil achieving 0.7-0.8 of RYP. However, even on these soil types, the best that could be achieved on the worst 25% of the area was only 0.5 of potential. The poorer performing soils were the loamy earth and gravel which comprising about 20% of the farm had a median RYP of 0.48. The top yielding 25% of these soils achieved 0.6 RYP and the worst 25% achieved 0.38 of RYP. Many of the soils in this category had intractable soil constraints, such as coarse soil texture or shallow profile depth and hence are unable to be ameliorated. On the average performing soils, comprising 40% of the farm, the top yielding 25% of these soils achieved 0.7 of RYP and the worse 25% achieved 48%. These soils often had soil acidity as an identifiable constraint and can potentially be ameliorated.

The range of RYP within a soil type can be explained by variation of plant available water capacity (PAWC) within a soil group (Oliver et al, 2006). This variation in PAWC can be caused by a subsoil constraint, for example the deep yellow sand can have a PAWC of 100m while an acidic deep yellow sand can have a PAWC of 30mm. On a paddock-by-paddock basis the poor performing area was assigned a constraint based on the dominant soil type in the paddock. Other possible explanations for poor performance, unrelated to soil type, were also accounted for, e.g. competition from tree-lines. An estimate was made of the area of the farm that was potentially subject to constraints of various types that were resulting in poor relative yield performance. The resulting analysis suggests that 16% of the farm was poor performing due to soil acidity (sands), 10% due to poor soil structure, (loamy earth) , 3% due to intractable soil characteristics such as coarse texture or shallow profile depth (gravel), 5% due to the influence of tree-lines and trees within paddocks and 3% to other non-defined factors. The results of this analysis and maps lead to discussion with the farmer about areas to target for more soil testing, improvement of soil maps, and gaining of more information prior to actioning amelioration.

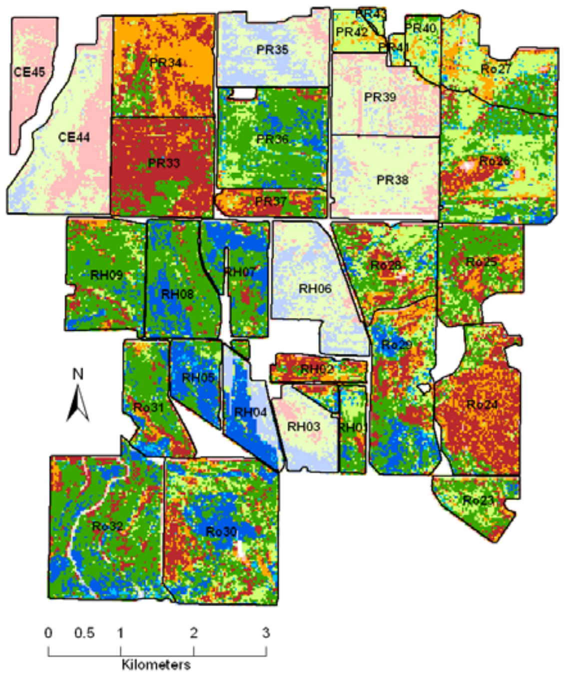

Figure 1a: RYP averaged over 2004, 2005, 2008, 2009 defined as above-average (blue), average (green) and below-average (red) and stable (CV <50%, bold colours) and or unstable (>50% CV, pale colours). The paddocks with faded colours did not have sufficient yield maps.

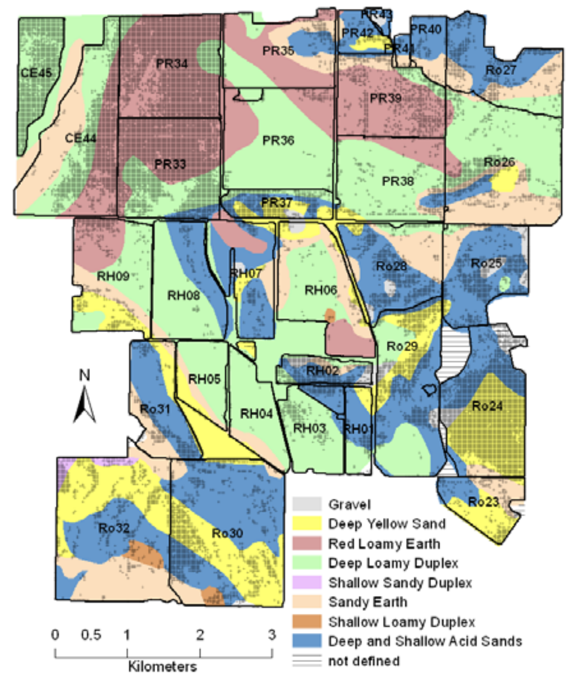

Figure 1b: Farm soil map overlaid shaded with areas of below-average RYP averaged over the 2004, 2005, 2008 and 2009 seasons.

Conclusion

The yield gap ranged from 0.6 t/ha in the dry year of 2007 to 1.5 t/ha in the high yielding year of 2005. Over the farm, 31% was below average performing (20-49%) in the "normal" seasons (2004, 2005, 2008, 2009) and 70% was below-average performing (63-77%) in weedy/dry seasons of 2006 and 2007. The soil maps drawn by the farmer, and improved through the additional soil test information, were an important data layer in determining the RYP-soil relationship and to estimate the causes of the yield gap. In this case study, it was better to focus on the average performing soil (such as the sands), as there as potential for amelioration compared with the below-average performing gravels and shallow soil, which has intractable soil constraints. By focusing on poor yielding areas and soil types on a paddock we found that 26% of the farm can be improved from amelioration such as overcoming acidity or improving soil structure. The farmers found that this process of associating relative yield performance with soil type and constraints allowed them to develop a rational approach for studying, attending to and overcoming constraints, or altering inputs as a means to prioritise investment.

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