

Influence of management and environment on Australian wheat: information for sustainable intensification and closing yield gaps

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Abstract

In the future, agriculture will need to produce more, from less land, more sustainably. But currently, in many places, actual crop yields are below those attainable. We quantified the ability for agricultural management to increase wheat yields across 179 Mha of potentially arable land in Australia. Using the Agricultural Production Systems Simulator (APSIM), we simulated the impact on wheat yield of 225 fertilization and residue management scenarios at a high spatial, temporal, and agronomic resolution from 1900 to 2010. The influence of management and environmental variables on wheat yield was then assessed using Spearman's non-parametric correlation test with bootstrapping. While residue management showed little correlation, fertilization strongly increased wheat yield up to around 100 kg N ha⁻¹ yr⁻¹. However, this effect was highly dependent on the key environment variables of rainfall, temperature, and soil water holding capacity. The influence of fertilization on yield was stronger in cooler, wetter climates, and in soils with greater water holding capacity. We conclude that the effectiveness of management intensification to increase wheat yield is highly dependent upon local climate and soil conditions. We provide context-specific information on the yield benefits of fertilization to support adaptive agronomic decision-making and contribute to the closure of yield gaps. We also suggest that future assessments consider the economic and environmental sustainability of management intensification for closing yield gaps.

Keywords: yield gap, land sparing, sustainable intensification, APSIM, crop model, ecosystem services, food security

1. Introduction

Agricultural production needs to increase in order to ensure the food and energy security of an expanding global population



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with changing consumption patterns (Johnston *et al* 2011, Tilman *et al* 2011). These production increases need to occur despite multiple interacting challenges such as the need to adapt to a rapidly changing climate, increased competition for agricultural land from other land uses, and societal demands for environmental stewardship (Godfray *et al* 2010, Lambin and Meyfroidt 2011, Vermeulen *et al* 2012). With limited opportunities for the expansion of agricultural land, and with

vigilance against local environmental impacts (Licker *et al* 2010, Bommarco *et al* 2013), intensification and improvement in resource use efficiency have been identified as two of the most prospective ways to increase agricultural production (Green *et al* 2005, Ahrens *et al* 2010, Foley *et al* 2011, Phalan *et al* 2011, Tilman *et al* 2011, Hochman *et al* 2013). Yield gaps—where farms produce less than the maximum currently attainable under ideal management (Mueller *et al* 2012, van Ittersum *et al* 2013)—often occur in practice, and closing this gap through the intensification of agricultural management is a global priority for addressing future food security (Neumann *et al* 2010, Foley *et al* 2011, Mueller *et al* 2012). With a focus on Australian wheat (*Triticum aestivum* L.) cropping, we analyzed the drivers of yield and provide information on the effectiveness of management for improving yields and contributing to the closure of yield gaps.

Yield gaps vary considerably between regions following differences in access to capital, technology, and labor. Larger yield gaps tend to occur in developing nations, although yield improvements are also possible in industrialized agricultural systems (Neumann *et al* 2010, Mueller *et al* 2012). For example, Hochman *et al* (2012) recently reported that on average actual yields were about half of attainable yields in the Wimmera cropping region of Australia. Within regions, yield gaps also vary between individual farms as farmers manage land according to their managerial skill, access to capital, attitude to risk, and other factors outside of their control (Hochman *et al* 2009, 2013, Monjardino *et al* 2013, van Ittersum *et al* 2013). However, simply quantifying the difference between actual and attainable yields provides little information on how yield gaps might be closed. More useful information for farmers is the quantification of the yield benefit expected from specific changes in agricultural management given existing local environmental (i.e. soil and climate) conditions. Farmers can use this information to support agronomic management decisions within the context of both economic viability and environmental sustainability (Rodriguez *et al* 2011).

Agricultural yields vary in response to management choices such as crop genotype, fallowing, crop rotation, break crops, sowing date, herbicide use, fertilization rates, and residue management (Anderson *et al* 2005, Ransom *et al* 2007, Florin *et al* 2009). Yields also vary spatially following heterogeneity in the environmental drivers of soil and climate (Luo *et al* 2003, 2005b, Wang *et al* 2009, Bryan *et al* 2010). At a global scale, Lobell and Field (2007) found that average monthly climate data explained 30% of the variance in wheat yields, leaving the remainder to be explained by other environmental and management drivers which vary over time and space. At finer spatial scales, many studies have quantified the influence of agricultural management and environmental drivers on wheat yield. In Western Australia, Asseng *et al* (2008) found that yields increased with rainfall but declined with temperature, and that potential existed to increase yields through higher rates of nitrogen application. In southern Italy, Basso *et al* (2012) found a significant influence of rainfall and soil water on wheat yield and Cossani *et al* (2010) identified a co-limitation of wheat to nitrogen and water availability in Spain. Seremesic *et al* (2011) found

that given proper management, increasing soil carbon could benefit wheat yield. Other studies have quantified the influence of zero tillage and crop residue retention on wheat yields through their effect on soil water relations (Anderson *et al* 2005, Grigoras *et al* 2012b, Sommer *et al* 2012). Together, these studies exemplify the multiple interacting management and environmental influences on wheat yield (Ransom *et al* 2007, Deryng *et al* 2011), and the geographic variation in their influence. Thus, to support efforts to increase yields, close yield gaps, and guide the sustainable intensification of agriculture, we need to quantify the spatially-explicit influence of management practices on yield in the context of local environmental conditions (Cunningham *et al* 2013, van Ittersum *et al* 2013).

In this study, we quantified the potential for agricultural management to increase and establish wheat yields across the current and potential cropping lands of Australia, respectively. Using the Agricultural Production Systems Simulator (APSIM; Keating *et al* 2003)—a process-based crop model—we simulated 225 management scenarios including combinations of fertilization (nitrogen) rates, residue removal and incorporation rates, crop cultivars, and sowing windows. Wheat production was simulated on a daily time step over 111 years for 11 715 spatial units with homogeneous climate and soil. A hybrid grid computing and parallel processing approach was used to process the simulations and the outputs were validated against census-reported yields. We assessed the relative influence of fertilization and residue management, in the context of climatic and soil variables, on simulated wheat yields using Spearman's non-parametric correlation analysis with bootstrapping. The individual effects of the four most influential management (fertilization) and environmental parameters (effective growing season rainfall, average maximum temperature, soil water holding capacity) on yield were quantified using boxplots. The effect of fertilization on yield was also assessed in the context of the three most influential environmental parameters using bivariate contour plots. Finally, we mapped the yield benefits of fertilization across a range of effective growing season rainfall. The results provide information sensitive to local environmental conditions that can support farm management decisions for improving wheat yields and thereby help to close yield gaps in Australia.

2. Methods

2.1. Study area

Wheat is the most widely produced crop in Australia and can be grown throughout most of the eastern states south of the tropic of Capricorn, in the southern parts of South Australia and in south-west Western Australia. Average total annual wheat production from 2002 to 2010 was 19.5 Mt produced from 12.6 Mha (Australian Bureau of Statistics 2012), constituting around 3% of global production (FAO 2013). In this study, the potential cropping area of Australia was defined by applying a 100 km spatial buffer to areas defined in national land use mapping as 'irrigated and dry land sown pastures and crops'

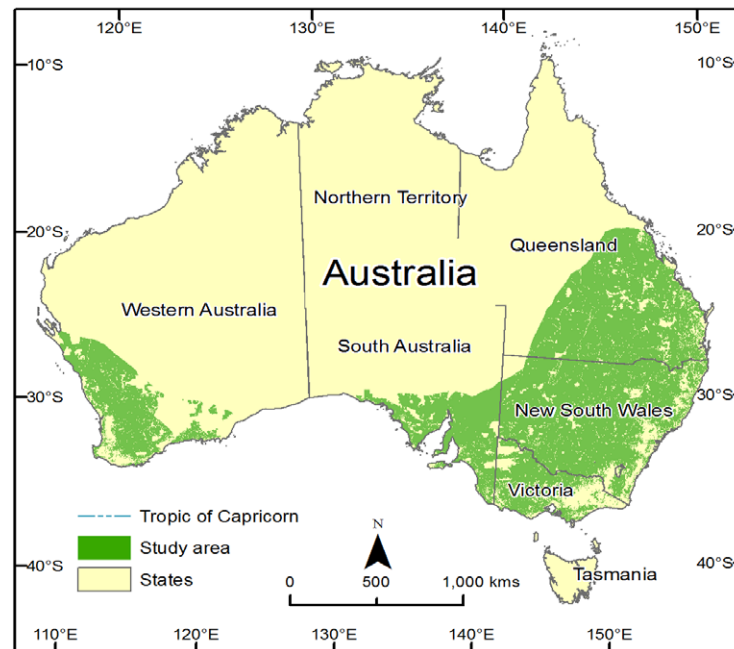


Figure 1. Study area.

(LU codes 320–338) and ‘irrigated sown crops and pastures’ (LU codes 420–438). With remnant vegetation and protected areas removed, the resulting 179 Mha study area is shown in figure 1.

2.2. Crop modeling

The APSIM model version 7.3, including its Wheat, SoilN, SoilWater, and Surface Organic Matter modules, has been demonstrated to perform well in simulating wheat crop growth, soil water dynamics, and soil nitrogen transformation under a variety of climatic, soil, and management conditions (Asseng *et al* 1998, Keating *et al* 2003, Wang *et al* 2003, Yunusa *et al* 2004, Asseng *et al* 2008, Zhang *et al* 2012). APSIM has been widely used to simulate the influence of management and environment on wheat systems (Luo *et al* 2005a,b, Asseng *et al* 2008, Wang *et al* 2009, Bryan *et al* 2010, 2011a, Bryan and Crossman 2013).

We simulated an annual continuous wheat system (planting wheat every year) from 1889 to 2010 with the first 11 years (1889–1899) used as model spin up time to equilibrate parameters such as soil carbon, soil water, and nitrogen flux. These initial 11 years are not included in the results. We modeled nine levels of fertilizer application between 0 and 200 kg N ha⁻¹ yr⁻¹ at 25 kg increments. In the simulation, 25 kg N ha⁻¹ yr⁻¹ was applied at sowing and the remainder at the stem elongation stage as a top-dressing. Crop residue was retained at five levels (0, 25%, 50%, 75%, 100% of total standing biomass) and this residue could be incorporated into the top 20 cm of soil through tillage at five levels of incorporation (0%, 25%, 50%, 75%, 100%). The sowing windows were specified based on expert knowledge of historical practices and prevailing growing season weather in each state (supplementary material 1 available at stacks.iop.org/ERL/9/044005

[/mmedia](#)). These rules allow for the sowing of early or late cultivars based on the timing of the break in season as defined by a rainfall threshold. Wheat was harvested at maturity.

2.3. Spatial units

Zones with homogeneous climate and soil characteristics at the landscape scale were delineated to provide spatial units for crop modeling (Zhao *et al* 2013a). This zonal approach eliminated redundancy associated with cell-by-cell simulation and made computation tractable. Raster spatial layers of mean annual rainfall and temperature (1921–2005) modeled by ANUCLIM (Xu and Hutchinson 2011) were classified using *k*-means clustering into 35 classes selected by trading off classification complexity with class homogeneity (Bryan 2006). The climate classification was then overlaid with the Australian Soil Classification (ASC) (Isbell 2002) to create spatially-explicit climate–soil units (CS units). The spatial layer of 35 climate clusters was overlaid with the 13 ASC soil types to identify 382 unique zones, each consisting of one or more discrete areas, totaling 11 575 individual spatial polygons (CS units). These CS units were used as the basic spatial units for APSIM modeling and ranged in size from very small (<1 ha) to very large (>1 Mha) with an average size of 15 246 ha and a median size of 2915 ha.

2.4. Soil data

For each CS unit, soil physical and chemical properties were derived from the Australian Soil Resources Information System (ASRIS) database. Soil attributes—including pH, bulk density (BD), drained upper limit (DUL), 15-bar lower limit (LL15), and layer depth (Thick)—were extracted from the ASRIS Level 4 database then mapped and converted to 0.01°

raster datasets. Where ASRIS Level 4 data was unavailable, Agricultural Production Systems Research Unit (APSRU) soil data points were converted to a 0.01° raster dataset and a two stage focal interpolation method was used to fill gaps in the soil attribute data using values from nearby data points. The interpolated DUL, LL15 and BD data was found to fit within the broad ranges specified in the ASC soil descriptions.

2.5. Climate

Daily climate data (as distinct from the annual layers used to create CS units) was assembled for the years 1889–2010 for input into the APSIM modeling. Raster layers of rainfall, minimum temperature, maximum temperature, solar radiation, and potential evapotranspiration were assembled from the Australian Bureau of Meteorology's long term national daily gridded climate database. At a spatial resolution of 0.05° (~25 km² grid cells), the layers have been interpolated from ~4600 long term climate station records using methods presented in Jeffrey *et al* (2001). We calculated the spatial average of each daily climate layer for each CS unit using a parallel zonal statistics algorithm (Zhao *et al* 2012) and converted it to APSIM meteorological file format.

2.6. Spatial crop modeling

We processed the simulations using a hybrid, high-performance computing methodology combining parallel processing with grid computing on CSIRO's Condor-based computing grid (Zhao *et al* 2013a). A parallel processing executable file, along with the APSIM application and data, was distributed to grid nodes. The processing task was partitioned by CS unit to minimize data transfer overheads with grid nodes processing all 225 management simulations for a CS unit. Management scenarios were processed in parallel on each grid node using Python's multiprocessing library (Zhao *et al* 2013a). Results were collected and stored in a MS SQL Server database.

2.7. Validation

Census and survey data offers an opportunity for validation of large scale model outputs (Bryan *et al* 2011b). We validated our simulations against census-reported yields sourced from the Australian Bureau of Statistics. Nitrogen application rates—a key management variable—were estimated from state government agricultural extension information (gross margin handbooks) for three key wheat-growing regions including the Western Australian wheatbelt, the South Australian and western Victorian cropping districts, and northern New South Wales. Wheat yields simulated at the level of nitrogen application specified in the gross margin handbooks were compared against census-reported yields by Statistical Local Area for 2006 for the three regions using a student's *t*-test to assess differences between the means.

2.8. Correlation analysis and visualization

Correlation analysis was used to quantify the impacts of management and environment on wheat yields. To avoid

Table 1. Management and environmental variables assessed for their influence on wheat yield.

Variable	Short description	Units
<i>Management</i>		
Fertilization	Total amount of Nitrogen fertilizer added	kg
Residue removal	% of crop residue removed from the field	%
Residue incorporation	% of unremoved crop residue incorporated in the top 30 cm of soil through cultivation	%
<i>Climate</i>		
Growing season length	Number of days from sowing to harvesting	days
Average maximum temperature	Average maximum daily temperature from sowing to harvesting	C
Average minimum temperature	Average minimum daily temperature from sowing to harvesting	C
Accumulated solar radiation	Total accumulated solar radiation from sowing to harvesting	MJ m ⁻²
Effective rainfall	Rainfall—runoff—drainage from sowing to harvesting	mm
<i>Soil</i>		
Depth	Depth of each soil layer	cm
Bulk density	Indicator of the degree of soil compaction	score
pH	Level of acidity/alkalinity	pH
Water holding capacity	Soils capacity to store water in its pore space	mm mm ⁻¹

bias in the correlation analysis, spatial autocorrelation, which is typical in spatial data, was reduced (Bryan *et al* 2011c). Following Zhao *et al* (2013b), we investigated the structure of the spatial autocorrelation using semivariograms which quantify the relationship between semivariance in yield and distance of separation between pairs of CS units. We selected a sample size of 500 CS units for bootstrapping correlation analysis to reduce spatial autocorrelation while maintaining statistical power.

Spearman's rank correlation test was selected for correlation analysis because of its robustness to the departures from normality common in our data. Correlation coefficients were calculated between wheat yield and a number of management, climatic, and soil variables (table 1). Estimates of Spearman's rank correlation coefficient (*Rho*) were bootstrapped using 1000 random samples of 500 CS units. For each of the 500 CS unit bootstrap samples, simulated data from all management scenarios for the years 1900–2010 were included in the correlation analysis. The bootstrap distributions were then plotted. Four of the most strongly yield-correlated management (fertilization) and environmental (effective rainfall, average maximum temperature, soil water holding capacity) variables were selected for further analysis. The influence of each of these four variables on wheat yield was graphed using boxplots and interactions were assessed using bivariate contour plots. The effect of fertilization (the most influential management

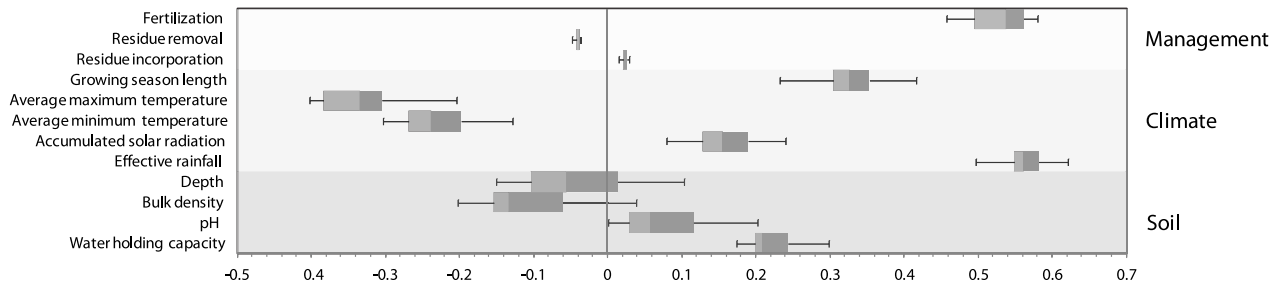


Figure 2. Boxplots of bootstrap estimates of Spearman's Rho correlation coefficients between wheat yield and a range of management and environmental variables. The break in gray shade is the median, the ends of the shaded area represent the 25th percentile (lower) and 75th percentile (upper), and the whiskers extend to the most extreme data point within 1.5 times the inter-quartile range.

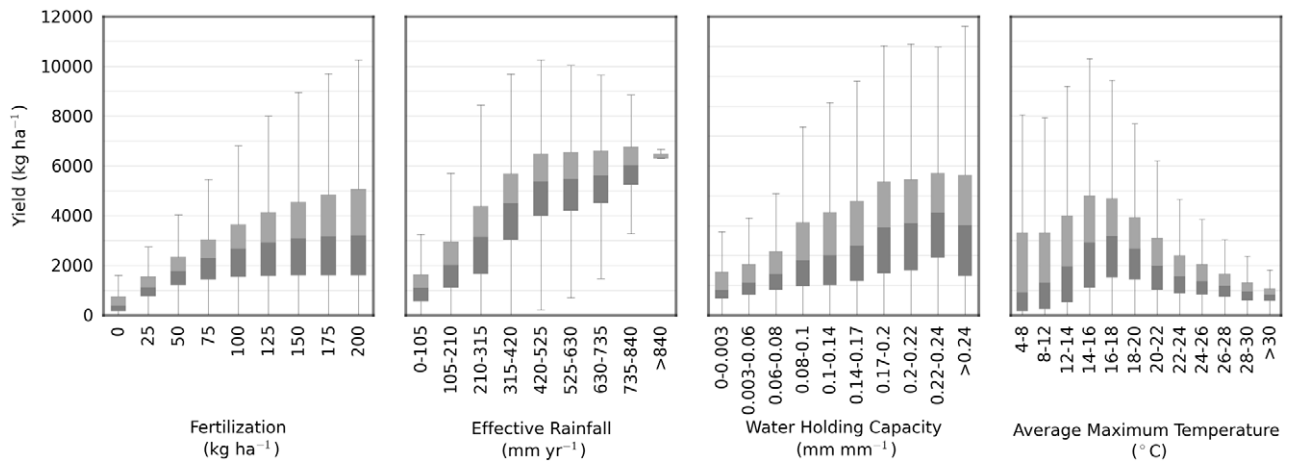


Figure 3. Effect of the four selected management and environmental variables on wheat yield. For each variable level, the boxplot represents yield variance calculated over all simulations (including CS units, simulation years, and management scenarios) displaying that specific level. The break in gray shade is the median, the ends of the shaded area represent the 25th percentile (lower) and 75th percentile (upper), and the whiskers extend to the most extreme data point within 1.5 times the inter-quartile range.

variable) on potential wheat yield benefit was then mapped across the range of effective growing season rainfall (the most influential environmental variable).

3. Results

3.1. Yield estimates and validation

The major cropping districts in south-eastern Australia and south-western Australia were the highest-yielding regions, with the drier, inland areas producing the lowest yields. For 2006, census-reported yields ranged from 540 to 2310 kg ha⁻¹ yr⁻¹ (median 1260 kg ha⁻¹ yr⁻¹) across the three validation areas. These estimates were comparable with modeled yields which ranged from 639 to 2906 kg ha⁻¹ yr⁻¹ (median 1553 kg ha⁻¹ yr⁻¹). In all three validation regions, *t*-test results found that simulated yield means were not significantly different to the means of census-reported yields (supplementary material 2 available at stacks.iop.org/ERL/9/044005/mmedia).

3.2. Wheat yield correlates

Of the management variables, fertilization was most strongly and positively correlated with wheat yield while residue

removal and residue incorporation were both weakly correlated with yield (figure 2). Of the climatic variables, yield was strongly and positively correlated with the effective rainfall and growing season length. Average maximum temperature and average minimum temperature were both negatively correlated with yield. Soil water holding capacity at layer 4 was the soil variable most strongly correlated with yield.

We selected the following variables for further exploration of their effects on wheat yield over the simulation period: fertilization; average maximum temperature; effective rainfall, and; soil water holding capacity (supplementary material 3 available at stacks.iop.org/ERL/9/044005/mmedia). Yield benefits of fertilization were significant across the study area, especially up to 50 kg N ha⁻¹ yr⁻¹ (figure 3). While these benefits diminished at application rates beyond 100 kg N ha⁻¹ yr⁻¹, this varied across the study area and from year to year. Yield also increased with effective rainfall up to around 500 mm yr⁻¹, beyond which further yield benefits were negligible. Soil water holding capacity displayed a positive influence on wheat yield up to 0.2 mm mm⁻¹, beyond which further benefits were limited. Wheat yields increased with average maximum temperature up to around 18 °C, after which point wheat yields declined with further increases in average maximum temperature (figure 3).

The influence of fertilization on yield varied non-linearly with maximum temperature, with fertilization having a

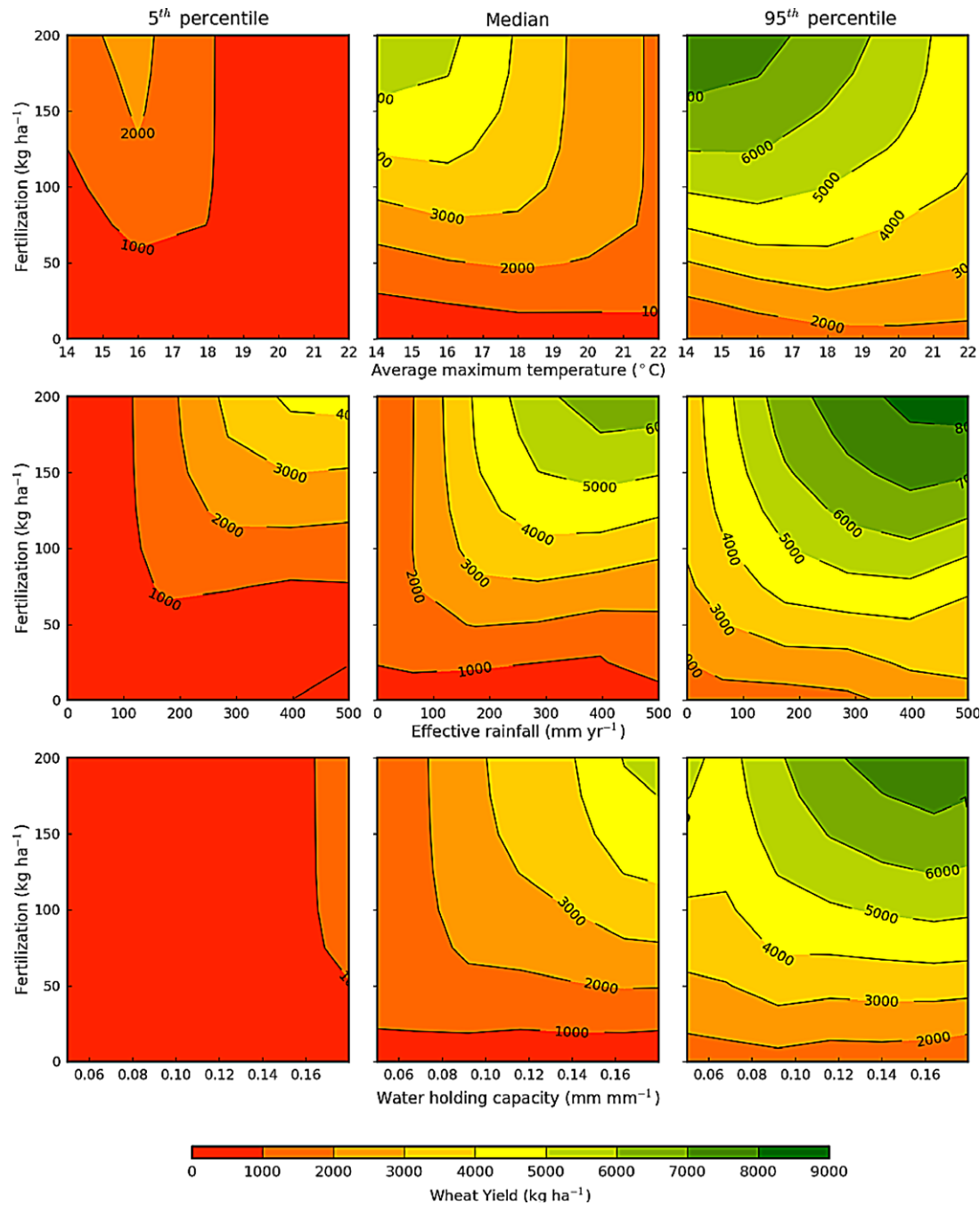


Figure 4. Bivariate contour plots of the combined influence of the four most influential management and environmental variables on crop yields. For each bivariate combination of variable levels, the median and 5th and 95th percentiles of yield variance were calculated over all simulations (including CS units, simulation years, and management scenarios) displaying that specific combination of levels.

stronger influence on wheat yield at lower maximum temperatures (figure 4). The influence of fertilization on yield also varied non-linearly with effective rainfall, with fertilization having a stronger influence on yield at higher levels of effective rainfall and the very highest yields occurring at high levels of fertilization and effective rainfall. A similar effect was found in the influence of fertilization and soil water holding capacity as the influence of fertilization was greatly reduced in soils with lower water holding capacity (figure 4).

3.3. Yield benefits of fertilization

The benefit of fertilization in increasing yields varied over the study area with the complex geographic interplay of environmental variables. At fertilization rates up to 100 kg N ha⁻¹ yr⁻¹, wheat yields were most responsive in the wheatbelt of Western Australia, in South Australia’s agricultural districts, and in the Murray–Darling Basin. Further yield increases were achieved with higher fertilization rates (> 100 kg N ha⁻¹ yr⁻¹), especially in the higher rainfall areas of southern Victoria and

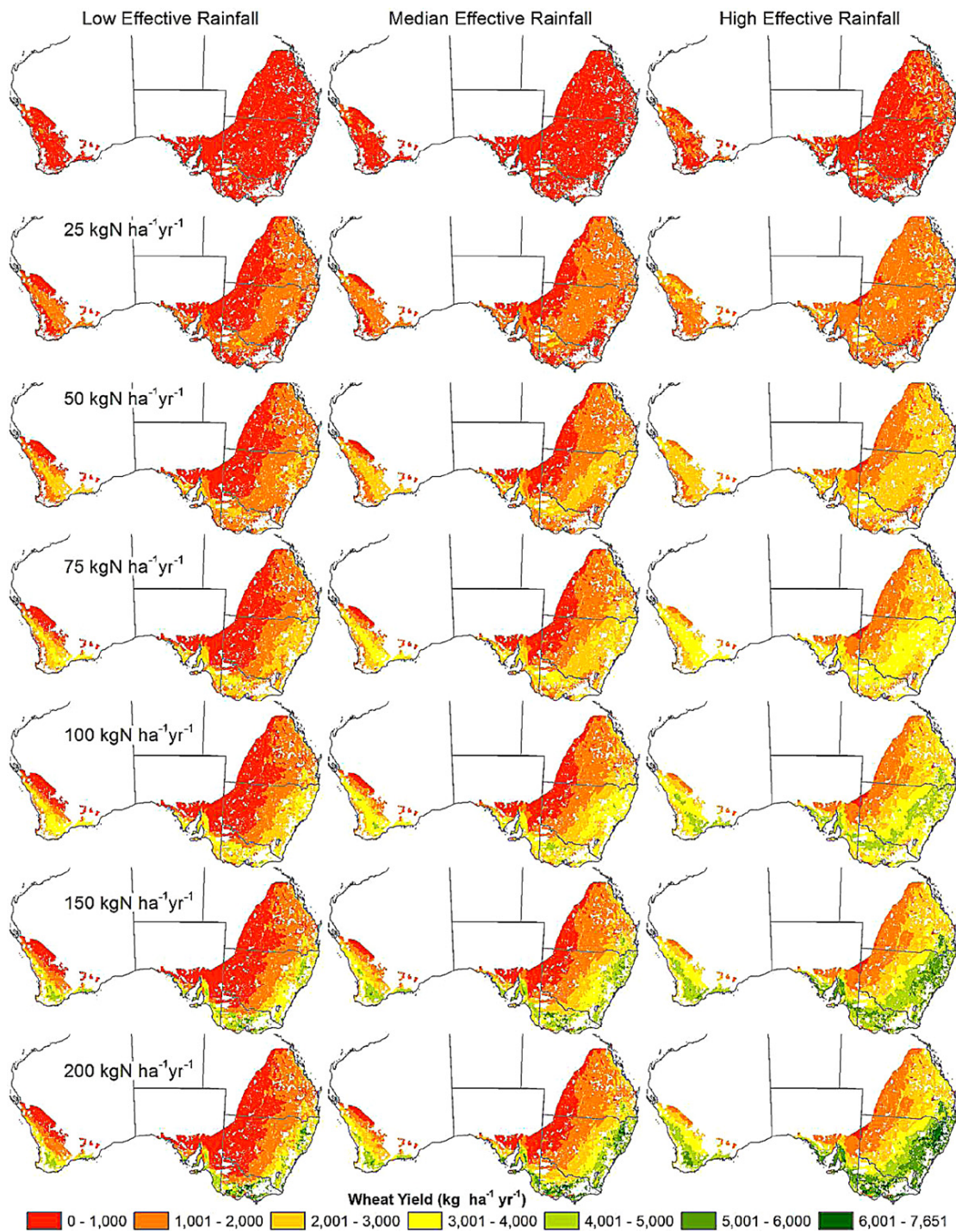


Figure 5. Long term wheat yields over the simulation period 1900–2010 under seven rates of nitrogen application and three levels of effective rainfall, assuming 0% residue removal and 0% residue incorporation. Left column: mean yield in the lowest 3 effective rainfall deciles (minimum to 30th percentile). Middle column: mean yield in the middle 3 effective rainfall deciles (35th to 65th percentile). Right column: mean yield in the highest 3 effective rainfall deciles (70th percentile to maximum).

coastal New South Wales. Yield benefits of fertilization were higher in seasons with higher effective rainfall (figure 5).

4. Discussion

4.1. Impacts of management on crop yield

We quantified the potential for management to increase wheat yields in Australia in the context of climate and soil

variables. Of the two management variables assessed, residue management—conserving crop residue biomass and incorporating it into the soil—provided little potential yield benefit. Fertilization however, had a strong influence on wheat yield. The greatest marginal increases in yield (i.e. kg wheat per kg N) were achieved at low rates of fertilization, with little additional benefit achieved above 100 kg N ha⁻¹ yr⁻¹. However, this was highly context-dependent—being strongly influenced by local

climate and soil conditions. Yield also increased with rainfall (up to around 500 mm yr⁻¹ in the growing season), soil water holding capacity (up to around 0.2 mm mm⁻¹), and temperature (up to around 18 °C but declining beyond). These results illustrate the complex co-limitation of wheat yield to management and environmental factors (Asseng *et al* 2001, 2008, Cossani *et al* 2010). At higher temperatures, crop growth and yield are increasingly limited both through evaporative demand and heat stress (Asseng *et al* 2011). In areas of lower rainfall, especially where soils have lower water holding capacity, crop growth and yield are increasingly limited by water stress (Cossani *et al* 2010). We found that fertilization was particularly effective in cooler, wetter climates, and in soils with greater water holding capacity typical of the southern and eastern coastal and upland parts of the study area. In these environments, crop growth is less limited by water availability and high temperatures, and more limited by nutrient availability. Where wheat growth is limited by water availability or high temperatures, additional fertilization provides little yield benefit.

Our study extends previous national and global scale assessments of the potential for management to address yield gaps. Mueller *et al* (2012) quantified the global potential for management to close yield gaps for maize, wheat, and rice using national and sub-national scale data. We used a high spatial (1 ha grid cells) and temporal (daily time step) resolution simulation approach in quantifying the influence of management and environment on wheat yields in Australia. We also extended the Hochman *et al* (2009) analysis—which calculated wheat yield gaps in the Wimmera region of southern Australia as the difference between actual (survey/census reported) and exploitable (model simulated) yields—by quantifying the influence of management and environmental drivers on yield as a basis for informing management. Our results support previous findings on the dual importance of management and environment in influencing wheat yield (Anderson *et al* 2005, Basso *et al* 2012, Mueller *et al* 2012), particularly the co-limitation of nitrogen, water, and temperature (Cossani *et al* 2010, Asseng *et al* 2011). While other studies have also found that potential exists to increase wheat yield through management such as nitrogen application (Asseng *et al* 2008, Licker *et al* 2010), with such a large and geographically diverse study area, we found complex interactions between management and environment. This contrasts with Anderson (2010) for example, which found that 80% of the impact on yield was driven by environmental variables, rather than management or genetic variables, and that interactions between these variables were generally unimportant. Our results align with the global findings of Mueller *et al* (2012) which suggest a much stronger role for management in increasing wheat yields. Our finding that residue management had little effect on wheat yield aligned with some studies such as the Sommer *et al* (2012) assessment of wheat in northern Syria and the Anderson *et al* (2005) review of factors affecting Western Australian yield improvements, but contrasted with others (Grigoras *et al* 2012a,b) which have found that no-till management decreased wheat yield in Romania. In general, our results support the conclusions of Deryng *et al* (2011) and Ransom *et al* (2007)

that wheat yield is highly nuanced, being affected by multiple interacting environmental and management variables.

Given these complex relationships, increasing crop yield through sustainable intensification demands locally-contextualized and adaptive management responses. The results presented here provide exactly this kind of information as a necessary basis for farm management decisions for improving wheat yields. The results identify for the first time, key management and environmental drivers of wheat yield and their interactions for the entire potential cropping area of Australia at high spatial, temporal, and agronomic resolution. The panel graphs in figure 4 illustrate the specific benefits of fertilizer application in the context of the three influential environmental variables (effective growing season rainfall, maximum temperature, and soil water holding capacity). With a little knowledge of the climatic and soil characteristics of their property farm managers and advisors can ascertain the contextualized potential yield benefit of additional fertilization. We also present detailed spatial information on the likely benefits of increasing fertilization rates on wheat yield under a range of effective growing season rainfall (figure 5). This information can help guide geographically specific management as fertilization rates can be cost-effectively tailored to specific soils with modern farming technology (Brennan *et al* 2007). As general rule of thumb—greater yield benefits of fertilizer application can be achieved in cooler, wetter regions, especially on soils with greater water holding capacity. In addition, this information can be used to support adaptive decisions on additional fertilizer application made throughout each growing season in response to weather conditions and seasonal forecasts. Supported by appropriate mechanisms to disseminate and communicate this information to farmers and farm advisors, the information presented can inform both general management strategies and more targeted, tactical management strategies adapted through the growing season.

The results also have implications for the effectiveness of management in increasing yields under climatic change (Luo *et al* 2005b, Wang *et al* 2011, Asseng *et al* 2013). The peaked relationship between average maximum temperature and yield (figure 3) suggests that fertilization will become less effective in warmer regions (i.e. where average maximum temperatures exceed 18 °C), but may become more effective in cooler regions, as the climate warms.

4.2. Methodological advances and limitations

The spatial simulation of agricultural production under a range of management scenarios is intensive both in terms of data requirements and computational demand (Stehfest *et al* 2007, Tao *et al* 2009). This has limited the application of crop models over large areas (regional to global) at the high level of spatial resolution required to assess of the impact of agricultural management on yield with a high level of confidence (Folberth *et al* 2012). The high-performance computing approach used here has enabled the modeling of agricultural systems for increasing wheat yields for an unprecedented spatial extent, resolution, and level of agronomic detail (Bryan 2013a, Zhao *et al* 2013a), thereby generating novel insights.

There are however, several limitations with the modeling which increase the uncertainty in the results. The quality and extent of the soil mapping in parts of the study area attenuates confidence in the modeled outputs in these areas. In addition, the soil data used does not capture topographical characteristics (e.g. slope, aspect) which affect crop production (Ferrara *et al* 2010). Discretization of management scenarios, particularly the 25 kg N ha⁻¹ yr⁻¹ fertilization rate increments, may miss significant impacts of subtle changes in management on crop productivity (Farquharson *et al* 2003, Dalal *et al* 2004, Liu *et al* 2009). Higher resolution fertilization rates could provide more precise estimates of management yield benefits, particularly at low fertilization rates in marginal land. We also did not consider the potential impact of a range of other crop management techniques such as crop rotation and mixed farming systems designed to prevent the establishment of disease (Schillinger and Paulitz 2006, Kirkegaard *et al* 2008, Seymour *et al* 2012). Nor did we consider inter-annual carryover in nitrogen, organic matter, or water as residual levels in the soil may benefit yields in the following season (Huang *et al* 1999, Hansen *et al* 2009).

4.3. Implications for sustainable intensification and closure of yield gaps

The information provided in this study can support farmer decisions to increase yields and thereby contribute to closing yield gaps. Of importance in closing yield gaps is environmental sustainability (Mueller *et al* 2012). Agricultural intensification and land sparing and has shown promise for conserving biodiversity (Green *et al* 2005, Phalan *et al* 2011). This is especially the case in the industrialized broad acre agricultural systems of Australia and elsewhere where agricultural land use forms a particularly hostile habitat for native plants and animals and conservation is more effective in dedicated reserves and remnants (Cunningham *et al* 2013). However, other aspects of intensification have contributed to environmental problems such as the impact of nutrients on surface and ground water quality (Tschardt *et al* 2012). The context-specific information presented here can increase the environmental sustainability of intensification by helping farmers target the use of fertilizer and avoid ineffective use or over-use (Mueller *et al* 2012). Crop residue management, despite the lack of effect on yield, has been found to increase soil organic carbon in Australian wheat systems (Luo *et al* 2013, Zhao *et al* 2013b) and thereby may be an important management action contributing to agricultural sustainability. Questions remain though around the effects of the increased herbicide and pesticide use associated with residue management practices such as minimum till on ecosystem services. These complex co-benefits and trade-offs suggest that the impacts of agricultural management practices on the full range of natural capital and ecosystem services, including biodiversity, needs to be considered in assessments of management effects on yield gap closure (Licker *et al* 2010, Power 2010, Bryan 2013b). Future assessments should strive to quantify the net impacts of agricultural management in an integrated way, capturing both direct and indirect effects, at scales from local to global, over the full life cycle.

A second important consideration in increasing yields and closing yield gaps is economic sustainability. For yield gaps to be closed on a large scale, it has to be economic for farmers to increase yields. While many yield gap studies have focussed on actual yields relative to either attainable yields or the biophysical potential of the land, broader perspectives have also recognized an economic ceiling—the maximum yields that make economic sense given the relative prices of inputs and outputs, market access, risk, and other considerations (Sumberg 2012). Crop production functions show that yield benefits taper off in response to increased inputs such as fertilizer (figure 5). However, the cost of inputs increases linearly with the application rate. This creates an agronomic optimum level of intensification where the marginal benefits of another kilogram of nitrogen equal the marginal costs (Park *et al* 2010). Yield at the agronomic optimum may well be less than the attainable yield and is likely to be significantly less than the biophysical maximum. Hence, attention to the economic viability and sustainability of management intensification is also an important aspect of yield gap closure.

5. Conclusion

Many studies have calculated crop yield gaps but few have assessed the impact of specific changes in management practices on yield—explicitly quantifying the crop yield benefit of spatial, context-specific management actions. Yet, it is this information that is required by farmers to support their management decisions if yield gaps are to be closed. We simulated wheat yield under various fertilization and residue management strategies from 1900 to 2010 across 179 Mha of arable land in Australia at a high spatial, temporal, and agronomic resolution. Crop yields varied considerably over space and time, in response to key environmental and management variables. While residue management had little effect on wheat yield, fertilization strongly increased yield up to rates of around 100 kg N ha⁻¹ yr⁻¹, with little further increase at higher application rates. Wheat yields also varied non-linearly with environmental variables. Yield increased with effective growing season rainfall up to around 500 mm yr⁻¹, and with soil water holding capacity up to around 0.2 mm mm⁻¹—with little marginal increase beyond. Yields also increased with average daily maximum temperatures, peaking at around 18 °C and declining beyond. Thus, higher fertilization rates led to increased yields but the effect was highly context-dependent—with better outcomes achieved in cooler, wetter regions, with greater soil water holding capacity. The information presented here can be used to support effective management responses for increasing yields, tailored to the local environmental characteristics of an area, and to support adaptive responses to seasonal weather conditions and forecasts over time. Along with considerations of economic and environmental sustainability, this information can form a key part of the farm management decision to increase intensification, boost crop yields, and thereby contribute to the closure of yield gaps.

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