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RESEARCH ARTICLE

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Quantifying the economic impact of soil constraints on Australian agriculture: A case-study of wheat

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Abstract

Soil sodicity, acidity, and salinity are important soil constraints to wheat production in many cropping regions across Australia, and the Australian agricultural industry needs accurate information on their economic impacts to guide investment decisions on remediation and minimize productivity losses. We present a modelling framework that maps the effects of soil constraints on wheat yield, quantifying forfeited wheat yields due to specific soil constraints at a broad spatial scale and assessing the economic benefit of managing these constraints. Of the three soil constraints considered (sodicity, acidity, and salinity), sodicity caused the largest magnitude of yield gaps across most of the wheat-cropping areas of Australia, with an average yield gap of 0.13 t·ha^{-1}yr^{-1}. Yield gaps due to acidity were more concentrated spatially in the high-rainfall regions of Western Australia, Victoria, and New South Wales, and averaged 0.04 t·ha^{-1}yr^{-1} across the wheat-cropping areas of Australia, whereas the yield gap due to salinity was estimated to be 0.02 t·ha^{-1}yr^{-1}. The lost opportunity associated with soil sodicity for wheat production was estimated to be worth A$1,300 million per annum, for soil acidity, A$400 million per annum, and for salinity, A$200 million per annum. The results of this work should prove useful to guide national investment decisions on the allocation of resources and to target areas where more detailed information would be required in order to reduce the yield gap associated with soil constraints on wheat yields in Australia.

KEYWORDS

soil acidity, soil salinity, soil sodicity, spatial distribution, wheat yield gaps

1 | INTRODUCTION

With a growing world population placing increasing pressure on food production, it is becoming more and more important to close the gap between actual and potential crop yields. The situation is made more difficult by changing climates, which are generally expected to decrease potential yields (Hochman, Gobbett, & Horan, 2017). Many studies have investigated these yield gaps and mapped them at national and global scales (e.g., Boogaard, Wolf, Supit, Niemeyer, & Ittersum, 2013; Lu & Fan, 2013; Schierhorn, Faramarzi, Prishchepov, Koch, & Müller, 2014; van Ittersum et al., 2013), with much of Africa and Eastern Europe producing less than 40% of their potential yields (Pradhan, Fischer, van Velthuizen, Reusser, & Kropp, 2015) and Australia around 50% of its potential wheat yields (Hochman, Gobbett, Horan, & Garcia, 2016). Yield gaps may be attributable to many causes, and not only do the causes vary substantially spatially, but there is also a large degree of uncertainty associated with them. Closing yield gaps can only come with a fuller understanding of their causes and of the spatial distribution of these causes.

Australia's arid climate, variation in land form, and inherent low soil fertility makes only about 10% of the 7.7 million km^2 land area suited to crops and improved pasture (Looney, 1991). Despite an increased awareness of susceptibility to land degradation and investment in remediation and management, in some agricultural regions, productivity growth in the cropping industry is constrained by land degradation, such as sodicity, acidity, and salinity. Climate change exacerbates these risks, making more areas becoming marginal for productive agriculture (Hochman et al., 2017). Hence, the expansion of the level of output requires greater use of inputs at an increasing cost (Ashton, Oliver, & Valle, 2016) and innovation in climate-smart agricultural practices (Lipper et al., 2014). This has implications for the sustainability of farm enterprises and the global food system, as Australia is an important contributor to global food supplies. Inability to arrest land degradation also creates other public costs in terms of loss of vegetation and biodiversity as well as health and infrastructure costs.

Soil sodicity, acidity, and salinity are significant constraints to wheat production on many cropping soils globally (Bot, Nachtergaele, & Young, 2000) and in Australia (National Land and Water Resources Audit, 2001). In Australia, Bot et al. (2000) estimated that 77% of soils have single or multiple constraints in both surface and subsoil, and the area affected is increasing over time. Despite their significance, the available information on the extent and impact of these soil constraints on Australian agriculture is based largely on extrapolations from soil surveys and expert opinion specific to regions (Clarke, George, Bell, & Hatton, 2002; Rengasamy, 2002). The most commonly reported financial impacts of soil constraints in terms of annual lost agricultural production in Australia are A$1,585 million for acidity, A $1,035 million for sodicity, and A$187 million for salinity (Hajkowicz & Young, 2005). Also, subsoil constraints have been estimated to cost the Australian farming economy around A$1,330 million per year (Rengasamy, 2002). The Australian agricultural industry needs accurate and standardized nationwide information on the costs of these constraints, to guide investment decisions on amelioration to minimize productivity losses and to set priorities for the selection of traits for the breeding of adapted crop cultivars (Dang & Moody, 2016). Improved methods of assessment provide useful guides to undertake similar assessments elsewhere.

Yield gaps (Y_g) are generally quantified (Fischer, 2015; Hochman et al., 2012; van Ittersum et al., 2013) as the difference between yields that are currently achieved by farmers (Y_a) and the *water-limited* yield (Y_w), the yield that is potentially attainable (by an adapted crop variety without growth limitations from nutrients, pests, or diseases) under rainfed conditions:

$$Y_g = Y_w - Y_a. \tag{1}$$

Previous work in the wheat belt of Australia (Hochman et al., 2012; Hochman et al., 2016) has used biophysical models such as Agricultural Production Systems Simulator (APSIM) (Holzworth et al., 2014) to simulate Y_w and thus calculate yield gaps attributable to management factors. The impact of soil constraints was not specifically addressed in those studies, where the soil effects were calculated on the basis of typical representatives of up to three dominant soils (Australian Soil Classification Order; Isbell, 1996) per weather station, and soil constraints were averaged out within each Australian Soil Classification Order. In the current study, we are concerned with individual contributions to forfeited yield from three specific soil constraints: soil sodicity, acidity, and salinity. Our approach and terminology build on previous studies including Hochman et al. (2012, 2016).

Soil sodicity, an excess of sodium ions in relation to other cations, measured through the exchangeable sodium percentage (ESP), can lead to soil dispersion, poor soil structure, low water infiltration, high susceptibility to erosion, and nutrient imbalance, and thus can have an impact on wheat growth and economic return. Bot et al. (2000) estimated that 3% globally and 17% of Australia's land area is sodic, noting that worldwide contrasts would be partly due to different interpretations over what constitutes a sodic soil. Under Australian conditions, sodic soils are classified as those with an ESP >6% (Northcote & Skene, 1972). Application of gypsum can improve the structure of sodic soils by increasing flocculation of clay particles and by replacing Na with Ca on the exchange complex near the soil surface (Shainberg et al., 1989). Over time and with adequate rainfall, Ca can move down the soil profile thereby ameliorating subsoil sodicity; though in arid and semiarid environments, this movement down the profile can be limited.

In acidic soils, increased solubility of Al and Mn can inhibit plant growth (Tang, Rengel, Diatloff, & Gazey, 2003; von Uexküll & Mutert, 1995). It has been estimated that 30% of the world's ice-free land area, and also 30% of Australia and New Zealand's land area, is composed of acid soils (von Uexküll & Mutert, 1995). Application of lime is a common practice to ameliorate soil acidity (Caires, Garbuio, Churka, Barth, & Corrêa, 2008), and studies on soil acidity and the effects of liming in Western Australia (Gazey & Davies, 2009) have considered soil pH target values of 5.5 in the topsoil and 4.8 in the subsoil (1:5, 0.01 M $CaCl_2$).

Saline soils are defined by high values of electrical conductivity, a measure of the total concentration of salts, with values greater than 0.3 dS m^{-1} in the topsoil or 0.7 dS m^{-1} in subsoils (1:5 soil:water suspension) being considered saline (Dang et al., 2008). Electrical conductivity alone reflects total salts, some of which (e.g., gypsum) will vary in the extent to which they impact negatively on crop yields. The chloride (Cl) concentration provides additional information as a measure of the Cl component of soil salinity, with concentrations over 300 mg kg^{-1} in the topsoil or 600 mg kg^{-1} in subsoil providing toxic conditions for many crop species (Dang et al., 2008). It has been estimated that globally, 3% of soils and also 3% of Australia's soils are affected by salinity (Bot et al., 2000).

Given the variation in existing information on the costs of each of these soil constraints to Australian agriculture, the objectives of this work were to (a) develop national maps quantifying forfeited wheat yields due to the specific soil constraints of sodicity, acidity, and salinity at broad-area level and (b) develop a framework for assessing the economic benefit of ameliorating or managing specific soil constraints. The aim was to summarize by region the most likely important constraints and to provide some indication of the likely general benefits of remediation. The information gained should prove useful as a guide for national investment decisions on the allocation of resources to reduce the impact of soil constraints to crop production. This will further facilitate industry's knowledge and awareness of soil constraints and the aspiration to combat soil constraints to meet food security needs and manage finite soil resources for future generations globally.

2 | METHODS

The yield gap due to soil constraint “c” is defined as

$$Y_{gc} = Y_{oc} - Y_{ac}. \tag{2}$$

The yields that are referred to here as ‘actual yields,’ Y_{ac}, are those predicted by a model (that represents the effects of soil constraint c on yield) using observed soil and climate parameters as inputs, whereas the ‘constraint-optimized yields,’ Y_{oc}, are those predicted by the same model with the same climatic inputs but with soil constraint c set to some defined optimum (i.e., nonlimiting) value. Our challenge was to formulate models that could represent the effects of soil constraints on yield across the variety of environmental conditions in the wheat-growing regions of Australia.

We employed a multistage empirical modelling approach to represent the effects of soil constraints on yield to estimate yield gaps due to soil constraints. Our approach brought together data from a number of sources (Table 1): (a) wheat yield data as averages over Statistical Local Areas (SLA; data from 254 SLAs, which have an

TABLE 1 A summary of data sources used to derive estimates of yield gaps due to soil constraints

Variables	Spatial/temporal data support	Grid size/number of data	Source
Land use categories; dryland cropping, irrigated cropping, other	Point (each pixel's class observation assumed to be representative class for the entire 100-m × 100-m pixel)	On 100-m × 100-m grid	ACLUMP; http://www.agriculture.gov.au/abares/aclump
EVI	30-m × 30-m (Landsat) and 250-m × 250-m (MODIS) pixels (value of pixel assumed to be representative of entire pixel); point-in-time measurements	On 30-m × 30-m (Landsat) and 250-m × 250-m (MODIS) grids; measurements approximately every 16 days from both Landsat and MODIS, with those from MODIS representing the maximum EVI in a 16-day window from overpasses every 1–2 days	Landsat: USGS; https://landsat.usgs.gov/ MODIS: USGS; https://lpdaac.usgs.gov/dataset_discovery/modis
Yield	Averages over the active cropping areas of SLAs, which vary in area of potential cropping from <500 ha to 1.3 million ha	254 SLAs with wheat yield data across Australia, each with one average value for each winter-wheat growing season from 1999 to 2012	ABS and CSIRO; http://www.yieldgapaustralia.com.au/wordpress/[a]
Climate; VPD	Point (each pixel's value assumed to be representative of entire 5-km × 5-km pixel); point-in-time measurements	On 5-km × 5-km grid; daily measurements over the period September–October for each growing season from 1999 to 2012	SILO (gridded dataset); https://www.longpaddock.qld.gov.au/silo/index.html
Soil; pH, ESP, EC, Cl, sand, clay	Point, each from a single soil profile. Each soil profile consists of a number of depth intervals (an average of 4 depth intervals per profile), each measurement representing the average of the soil property over that interval	Data from 30,549 depth intervals within 7,015 soil profiles; varying numbers of data for between soil properties	Originally from State and Territory agencies, and collated in NSSC; Searle (2014) Victoria Government (Mark Imhof, pers. Comm.)

[a]Note that the above source has recently updated the spatial support of yield data from SLA to SA2; we work with SLA-level data that were available at the time of commencing the project. ABS: Australian Bureau of Statistics; ACLUMP: Australian collaborative land and management program; Cl: chloride; CSIRO: Commonwealth Scientific and Industrial Research Organisation; EC: electrical conductivity; ESP: exchangeable sodium percent; EVI: enhanced vegetation index; MODIS: MODerate Resolution Imaging Spectrometer; NSSC: National Soil Site Collation; SA2: Statistical Area Level 2; SILO: Scientific Information for Land Owners; SLA: Statistical Local Area; USGS: United States Geological Survey; VPD: vapour pressure deficit.

average area of around 500,000 ha, varying from 2,000 ha to over 4 million ha) from the Australian Bureau of Statistics (ABS), (b) land use data from the Australian collaborative land and management program, (c) remote sensing data on 30- and 250-m pixels from the Landsat and MODIS (MOD13Q1) satellites, (d) climate data on a 5-km grid across Australia from the Scientific Information for Land Owners (Jeffrey, Carter, Moodie, & Beswick, 2001) database hosted by the Queensland Government, and (e) soil data from soil profiles across Australia's cropping land, predominantly from the National Soil Site Collation (Searle, 2014).

The procedure is described in detail in Methods S1–S2, Figures S1–S7, and Tables S1–S3. In brief, SLA-average yield data were disaggregated via area-to-point kriging (Kyriakidis, 2004), with remote sensing data (enhanced vegetation index; Huete, Liu, Batchily, & van Leeuwen, 1997) as a covariate, to estimate yield at the locations of the soil profile data; this method ensured the disaggregation could reflect both fine-scale (via the enhanced vegetation index data) and broad-scale (through area-to-point kriging) yield differences. A statistical model (a Cubist model; Quinlan, 1992) was then fitted to predict yield as a function of soil constraints (with each constraint assumed to have an impact on yield when it exceeded its critical values, Table 2) and climate and applied to calculate yield gaps due to each soil constraint through Equation (2). The yield gaps were interpolated to a 1-km grid of the study area and aggregated to the level of Statistical Area Level 2 (SA2; a recent replacement for SLAs made by the ABS) for reporting and economic analysis. The area of each SA2 affected by each soil constraint was estimated by interpolating an indicator variable (taking the value 1 if the yield gap at a data location was >0 t·ha^{-1}yr^{-1} and the value 0 otherwise) to the 1-km grid and aggregating. Economic analysis was undertaken using a constraints analysis approach with indicative costs (Table 3; Ashton et al., 2016; Petersen, 2015; Rural Solutions, 2016; Upjohn, Fenton, & Conyers, 2005). Given the vast geographical area that we cover in this analysis, there will be considerable variability in the response of crop yields to application rates and frequencies. In some cases, the indicative values considered here will be inadequate to fully close yield gaps, whereas in most cases, they would be sufficient.

3 | RESULTS

3.1 | Magnitudes of yield gaps due to soil constraints

The estimated yield gaps were generally largest for sodicity across much of Australia's wheat-cropping land, with average gaps of 0.2–0.4 t·ha^{-1}yr^{-1} over many SA2s (Figure 1). Yield gaps due to acidity were largest in the high-rainfall regions of Western Australia, Victoria, and New South Wales, where they were generally estimated to be 0.1–0.2 t·ha^{-1}yr^{-1}. Yield gaps due to salinity were considerably smaller and predominantly estimated to be <0.1 t·ha^{-1}yr^{-1}. As averages across Australia's wheat-cropping land, the yield gap was 0.13 t·ha^{-1}yr^{-1} due to sodicity, 0.04 t·ha^{-1}yr^{-1} due to acidity, and 0.02 t·ha^{-1}yr^{-1} due to salinity. Relative to the long-term average of our SLA-level yield data, 1.76 t ha^{-1}, the yield gaps represented 8% (sodicity), 3% (acidity), and 1% (salinity) of actual yields. At SA2 level, the yield gaps relative to the long-term SA2-average yield (i.e., $100Y_{gc}/Y_{ac}$) ranged from 0% to 21% for sodicity, to 20% for acidity, and to 4% for salinity.

TABLE 2 Summary of critical values for soil constraints and for the three depths, *d*; A: 0–10 cm, B: 10–50 cm, C: 50–200 cm

d	$ESPCrit_{sdcty}$ [*d*]	$pHCrit_{acdty}$ [*d*]	$pHCrit_{alkty}$ [*d*]	$ECCrit_{slnty}$[*d*], dS m^{-1}	$ClCrit_{slnty}$[*d*], ppm
A	6.0	6.0	7.4	0.3	300
B	6.0	4.8	7.4	0.7	600
C	6.0	4.8	7.4	0.7	600

Note. $sCrit_c$: the critical value of soil property *s* for negative effects of soil constraint *c*.

TABLE 3 Key parameters used in economic assessment

Parameter	Unit	Value
Average wheat price	A$ t^{-1}, delivered	260
Marginal cost of wheat	A$ t^{-1}, assuming an average yield of 2 t ha^{-1}	28.14
Treatment costs		
(a) Gypsum for sodicity		
Gypsum rate	t ha^{-1}	2.5
Frequency of application	1 in 12 years, split annually	0.8
Price of gypsum	A$ t^{-1}	35
Transport	A$ t^{-1}	19
Application	A$ t^{-1}	19
(b) Lime for acidity		
Liming rate	t ha^{-1}	2.8
Frequency of application	1 in 12 years, split annually	0.8
Price of lime	A$ t^{-1}	32
Transport	A$ t^{-1}	20
Application	A$ t^{-1}	9

3.2 | Areas affected by soil constraints

The area of wheat-cropping land affected by each of the soil constraints varied (Figure 2). For sodicity, regions of Queensland showed more than 90% of cropping land affected, though for much of Australia, in the regions that showed large yield gaps, 75–90% of the cropping land was affected. In the regions affected by acidity (those noted in Section 3.1), upwards of 90% of the land was predicted to be affected. Salinity was predicted to be affecting yield in the south of Western Australia and the south of Queensland, although from Figure 1c, it seems that the magnitudes of the yield gaps due to salinity in these regions were not as large as those for sodicity. The areas predicted to be affected by soil constraints (Figure 2) were compared with predictions based on other datasets (Methods S3 and Table S4) and showed reasonable agreement (Appendix S1, Figures S8–S10, and Tables S5–S7).

3.3 | Economic impact of soil constraints

Based upon the estimated yield gaps per hectare, the gross value of production attributable to these estimated yield gaps was calculated (Figure 3). Then, the net value of forgone production was estimated,

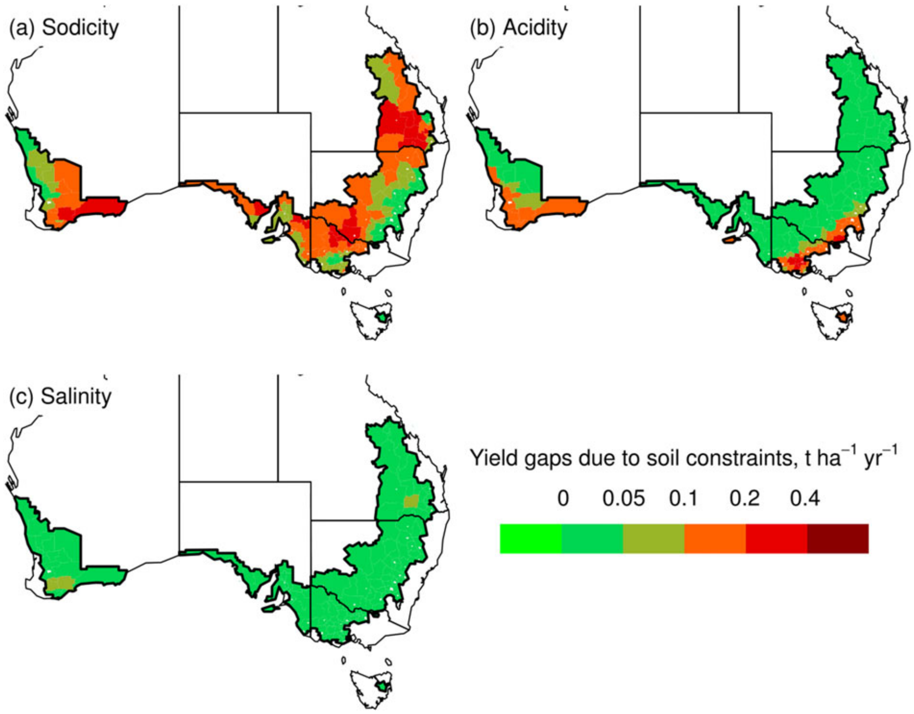

FIGURE 1 Yield gaps due to (a) sodicity, (b) acidity, and (c) salinity at SA2 level [Colour figure can be viewed at wileyonlinelibrary.com]

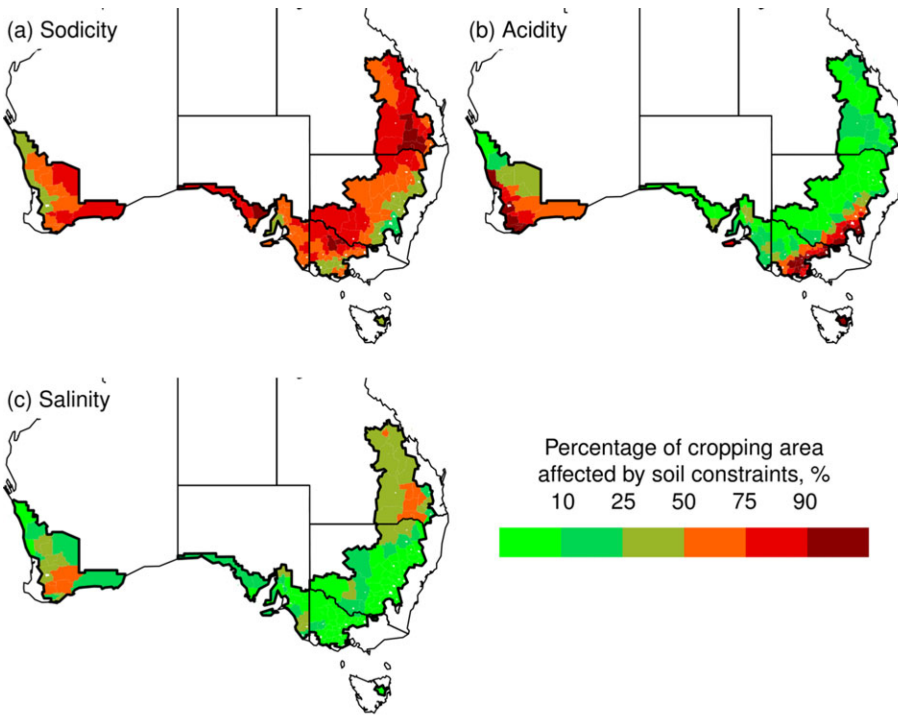

FIGURE 2 Areas of land, as a percentage of the cropping land, affected by (a) sodicity, (b) acidity, and (c) salinity at SA2 level. SA2: Statistical Area Level 2 [Colour figure can be viewed at wileyonlinelibrary.com]

using indicative treatment costs for sodicity (gypsum application) and acidity (lime application; Figure 4). The gray regions of Figure 4 show where the average yield gap for an SA2 was less than 0.05 t·ha^{-1}yr^{-1} (no economic analysis carried out) or the predicted net value of ameliorating the soil constraint was less than A$10 ha^{-1}yr^{-1} (minimal economic benefit). The predicted potential benefits of applying gypsum to ameliorate soil sodicity covered the largest area, with predicted net benefits of A$20–60 ha^{-1}yr^{-1} across much of Australia's wheat-cropping land. For acidity, much of Australia fell into the minimal economic benefit category, although there were concentrated parts of Western Australia, New South Wales, and Victoria where potential net benefits ranged from A$20–60 ha^{-1}yr^{-1}.

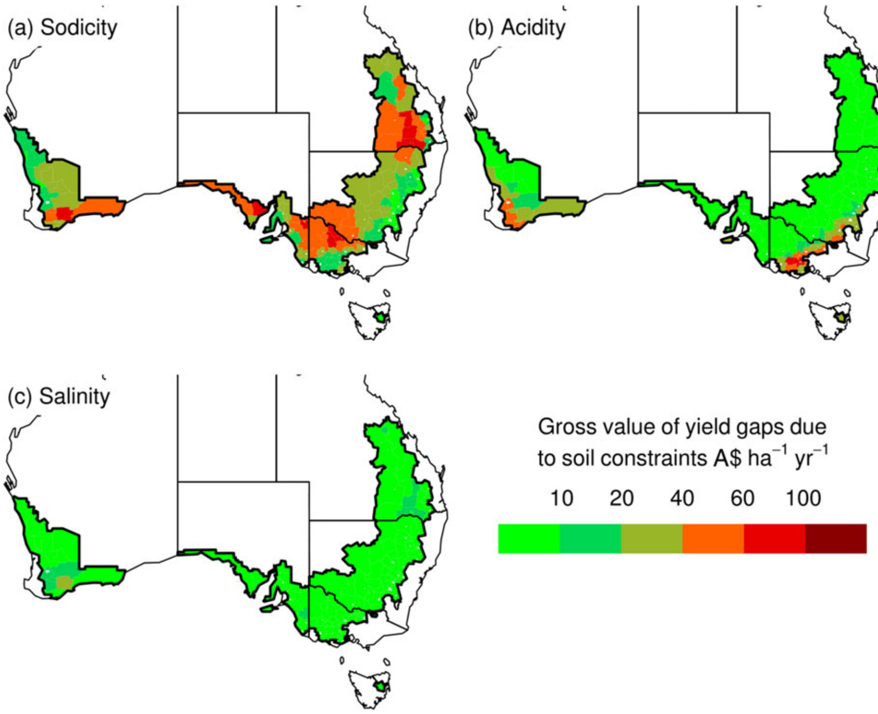

FIGURE 3 Gross economic value of yield gaps due to (a) sodicity, (b) acidity, and (c) salinity at SA2 level. SA2: Statistical Area Level 2 [Colour figure can be viewed at wileyonlinelibrary.com]

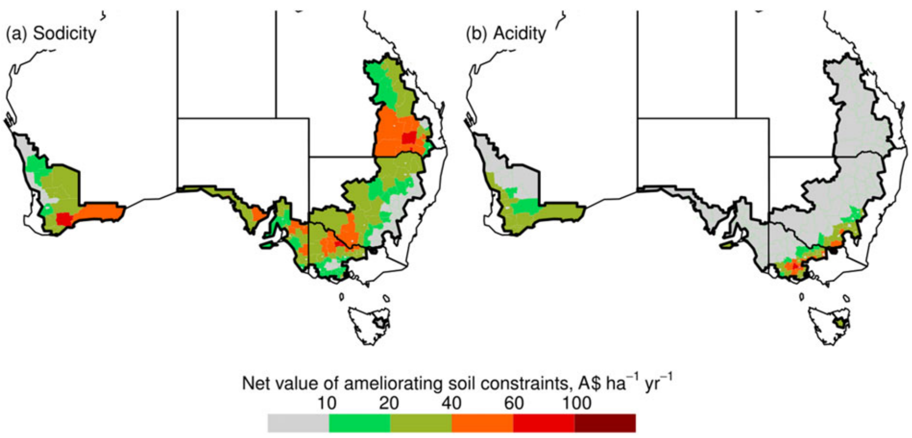

FIGURE 4 Net economic value of ameliorating the soil constraints of (a) sodicity and (b) acidity at SA2 level. SA2: Statistical Area Level 2 [Colour figure can be viewed at wileyonlinelibrary.com]

3.4 | Broad-scale comparisons

Although we provide information at the SA2 level, it can be informative to also summarize at broader scales, by state, and nationally (Table 4). Results highlight the importance of sodicity nationally and acidity in Western Australia, Victoria, and New South Wales. It was estimated that 68% of Australia's wheat-cropping land is affected by sodicity, 35% by acidity, and 24% by salinity. In Queensland, sodicity was estimated to be affecting 80% of the wheat-cropping land, and the average yield gap due to sodicity was 0.17 t·ha^{-1}yr^{-1}. In Western Australia, the percentage affected by acidity was 55%, with an average yield gap of 0.07 t·ha^{-1}yr^{-1}; within just the areas of Western Australia affected by acidity, the average yield gap due to acidity was 0.11 t·ha^{-1}yr^{-1}. In Victoria and New South Wales, 22% of wheat-cropping land was impacted by acidity, and the average yield gap was 0.03 t·ha^{-1}yr^{-1}. Within just the affected areas of Victoria, the average yield gap due to acidity was 0.13 t·ha^{-1}yr^{-1}, and within the affected areas of New South Wales, it was 0.11 t·ha^{-1}yr^{-1}. The sensitivity of the predicted yield gaps to the critical values was investigated (Methods S3), and results (Appendix S1) showed sodicity to still contribute to the largest yield gaps even with a critical value for sodicity of ESP > 15% (compared with the value of ESP > 6% used in the main study).

4 | DISCUSSION

4.1 | Yield gaps due to soil constraints

Of the three soil constraints considered, sodicity has the largest effect on wheat yields across Australia, with acidity also producing large yield

TABLE 4 Yield gap information, summarized by state and nationally

State	Area of cropping, kha	Soil constraint, c	Average yield gap due to c, t·ha^{-1}yr^{-1}	Area affected by c, kha	Average yield gap due to c within affected area, t·ha^{-1}yr^{-1}	Gross value of yield gap due to c, A\$ million yr^{-1}	Net value of ameliorating c, A\$ million yr^{-1}
NSW	8,064	Sodicity	0.11	5,246	0.13	222.2	191.7
		Acidity	0.03	1,590	0.11	58.6	50.7
		Salinity	0.01	1,074	0.02	17.6	NA
Qld	3,278	Sodicity	0.17	2,631	0.20	147.2	126.9
		Acidity	0.01	367	0.03	7.5	6.5
		Salinity	0.03	1,492	0.04	21.7	NA
SA	4,964	Sodicity	0.15	3,532	0.18	195.6	168.7
		Acidity	0.01	504	0.03	10.1	8.7
		Salinity	0.01	722	0.02	12.8	NA
Tas	108	Sodicity	0.03	24	0.05	0.7	0.6
		Acidity	0.18	102	0.19	5.1	4.4
		Salinity	<0.01	1	0.01	0.1	NA
Vic	4,614	Sodicity	0.19	3,618	0.21	223.3	192.6
		Acidity	0.04	1,204	0.13	48.1	41.6
		Salinity	<0.01	139	0.02	5.7	NA
WA	17,326	Sodicity	0.12	10,946	0.16	546.7	471.5
		Acidity	0.07	9,576	0.11	310.8	268.6
		Salinity	0.03	5,612	0.05	124.4	NA
National summary							
	38,354	Sodicity	0.13	25,997	0.17	1,335.7	1,152.1
		Acidity	0.04	13,342	0.10	440.3	380.6
		Salinity	0.02	9,040	0.04	182.3	NA

gaps in the high-rainfall areas of Western Australia, Victoria, and New South Wales. Hajkowicz and Young (2005) also found these two constraints to have larger impacts on Australian wheat yield when compared with those of soil salinity. Our estimates for the areas affected by soil constraints (estimated by aggregating indicator kriging predictions to SA2 level, Figure 2) also show broad agreement with van Gool (2016), which examined a number of soil constraints across Western Australia. The percentage of Australia's land affected by sodicity was estimated as 17% by Bot et al. (2000), compared with a global estimate of 3%; Bot et al. (2000) also estimated that 3% of both the world's and Australia's soils are affected by salinity, whereas von Uexküll and Mutert (1995) estimated that 30% of the world's and of Australia's soils are affected by acidity. These data suggest that sodicity might have relatively more importance in Australia than worldwide, though for any comparison with our results, it should be noted that we considered only the area defined as potential wheat-cropping land.

The approach used in the present study extends those used in previous studies for Australia, where the average yield gap due to management factors (suboptimal management of pests and diseases, nutrient supply, time of sowing, crop density, and variety choice) was estimated at 1.8 t·ha^{-1}yr^{-1} (Hochman et al., 2016). Importantly, relative to the overall yield gap, our estimated impact of sodicity represented 8% of the total wheat yield gap, whereas that for acidity represented 3%.

4.2 | Economic value of addressing soil constraints

Hajkowicz and Young (2005) reported that, across the Australian wheat-cropping belt, costless removal of soil constraints represented potential annual profit increases of A\$1,000 million for sodicity, A\$1,600 million for acidity, and A\$200 million for salinity. The corresponding values estimated in the current work (to the nearest A\$100 million) are A\$1,300 million for sodicity, A\$400 million for acidity, and A\$200 million for salinity.

The most notable difference between our estimates and those of Hajkowicz and Young (2005) for the value for acidity could be due in part to the extent of remediation already undertaken by land managers, as well as refinements in the method of assessment. Soil acidification is a natural process accelerated by agricultural practices, its main cause in cropping soils being inefficient use of nitrogen, followed by the export of alkalinity in produce. The treatment of acidity is reasonably straightforward, liming being the most economical method of amelioration. The amount of lime required will, however, depend on the soil pH profile, lime quality, soil type, farming system, and rainfall.

We note that our estimates of the economic impacts of soil constraints are based on the entirety of Australia's 'potential cropping land' (i.e., that classified as dryland or irrigated cropping in the Australian collaborative land and management program map). Across Australia, this covers 38 million ha, whereas on average, only 13 million ha is cropped with wheat in any given season. Hence, we overestimate the likely increase in profits due to the treatment of soil constraints. However, in considering future benefits of amelioration, this 'optimistic' potential area may prove useful in any given region as the wheat crop often moves around available land following rotations and seasonal conditions. Once ameliorated, the land is available for production, offering potential benefits.

4.3 | Limitations of study

4.3.1 | Methodology for yield gap estimation

Lobell (2013) outlined general approaches that might be applied to understand yield heterogeneity at the landscape scale, and our approach is based on one of these: maps of yields derived from remote sensing are compared with ancillary datasets on factors thought to control yields, in our case climate and soil properties. Statistical analyses are then used to evaluate the relative importance of each factor in driving observed yield variations.

We note that an alternative approach could utilize biophysical models, for which yield gap due to a soil constraint could be defined as the difference between water-limited potential yield (in the same sense as Hochman et al., 2012) and a soil-constraint-affected water-limited yield. The difference between the two alternatives is that this second definition considers the negative impact of imposing the soil constraint on the water-limited yield potential, whereas the definition of Equation (2) adapted in this paper considers the positive effect that ameliorating the soil constraint would have on actual yield. Under this alternative definition of yield gap due to soil constraints, biophysical models such as APSIM could be used to calculate the yield gap components, because the management factors could be taken to be optimum (see Christy et al., 2013 for an example estimating yield differences due to the choice of cultivar). However, to do so, it is imperative that the biophysical model adequately represents the effects of the factors under consideration (specific soil constraints) on yield over a range of climatic conditions; in the case of APSIM and the soil constraints of our study, the broad-scale applicability of these components of the model remains untested. We therefore opted for the definition of Equation (2) with an empirical modelling approach.

The methodology was designed to make the best use of data available to estimate yield gaps at large spatial scales (SA2). However, there are a number of steps in the process, all of which will carry some level of uncertainty. These include uncertainty in the

- ABS SLA-level yield data
- disaggregated yield predictions
- soil data (resulting from measurement errors and the soil-depth harmonization process)
- Cubist model fitted to the data
- estimated yield gaps at the soil data locations (as a result of all the former uncertainties)
- interpolated yield gaps

Although we have attempted to capture these sources of uncertainty (see Methods S1), we have not accounted for all sources and that remains a focus for future work. Therefore, the estimates produced need to be taken in the light of these uncertainties and as a guide to decision making at appropriate scales, such as SA2 and above, rather than as a tool for individual farmers to diagnose soil constraints at fine spatial scales.

4.3.2 | Limitations of economic analyses

The net estimates of the potentially forgone value of agricultural production due to principal soil constraints, soil sodicity and soil acidity, produced in this study need to be considered in the broader context of Australian farm financial performance. For instance, the estimated gross value of production for the grains industry in 2014–2015 was around A$14 billion. Wheat accounts for around half of this value, as well as half the volume of grains production (Ashton et al., 2016).

In evaluating measures to address any identified yield gaps, a key step is to ascertain the nature and severity of any barriers that may prevent profit-maximizing farmers from adopting measures that would profitably address these soil constraints. In doing so, the marginal-cost approach that we have adopted in this analysis will prove suboptimal.

Our analyses omitted the final step of evaluating the net economic benefits of ameliorating soil salinity, for two reasons. First, the estimated yield gaps due to salinity were small (a mean yield gap of 0.02 $t{\cdot}ha^{-1}yr^{-1}$, a relative yield gap at the SA2 level of 0 to 4%, and an estimated annual gross economic cost of around A$200 million). Second, there is no single agronomic measure that can ameliorate soil salinity of varying origin, making it impossible to relate the costs and benefits of amelioration to assess economic benefits.

Measures to ameliorate soil salinity at farm scale vary from the removal of salts through leaching involving irrigation and drainage management, enhanced crop nutrition, and the use of salt tolerant crop species. Among these, cropping in conjunction with leaching has been noted as the most successful and sustainable for ameliorating saline soils (Qadir, Ghafoor, & Murtaza, 2000). Moreover, transient salinity, the accumulation of salts in the root zone, is extensive in many sodic soil landscapes in Australia. Hence, based on the source of salinity, adoption of different strategies is essential for the sustainable management and improved productivity of rainfed dryland areas (Rengasamy, 2002; Rengasamy, 2006). Given the nature of costs and the likelihood of their increase under climate change, the long-term cost-effective amelioration would involve integrated strategies including the breeding and selection of adapted crop cultivars and enhanced monitoring to better align management to specific constraints.

4.3.3 | Presentation of results

We have presented maps at SA2 level of soil constraints and their costs to Australian agriculture, which should be interpreted with care. The SA2s themselves are of vastly different sizes (those within the cropping region vary in surface area from 1,200 to 6 million ha) and furthermore vary considerably in the intensity of cropping land (from less than 1% to more than 99% cropped). Therefore, data presented in such maps may create biases in interpretation. For instance, the importance of an SA2 with large surface area and very sparse cropping could be overemphasized compared with a small SA2 with concentrated cropping activity.

4.4 | Concluding remarks

Of the three soil constraints considered in this work (sodicity, acidity, and salinity), sodicity gave the largest magnitude of yield gaps across Australia, with an average yield gap of more than twice that of acidity. Yield gaps due to acidity were more concentrated spatially, in the high-rainfall regions of Western Australia, Victoria, and New South Wales. Across the wheat-growing land of Australia, the total potential annual economic benefit of ameliorating these soil constraints was estimated to be approximately A$1.15 billion per annum for sodicity (application of gypsum) and A$380 million per annum for acidity (application of lime). We note that these are based on indicative costs only and are intended to provide information at broad rather than fine spatial scale. The next stage of utilizing the results from the current study to bring benefits to Australian agriculture should involve conversations with farmers in the regions deemed to be most heavily affected by particular soil constraints, in order to confirm if appropriate management of these constraints would be feasible for them.

With an increasing population and greater stresses on food production, it is becoming more important to utilize the land as efficiently as possible. There are potential increases in yield and economic benefits to be earned from investment in strategies to combat soil constraints, and these benefits should contribute towards ensuring greater profits for farmers and better food security globally.

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