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Sustainability of nutrient management in grain production systems of south-west Australia

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Abstract. Balancing nutrient inputs and exports is essential to maintaining soil fertility in rainfed crop and pasture farming systems. Soil nutrient balances of land used for crop and pasture production in the south-west of Western Australia were assessed through survey data comprising biophysical measurements and farm management records (2010–15) across 184 fields spanning 14 Mha. Key findings were that nitrogen (N) inputs via fertiliser or biological N_2 fixation in 60% of fields, and potassium (K) inputs in 90% of fields, were inadequate to balance exports despite increases in fertiliser usage and adjustments to fertiliser inputs based on rotations. Phosphorus (P) and sulfur (S) balances were positive in most fields, with only 5% returning losses >5 kg P or 7 kg S/ha. Within each of the three agroecological zones of the survey, fields that had two legume crops (or pastures) in 5 years (i.e. 40% legumes) maintained a positive N balance. At the mean legume inclusion rate observed of 20% a positive partial N budget was still observed for the Northern Agricultural Region (NAR) of 2.8 kg N/ha.year, whereas balances were negative within the Central Agricultural Region (CAR) by 7.0 kg N/ha.year, and the Southern Agricultural Region (SAR) by 15.5 kg N/ha.year. Hence, N budgets in the CAR and SAR were negative by the amount of N removed in ~0.5 t wheat grain, and continuation of current practices in CAR and SAR fields will lead to declining soil fertility. Maintenance of N in the NAR was achieved by using amounts of fertiliser N similar to other regions while harvesting less grain. The ratio of fertiliser N to legume-fixed N added to the soil in the NAR was twice that of the other regions. Across all regions, the ratio of fertiliser N to legume-fixed N added to the soil averaged ~4.0:1, a major change from earlier estimates in this region of 1:20 under ley farming systems. The low contribution of legume N was due to the decline in legume inclusion rate (now 20%), the low legume content in pastures, particularly in the NAR, and improved harvest index of lupin (*Lupinus angustifolius*), the most frequently grown grain legume species. Further quantifications of the effects of changing farming systems on nutrient balances are required to assess the balances more accurately, thereby ensuring that soil fertility is maintained, especially because systems have altered towards more intensive cropping with reduced legume production.

Keywords: fertiliser, land use, nutrient budget, nitrogen, organic carbon, rotation, soil fertility.

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Introduction

Changes in Australian rainfed crop and pasture systems over the past 70 years have led to increased fertiliser use (Angus *et al*. 2006; Kirkegaard *et al*. 2011). Nitrogen (N) fertiliser usage in Australia increased from 1000 t to 1.0 Mt N/year over the period 1950–2000, continuing to rise to 1.5 Mt/year in 2017 (McDonald 1989; Angus and Grace 2017; ABARES 2019), with average N fertiliser application to wheat increasing from 30 kg N/ha in 2000 to 45 kg N/ha in 2017 (Angus 2001; Angus and Grace 2017). Potassium (K) use has doubled over the past three decades to ~0.22 Mt/year, whereas phosphorus (P) usage has remained relatively stable at ~0.43 Mt/year over the same period (ABARES 2019; Angus *et al*. 2020). The increased usage of fertiliser in Australia is in line with global trends between 2002 and 2017; global fertiliser N use increased from 83 to 109 Mt, fertiliser P from 35 to 46 Mt and fertiliser K from 23 to 38 Mt annually (FAO 2020).

Historically, legume based pastures, in conjunction with targeted fertiliser inputs, have been employed to improve soil fertility across southern Australia (Donald and Williams 1954;

Helyar *et al*. 1997; Kirkegaard *et al*. 2011; Angus and Grace 2017). Indeed, within south-west Western Australia (WA) alone, it is estimated that >8 Mha of infertile land has been converted to arable cropping land through these practices (Gartrell and Glencross 1968), with the total area cropped per year increasing from 1.4 to 8.5 Mha between 1950 and 2017 (ABARES 2018). Consequently, south-west WA has become a major contributor to national grain production, producing ~34% of Australia's broadacre grain tonnage over the period of the present study (2010–15) (ABS 2016).

Despite the well documented benefits of legume based pastures, there has been a long-term decline in N derived from rainfed pastures across southern Australia, due to a decline in area of pastures grown and in legume content of pastures, since the early 1990s (Angus and Peoples 2012). Within south-west WA, the proportion of farm area dedicated to pasture declined by up to 30% in some agroecological zones between 2000 and 2015 (Planfarm and Bankwest 2016) and sheep numbers decreased from 26 to 14 million between 2005 and 2015 (ABS 2016). The increased area sown to crop has been accompanied by a move towards cereal and oilseed crops across most agroecological zones of south-west WA (Harries *et al*. 2015; Planfarm and Bankwest 2016), with grain legume production declining by 0.7 Mha from 2000 to 2015 (ABS 2016).

Reasons for this shift in land use include changes in commodity prices and production constraints, and the adoption of technical advances in crop production (Kirkegaard *et al*. 2011). Nevertheless, despite these technical advances, the reduction in rotation diversity may be diminishing benefits from rotations, including breaks in disease cycles, opportunities to use a wider range of herbicides and integrated weed management tools (Bullock 1992; Kirkegaard *et al*. 2008; Davis *et al*. 2012; Seymour *et al*. 2012), and improved soil fertility through increased soil N and organic carbon (OC) via legumes (Ellington *et al*. 1979; Drinkwater *et al*. 1998; Blair and Crocker 2000; Chan *et al*. 2011; Hoyle *et al*. 2011; Congreves *et al*. 2015; Kumar *et al*. 2018).

The average cost of fertiliser inputs to annual cropping systems in Australia (and WA) during 2017 was ~AU$95 per cropped hectare (ABARES 2018; Planfarm and Bankwest 2018). Fertiliser constituted the largest operating expense on farms in south-west WA at this time, at 19.3% of operating costs, with the next largest expense being weed and pest control, at 15.3% of operating costs (Planfarm and Bankwest 2018).

The increased use of fertiliser and intensification of cropping globally has led to concerns about the sustainability of soil fertility in current cropping systems. In particular, that optimisation of economic returns on an annual basis may lead to negative nutrient balances and a decline in soil fertility in the longer term (Craswell *et al*. 2004; Alexandratos and Bruinsma 2012). However, assessments of nutrient budgets under current cropping systems in southern Australia are constrained by a scarcity of data on which to compare fertiliser inputs to nutrient exports over time, with data restricted to a few long-term experiments (Norton *et al*. 2007). Additionally, time series datasets linking nutrient inputs, outputs and changes in soil nutrient levels at the commercial field scale are even rarer (Lacoste 2017).

The recent changes in land use within south-west WA and increasing reliance on inorganic fertilisers raises concerns about sustaining the fertility that has been achieved since land was cleared for agriculture. Our research objective was to identify relationships between land use, fertiliser inputs and soil nutrient dynamics to assess whether soil fertility is being maintained. We did this by tracking changes in soil nutrients over time and relating this to farmer practices in a series of selected fields. Here, we document the proportion of fields with adequate levels of macronutrients, estimate partial nutrient budgets for N, P, K and sulfur (S), and estimate the ratio of legume-fixed N to fertiliser N in commercial fields across three agroecological zones of south-west WA.

Materials and methods

Data sources

Data were obtained from the 'Focus Paddocks' database (Harries *et al*. 2015), which pairs records of biophysical measurements of weeds, soilborne diseases, and soil chemical and physical properties to land management actions from the same fields over the period 2010–15. The database comprised 184 fields across south-west WA (Fig. 1), providing 1017 field-years in total, accounting for missing data. Field measurements were from a geo-referenced area of 1 ha within each field. Farmers who managed the fields used for the database were interviewed annually, providing information on land use, agronomic inputs and insights into management rationale. Wheat (*Triticum aestivum*) was grown in all fields in the first year of monitoring, followed by farmer-specified land uses in the following years. Climate data were obtained for each field by using the SILO (Scientific Information for Land Owners) database (Jeffrey *et al*. 2001). Mean daily air temperature was calculated for each field-year as (maximum daily temperature + minimum daily temperature)/2. Soil classification data appear in Harries *et al*. (2015).

Soil chemistry

The area (1 ha) was divided into four replicates of 25 m by 100 m and sampling was conducted in a zig-zag transect through each. Soil cores were taken before seeding each year: 44 samples from depth 0–10 cm, 1 cm in diameter; and four cores from 0–90 cm, or as close to 90 cm as possible, using a 4.4 cm diameter, pneumatic percussion soil sampling machine (Christie Engineering, Sydney). Cores were divided into five depths (0–10, 10–20, 20–30, 30–50 and 50–90 cm), and samples within each depth were combined for analysis. In total, 990 field-years were sampled at 0–10 cm, reducing to 627 at the deepest sample layer of 50–90 cm. Soil chemical properties were measured according to Rayment and Lyons (2011); these included nitrate (method 7c2B); ammonium (7c2B); P (9b); K (18A1); S (10D1); trace elements: copper, zinc, manganese and iron (12A1), boron (12C2); pH (4B41); electrical conductivity (3A1); and soil OC (%) (6A1 Walkley–Black).

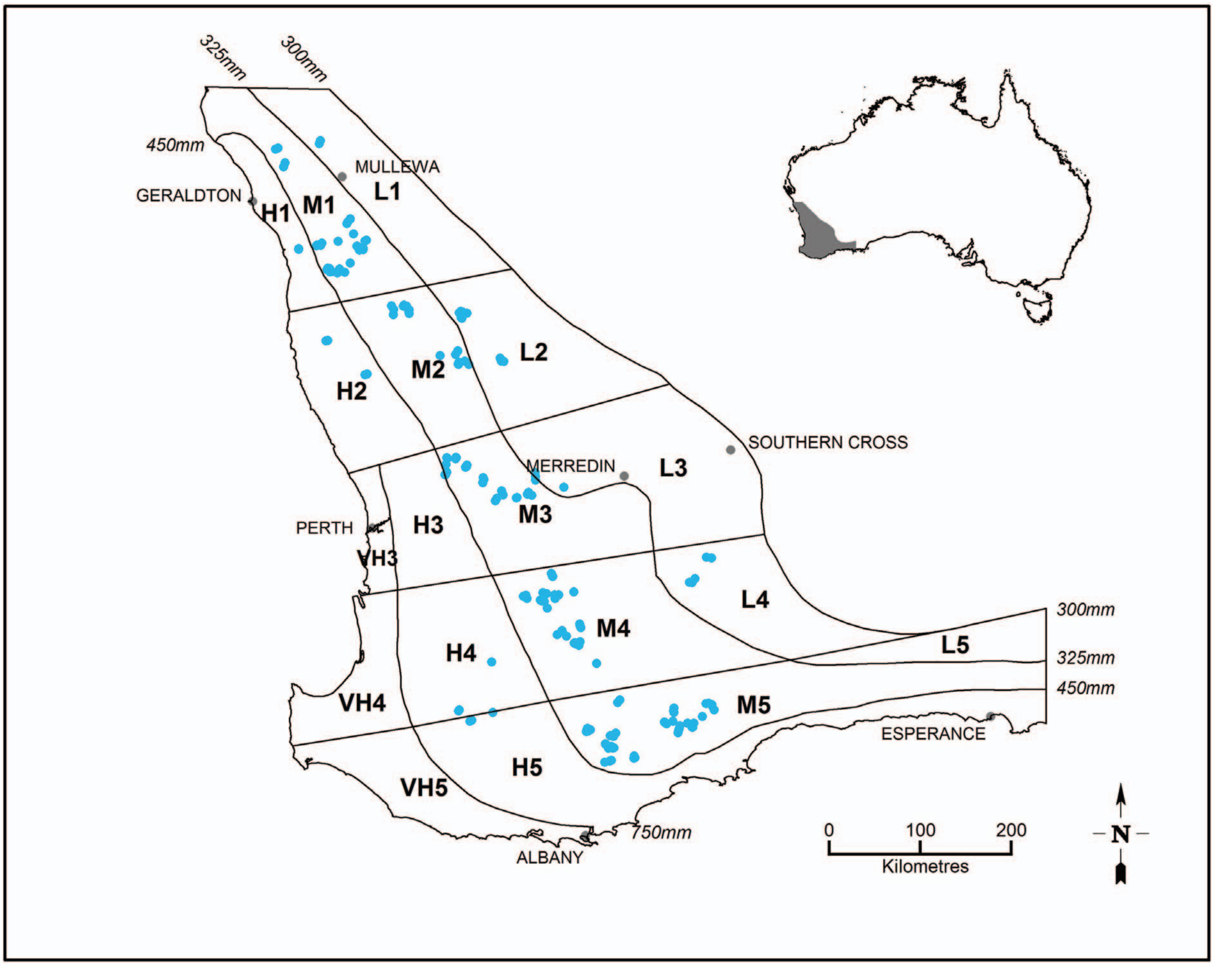

Fig. 1. Locations of 184 survey paddocks (blue dots) from 2010 to 2015 in the south-west of WA. Boundaries depict Western Australian Department of Primary Industries and Regional Development (DPIRD) agroecological zones according to rainfall. Letters refer to rainfall zones: VH, very high; H, high; M, medium; L, low. Numbers refer to regions Northern (1 and 2), Central (3 and 4) and Southern (5) Agricultural Regions.

Table 1. Critical concentrations (mg/kg) of NO_3^-, NH_4^+, P, K, S, B, Cu and Zn in the 0–10 cm soil layer

For N, critical values are difficult to define (Bell *et al*. 2013*a*); as such NO_3^- and NH_4^+ were categorised as low, medium or high. For S: C (canola), P (pasture), O (all other crops)

NO_3^- Low	NO_3^- Med.	NO_3^- High	NH_4^+ Low	NH_4^+ Med.	NH_4^+ High	P	K	S Canola	S Pasture	S Other	B	Cu	Zn
<10	10–30	>30	<2	2–6	>6	25	50	7.7	6.5	7.0	0.2	0.2	0.2

Critical values used to indicate deficiency within the 0–10 cm soil layer (Table 1) are taken from Bell *et al.* (2013*a*, 2013*b*, 2013*c*), Brennan and Bell (2013) and Anderson *et al*. (2013).

Fertiliser use

Data on fertiliser inputs were collated from 644 field-years spanning 2010–14; the field-years comprised barley 49, canola 96, lupin 40, pasture 57, other crop or fallow 17, and wheat 385. For each field-year, the amount of each nutrient applied was calculated from the rate of each product applied and its composition. Patterns of fertiliser use were assessed by categorising data according to land use and amount of fertiliser applied.

Estimated partial balances of N, P, K and S

Grain or seed yield was measured for 635 field-years by recording the crop row spacing and taking hand cuts of crop row (1.0 m) in each of the four replicates. Legume N fixed from the atmosphere (Nfix) was estimated from shoot biomass sampled in spring, from each of the four replicates from 55 grain legume crops (1.0 m row × row spacing) and 75 pastures (0.3 m^2). The dry weight of each species within pastures were recorded, with total legume biomass calculated and classified as subterranean clover (*Trifolium subterraneum*), medic (*Medicago* spp.) or other legumes. Species-specific empirical relationships between legume shoot biomass and fixed N that were previously developed for Australian-grown legumes, and the root multiplication factors to adjust shoot-based N data to a whole-plant basis, were applied to the observed measures of legume biomass to estimate Nfix: chickpea (*Cicer arietinum*), $y = (-1.05 + 10.7x) \times 2.06$ (root factor); faba bean (*Vicia faba*), $y = (-1.38 + 21.3x) \times 1.52$; field pea (*Pisum sativum*), $y = (-1.38 + 21.3x) \times 1.47$; lupin, $y = (4.03 + 14.2x) \times 1.50$; pasture legumes, $y = (-0.19 + 24.3x) \times 1.49$; vetch (*Vicia* spp.), $y = (-1.38 + 21.3x) \times 1.47$ (McNeill and Fillery 2008; Unkovich *et al*. 2010). In the equations, y is Nfix (kg/ha) and x is shoot dry weight (t/ha). Annual and rotational partial N balances were calculated for each field as the sum of N applied as fertiliser and Nfix, minus export in grain. Annual and rotational partial balances of P, K and S were calculated as the total amount applied as fertiliser minus export in grain. Nutrient concentrations in the grain, used to calculate partial nutrient budgets (Unkovich *et al*. 1994; Reuter and Robinson 1997; Mayfield 2008; Norton 2009; Bolland 2011), are shown in Table 2. Nfix and fertiliser N applied were multiplied by the area sown to each land use within the survey to estimate the total Nfix and N fertiliser applied across all field-years. Nfix remaining after the removal of N in legume grain was termed residual Nfix (RNfix); N in mineral form (Nmin) derived from legumes and supplied to subsequent years was assumed at 30% of RNfix in the first year after a legume, 10% in the second year and 5% in the third year, based on previous studies conducted in southern Australia (Bowden and Burgess 1993; Evans *et al*. 2001; McNeill and Fillery 2008; Angus and Peoples 2012; Peoples *et al*. 2017). For pasture, no grazing records were kept; therefore, it was assumed that no export occurred, Nfix = RNfix. Imputation of missing survey data, where required to complete field sequences and enable sequence balance estimates, was on the basis of regional land use means of the Focus Paddock dataset.

Table 2. Approximate nutrient removal in grain (kg/t) used to calculate partial nutrient budgets

From: Unkovich *et al*. 1994; Reuter and Robinson 1997; Mayfield 2008; Norton 2009; Bolland 2011

Land use	N	P	K	S
Wheat	23	3.0	4.0	1.4
Barley	20	2.9	4.4	1.1
Oats	16	3.0	4.0	1.5
Canola	40	6.5	9.2	9.8
Lupins	51	3.8	8.8	3.1
Chickpeas	34	3.8	8.9	1.8
Faba beans	39	3.8	9.8	1.4
Field peas	37	4.0	8.2	2.0

Statistical analyses

Analyses were conducted using R statistical software version 3.6.0. (The R Foundation, Vienna). Shapiro–Wilk tests and QQ plots were applied to test normality, with log-transformations applied to N, P, K and S concentration in soil before analysis of variance (ANOVA). If means were significantly different ($P \leq 0.05$), further analysis was conducted to differentiate between groups, using appropriate tests such as unpaired *t*-tests and their pairwise comparisons or Tukey HSD tests. Regression tree analysis was conducted, using the 'r.part' package of R statistical software (ANOVA method) (Therneau and Atkinson 2019), to identify which variables had greatest influence on soil N levels in the following autumn. Chi-square tests were applied, first to assess the effect of the length of sequence without a legume on N concentration at 0–10 cm, for which soil N was grouped into two levels based on the third quartile (37 mg/kg); and second to assess the effects of annual rainfall and temperature on soil OC percentage, for which rainfall and temperature were grouped into two levels based on the first quartile (273 mm and 16.7°C) and OC was grouped into two levels based on the third quartile (1.68%). A linear model was applied to describe the relationship between lupin shoot dry matter and lupin yield. All data are presented back-transformed.

Results

Land use

Regionally, more fields were sown to wheat and lupin in the Northern Agricultural Region (NAR), whereas more fields were used for pasture and barley in the Southern Agricultural Region (SAR). Canola accounted for ~12% of field-years in each region (Fig. 2), and pastures and grain legumes combined accounted for 21% of field-years. Although wheat was the dominant land use, it was not frequently used in long sequences; however, wheat, barley and canola were often used in combination in long sequences, such that 19% of fields had 6 years without a legume (i.e. no legume for the duration

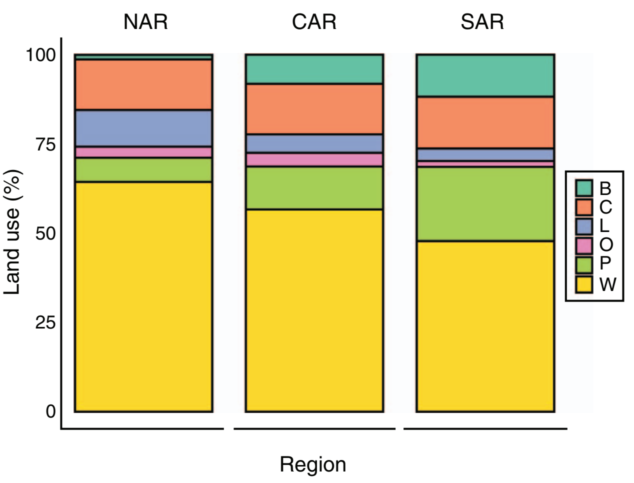

Fig. 2. Proportion of each land use category within the Focus Paddock database grouped by DPIRD Region: B, barley; C, canola; L, lupin; O, other; P, pasture; W, wheat.

of the survey), 35% 5 years, 22% 4 years, 14% 3 years, 9% 2 years, and 1% of fields with only 1 year without a legume over the duration of the study. These results are similar to industry level data (ABS 2016; Planfarm and Bankwest 2016); for more detail on land use see Harries *et al*. (2020).

Climatic conditions

Western Australia has a Mediterranean-type climate, with the growing season occurring between May and November. There were large differences in rainfall between years and regions, with annual rainfall ranging from 246 to 480 mm (Table 3). Analysis of mean daily air temperature, of each field over the years 2010–15, showed that temperature increased with latitude (Fig. 3).

Soil analyses

Concentrations of elements in soil

For all nutrients except N, the majority of samples were above the critical values within the 0–10 cm soil layer (Table 4). All nutrient concentrations, OC and pH in the 0–10 cm layer of soil preceding sowing for each land use and region are shown in Supplementary Material Table S1 (available at the journal's website).

Annual variation in soil mineral N concentration

Mineral N concentration in the 0–10 cm layer varied among years (P = 0.001); for 2010 to 2015, respectively, values were (mg/kg) 21 (±1.0), 38 (±1.7), 34 (±1.7), 36 (±1.6), 18 (±1.0) and 27 (±1.4). There were corresponding differences in summer (out of growing season) rain: 60 mm

Table 3. Annual rainfall (mm) in the Northern Agricultural Region (NAR), Central Agricultural Region (CAR) and Southern Agricultural Region (SAR) regions during 2010–15

	NAR	CAR	SAR	Mean
2010	252	196	301	246
2011	468	440	546	480
2012	313	281	321	304
2013	320	383	411	366
2014	301	358	419	353
2015	350	296	367	335
Mean	326	334	394	351

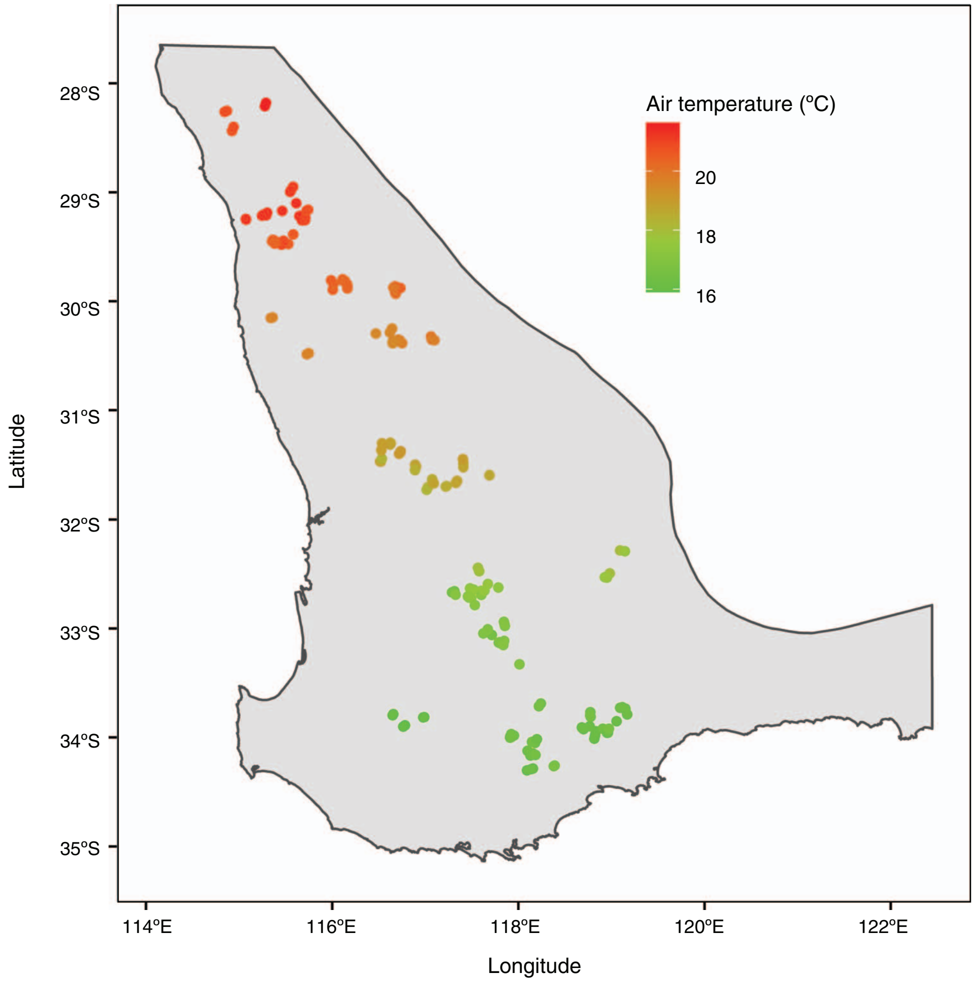

Fig. 3. Mean daily air temperature °C (max. + min./2), for each paddock of the Focus Paddock dataset, 2010–15.

(±1.8) in 2009–10, 98 mm (±3.1) in 2010–11, 86 mm (±3.1) in 2011–12, 109 mm (±2.0) in 2012–13, 51 mm (±1.4) in 2013–14, and 101 mm (±2.8) in 2014–15. Regression tree analysis indicated that summer rainfall and soil OC affected topsoil N concentrations in the following autumn to a greater degree than previous land use or management (Fig. 4). Summer rain >59 mm increased N concentration by 14 mg N/kg, and OC >1.5% resulted in an additional 8 mg N/kg. Land use was a low order variate and did not differentiate legumes; however, it should be noted that this analysis only captured mineralisation over the summer period.

Variation in soil N concentration by land use sequence

A longer term analysis than the annual values presented above showed that long sequences without a legume (grain legume or pasture) resulted in lower ($P < 0.001$) soil mineral N at 0–10 cm. Overall, soil mineral N at 0–10 cm was 39 (±2) mg/kg after a legume, 46 (±2) after one non-legume year, and 38 (±2), 42 (±2), 24 (±2) and 28 (±3) after two–five successive non-legume years respectively. Chi-square analysis indicated that the soil mineral N concentration at 0–10 cm was 8 times more likely to be ≤37 mg/kg after four successive non-legumes ($P < 0.001$), and none of the fields without a legume had mineral N concentration ≥37 mg/kg at the end of the survey.

Organic C

Soil OC concentration was influenced by rainfall. Chi-square analysis showed that fields with annual rainfall <278 mm were three times more likely to have OC <1.68%

Table 4. Percentage of 0–10 cm soil tests above critical concentrations for deficiency (high), and within low, medium and high categories for NO_3^- and NH_4^+

See Table 1 for the critical concentrations. For N, critical values are difficult to define (Bell *et al*. 2013*a*); as such NO_3^- and NH_4^+ were categorised as low, medium or high. For S: C (canola), P (pasture), O (all other crops)

	NO_3^-			NH_4^+		P	K		S		B	Cu	Zn
Low	Med.	High	Low	Med.	High			Canola	Pasture	Other			
18	58	24	5	58	37	74	99	81	86	89	96	98	99

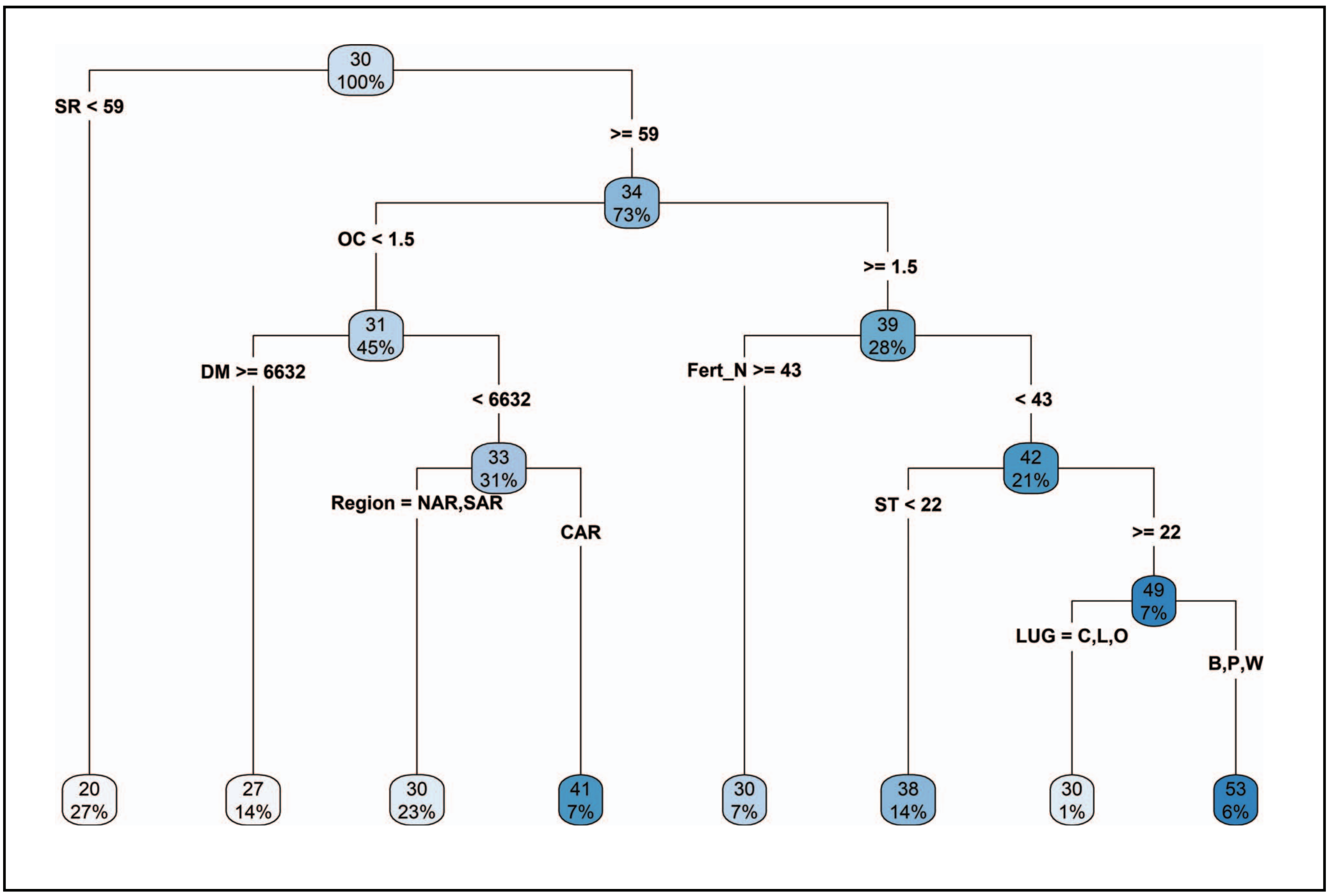

Fig. 4. Classification and regression tree analysis (CART) including summer rainfall (SR), summer temperature (ST), organic carbon percentage 0–10 cm (OC), dry matter (DM), applied fertiliser N (Fert_N), region (Northern, Central and Southern Agricultural Regions) and land use group (LUG: B, barley; C, canola; L, lupin; O, other; P, pasture; W, wheat) as variates for predicting N concentration at 0–10 cm in the following autumn.

($P < 0.001$) (Fig. 5*a*). There was a statistically significant, negative linear relationship between temperature and OC, higher temperature resulting in lower OC ($P < 0.001$, R^2 = 0.39); chi-square analysis showed that fields with daily mean air temperature >16.7°C were 13 times more likely to have OC <1.68% ($P < 0.001$) (Fig. 5*b*). OC was also influenced by soil texture (P = 0.011), with coarse-textured soils having lower OC (sands 1.26 ± 0.10%) than fine-textured soils (loamy clays 1.65 ± 0.13%). This resulted in regional differences in OC at 0–10 cm: NAR 0.94 ± 0.2%, Central Agricultural Region (CAR) 1.36 ±0.3% and SAR 2.34 ±0.7%. OC also had a large influence on soil N (Fig. 4). We assessed net change in OC (final year – starting year) for each field, within each soil layer sampled. There was no consistent trend of OC change over successive years of the survey period. Net change in OC in the 0–10 cm soil layer was +0.02%, with a mean of +0.08% using all soil layers to 90 cm. The number of legumes grown in a field did not have a significant effect on change in OC in any soil layer. For each region there was a positive change in OC from the first to the last year of monitoring, and there were small but significant ($P < 0.001$) differences between regions. Mean change of all soil layers was greater ($P < 0.001$) in NAR (0.12 ± 0.01%) and SAR (0.09 ± 0.01%) than in CAR (0.01 ± 0.02%), which was due to differences within the 10–20, 20–30 and 30–50 cm soil layers.

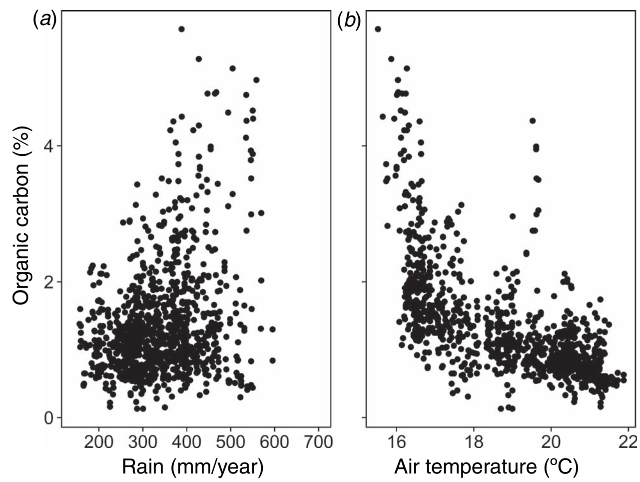

Fig. 5. Organic carbon in the 0–10 cm soil layer as affected by annual rainfall and mean daily air temperature for each paddock-year.

Fertiliser

Overall there were 1.8 fertiliser applications per field-year, with fewer applications to lupin than to other crops and fewer applications to pasture than to all other land uses (Table 5). Nitrogen applications were made in 91% of field-years compared with P, K and S applications in 92%, 37% and 93% of field-years; cumulative frequency of amounts of N, P, K and S applied as fertiliser per field-year are presented in Fig. 6. The amount of N, P, K or S applied did not differ among regions, but differed among land uses (Table 5). For N, the mean amount applied was 33.2 kg/ha.year, or 36.7 kg/ha.year for field-years receiving N, with more ($P < 0.001$) N applied to canola than all other land uses and less ($P < 0.001$) to pasture than all other land uses except lupin. When all grain legume and pasture years were excluded, mean N application rate was 39.1 kg/ha.year, with only one field-year not receiving fertiliser N. For P, the mean amount applied was 9.9 kg/ha. year, or 10.7 kg/ha.year for field-years receiving P. Less ($P < 0.001$) P was applied to pasture than all other land uses and less ($P < 0.035$) to lupin than canola. For K, the mean amount applied was 4.3 kg/ha.year, or 11.7 kg/ha.year for field-years receiving K. Less K was applied to pasture than crops and more to lupin than barley (P = 0.041), canola ($P < 0.001$) or wheat ($P < 0.001$). For S, the mean amount applied was 6.5 kg/ha.year, or 6.9 kg/ha.year for field-years receiving S, with less ($P < 0.001$) applied to pasture than crops and more to canola than all other land uses.

A greater amount of N was applied as the number of consecutive years without a legume increased ($P < 0.001$) and for sequences with no legumes in later years of the study

Table 5. Fertiliser inputs per paddock-year of macronutrients for each land use and within the Northern Agricultural Region (NAR), Central Agricultural Region (CAR) and Southern Agricultural Region (SAR) and ratios of fertiliser applied to grain harvested
Standard error of the mean in parentheses; mean number of applications per year in brackets

	Fertiliser inputs (kg/ha)				Fertiliser:grain (kg/t)			
	N	P	K	S	N	P	K	S
Land use								
Barley	37.2 (2.5) [2.8]	10.4 (0.5) [1.1]	5.8 (0.9) [0.6]	6.3 (0.6) [1.3]	12.2	3.4	1.9	2.1
Canola	47.7 (2.3) [2.8]	11.6 (0.5) [1.4]	4.2 (0.6) [0.4]	12.3 (1.0) [1.7]	30.6	7.4	2.7	7.9
Lupin	5.6 (1.4) [0.7]	10.0 (0.8) [1.0]	8.9 (2.1) [0.5]	6.6 (1.0) [1.1]	2.6	4.6	4.1	3.0
Other	19.7 (4.5) [1.4]	11.4 (0.8) [1.1]	2.0 (0.9) [0.3]	4.9 (0.9) [1.1]				
Pasture	1.3 (0.5) [0.2]	1.1 (0.4) [0.4]	0.3 (0.2) [0.1]	0.9 (0.3) [0.3]				
Wheat	37.2 (0.9) [2.4]	10.7 (0.2) [1.1]	4.4 (0.4) [0.4]	5.9 (0.2) [1.3]	14.9	4.3	1.8	2.4
F-prob.	<0.001	<0.001	<0.001	<0.001				
Region								
NAR	34.9 (1.5) [2.1]	10.4 (0.3) [1.2]	4.6 (0.6) [0.3]	6.7 (0.4) [1.3]	18.8	5.6	2.5	3.6
CAR	30.7 (1.3) [2.0]	9.5 (0.3) [1.0]	4.1 (0.4) [0.4]	6.8 (0.4) [1.2]	12.8	4.0	1.7	2.8
SAR	33.8 (1.7) [2.6]	9.9 (0.4) [1.2]	4.3 (0.5) [0.5]	5.8 (0.5) [1.3]	10.2	3.0	1.3	1.7
F-prob.	0.114	0.138	0.807	0.219				
Grand mean	33.2	9.9	4.3	6.5				

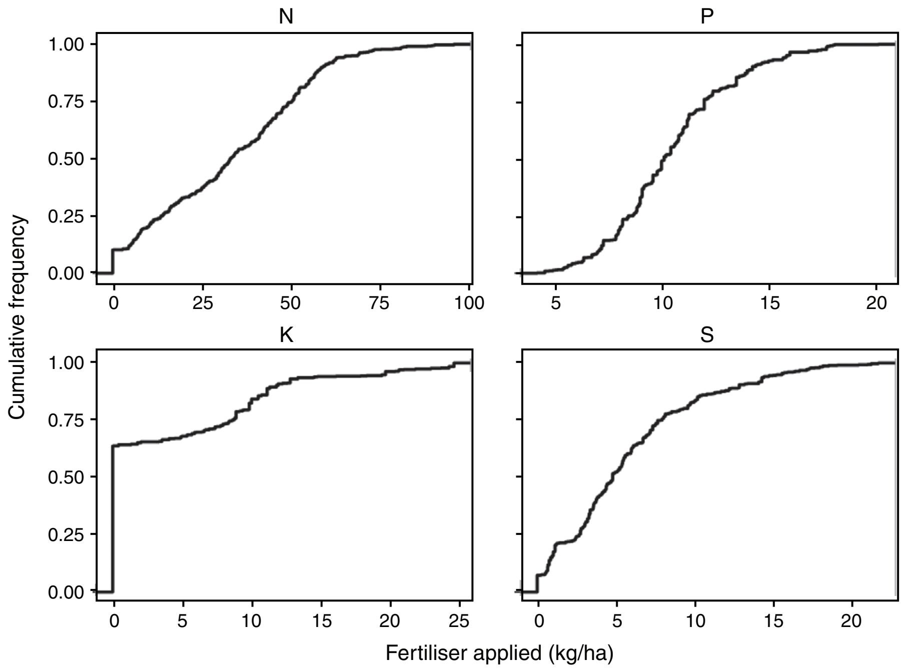

Fig. 6. Cumulative frequency showing amount of N, P, K and S fertiliser applied per paddock-year.

($P < 0.001$), more so in SAR than other regions ($P = 0.027$) (Table 6). Crop grain/seed yield (data not presented) per unit N fertiliser applied decreased ($P < 0.001$) as consecutive years without a legume increased (grain yield/ha.kg N fertiliser): 293 ± 45 kg in the legume year, 93 ± 6 kg in the first year after the legume, 100 ± 14 kg in the second year, 71 ± 8 kg in the third year, 82 ± 11 kg in the fourth year, and 57 ± 9 kg in the fifth year without a legume.

Seasonal starting conditions also had an influence on the mean amount of fertiliser N applied to wheat at sowing, although the adjustments were small. Less N was applied at sowing in 2010, which was a dry year (Table 3) with a late start (25 May) compared with all other years (N applied/ha): 19.6 ±1.6 kg in 2010, 22.5 ± 1.2 kg in 2011, 24.7 ±1.5 kg in 2012, 23.2 ±1.4 kg in 2013, and 22.9 ±1.3 kg in 2014. This adjustment was greater in NAR and CAR than SAR (Fig. S2).

Table 6. Nitrogen fertiliser inputs (kg/ha.year) for years since a legume was grown

Standard error of the mean in parentheses. L, Legume year; N1–N5, first to fifth year without a legume; NAR, Northern Agricultural Region; CAR, Central Agricultural Region; SAR Southern Agricultural Region

	L	N1	N2	N3	N4	N5
Year						
2010		29 (2)				
2011	3 (1)	34 (1)	39 (2)			
2012	2 (1)	37 (3)	41 (3)	39 (2)		
2013	6 (2)	26 (4)	45 (7)	43 (4)	43 (3)	
2014	3 (1)	35 (4)	45 (4)	56 (4)	50 (4)	52 (3)
Region						
NAR	3 (1)	32 (2)	40 (3)	44 (3)	48 (4)	51 (4)
CAR	6 (2)	29 (2)	36 (3)	37 (3)	37 (4)	48 (4)
SAR	2 (1)	35 (1)	48 (4)	46 (3)	50 (3)	69 (9)
Mean	3 (1)	32 (1)	41 (2)	42 (2)	45 (2)	52 (3)

Nutrient balances

Annual partial nutrient balances of each element differed ($P < 0.001$) by land use and region (Table 7). Nitrogen budgets were negative for all non-legume years, except for the fourth year of wheat, with a mean of 0.7 kg N/ha.year. The annual N balance moved closer to neutral as the number of wheat crops in succession increased (Table 7). This occurred because the amount of fertiliser N applied increased while yield declined; that is, for the first wheat year, mean yield was 2.4 t/ha with N fertiliser applied at 35 kg/ha, compared with 1.9 t/ha and N fertiliser applied at 44 kg/ha for the fourth wheat crop in succession. The same trend of increased fertiliser inputs relative to grain exports with successive wheat crops was also observed for P, K and S.

Annual P balance was positive for all land uses (mean 2.4 kg P/ha.year), K was negative for all land uses except pasture (mean –6.1 kg K/ha.year), and S was positive for all land uses except canola (mean 1.3 kg S/ha.year) (Table 7).

Sequence partial N balances, calculated for each field-year from the first year of monitoring, 2010 or 2011 to 2014, differed ($P < 0.001$) among regions. NAR had a positive N balance of 14 ± 7 kg N/ha compared with negative balances for CAR (–35 ± 13 kg N/ha) and SAR (–64 ± 17 kg N/ha). This occurred because NAR had considerably lower nutrient export with mean yield of all grains being 1860 kg/ha compared with 2404 kg/ha for CAR and 3320 kg/ha for SAR, and similar N fertiliser applied (Table 5). A comparison of yield to N fertiliser input shows grain produced/kg N applied differed between regions: 53 kg in NAR, 78 kg in CAR, and 99 kg in SAR. Overall, 74 fields had a positive partial N balance and 110 a negative partial N balance

(Fig. 7), resulting in a mean net deficit of 24 kg N/ha or 2518 t N across the 104 910 ha of the study. Fields with more legume years in the rotation had a higher ($P < 0.001$) N balance: no legume years –72 ± 10 kg N/ha, one legume year –31 ± 10 kg N/ha, two legume years 39 ± 16 kg N/ha, and three legume years 107 ± 25 kg N/ha. The mean N balance in all regions was positive when two legumes were grown: NAR 28 ± 20 kg N/ha, CAR 74 ± 20, SAR 5 ± 27 kg/ha. When there was one legume year, differences were larger among regions: NAR 9 ± 20 kg N/ha, CAR –52 ± 16 kg N/ha, SAR –83 ± 27 kg N/ha. This occurred because, for 49% of NAR barley, canola and wheat crops, the N exports in grain were met by fertiliser inputs, compared with 23% for CAR and 11% for SAR. Overall, the sequence balances of P and S were close to neutral, although ranges were large, whereas there was a mean depletion of 28 kg K/ha in each field over the duration of the study, with the majority of fields recording a deficit (Fig. 7).

Table 7. Nitrogen, P, K and S mean paddock-year balances for each land use, including successive wheat years, for the Northern Agricultural Region (NAR), Central Agricultural Region (CAR) and Southern Agricultural Region (SAR)

W2–W4, Second to fourth successive wheat

	N	P	K	S
	(kg/ha)			
Land use				
Barley	–24.0 (3.9)	1.5 (0.6)	–7.8 (1.1)	3.0 (0.6)
Canola	–15.0 (3.6)	1.5 (0.7)	–10.1 (0.9)	–3.1 (1.1)
Lupin	47.2 (4.7)	2.0 (0.7)	–9.9 (1.8)	0.1 (0.8)
Other	55.4 (15.5)	3.0 (1.0)	–10.6 (1.4)	1.7 (0.7)
Pasture	47.7 (5.3)	1.1 (0.2)	0.4 (0.1)	1.0 (0.2)
Wheat	–19.7 (1.4)	3.2 (0.2)	–5.5 (0.4)	2.5 (0.2)
W2	–23.9 (2.6)	1.9 (0.5)	–8.0 (0.6)	1.9 (0.5)
W3	–8.3 (3.3)	4.4 (0.5)	–6.7 (0.6)	3.5 (0.8)
W4	0.7 (6.1)	7.8 (3.5)	–4.6 (2.8)	3.2 (2.3)
Region				
NAR	2.8 (1.5)	4.6 (0.3)	–3.8 (0.4)	2.8 (0.2)
CAR	–7.0 (2.8)	1.7 (0.3)	–6.6 (0.5)	1.3 (0.3)
SAR	–15.5 (4.1)	0.4 (0.3)	–8.6 (0.7)	–0.6 (0.6)
Mean	–5.7 (1.7)	2.4 (0.2)	–6.1 (0.4)	1.3 (0.3)

Comparison of legume and fertiliser N inputs

Mean pasture legume shoot dry matter (DM) was 1.2 t/ha, fixing an estimated 46 kg/ha of atmospheric N_2, which was calculated to provide 21 kg mineral N/ha (RNmin) (Table 8). Shoot DM of pasture legume was low in NAR, such that pastures in this region provided little N (Table 8). Overall, mean shoot DM of lupin was 6.9 t/ha, fixing an estimated 152 kg/ha.year of atmospheric N_2, which was calculated to provide 19 kg mineral N/ha after grain was harvested. The relationship between lupin shoot DM and lupin yield derived from the Focus Paddocks database is given in Eqn 1:

$$\mathrm{DM} = 347 + 3.03 \times \text{grain yield}\ (R^2 = 0.76) \qquad (1)$$

Overall mean shoot DM of other grain legumes was 5.9 t/ha, fixing an estimated 167 kg/ha.year of atmospheric N_2, which was calculated to provide 42 kg mineral N/ha after grain was harvested. The discrepancy in RNmin between lupin and other grain legumes was due mainly to the higher protein content of lupin grain (Table 3), and similar harvest indices (yield:DM, from Table 8). Overall, a mean RNmin

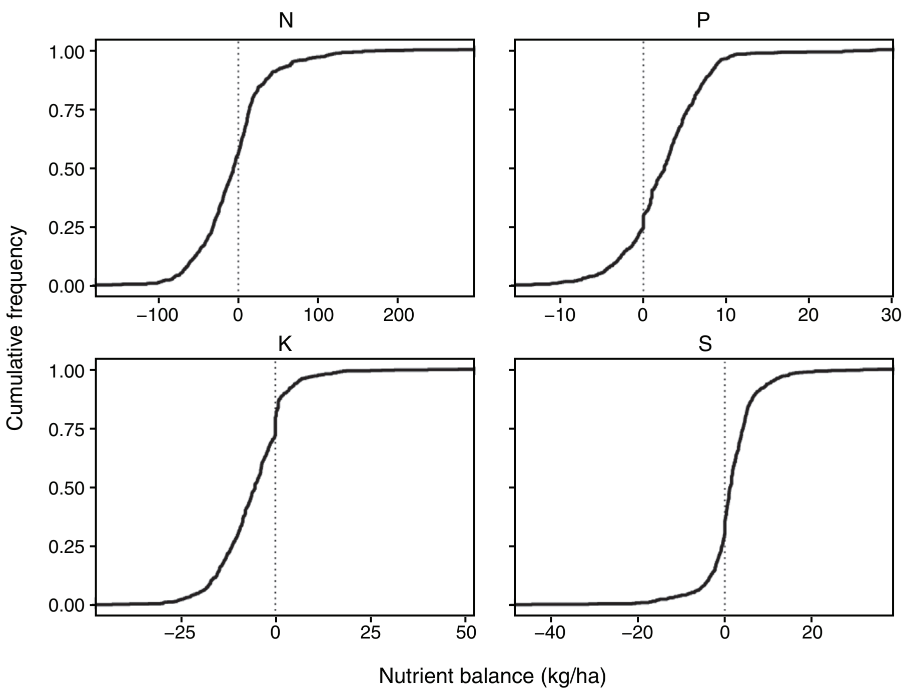

Fig. 7. Cumulative frequency of sequence nutrient balances of N, P, K and S for each paddock, taken from the first year of monitoring (2010 or 2011) to 2014.

Table 8. Modelled inputs of fixed N by legumes and subsequent assumed release of mineral N (McNeill and Fillery 2008; Unkovich *et al.* 2010) within the Northern Agricultural Region (NAR), Central Agricultural Region (CAR) and Southern Agricultural Region (SAR)

LSDM, Legume shoot dry matter; Nfix, N derived from atmosphere (see Methods for description of modelling); Nfert, N fertiliser, amount applied per annum; Nbal, N balance (Nfix + Nfert – N exported in grain); RNfix, residual Nfix after N removal in legume grain; RNmin, RNfix in mineral form in following 3 years, estimated at 45% RNfix (30% year 1, 10% year 2, 5% year 3); Area, total area of each land use in the Focus Paddocks database

	Yield	LSDM	Nfix	Nfert	Nbal	RNfix	RNmin	Area (ha, sum	Tot. Nfix	Tot. RNfix	Tot. RNmin
	(kg/ha.year, 2010–14)				(kg/ha)			2010–15)		(t)	
					Pasture						
NAR		190 (33)	6 (1)	0 (0)	7 (1)	6 (1)	3 (0)	3225	19	19	10
CAR		1727 (214)	65 (8)	2 (0)	67 (8)	65 (8)	29 (3)	2967	193	193	88
SAR		1319 (186)	50 (7)	0 (0)	51 (7)	50 (7)	22 (3)	4554	228	228	103
Mean		1202 (0.1)	46 (5)	1 (0)	47 (5)	46 (5)	21 (2)				
Total								10 746	440	440	200
					Lupin						
NAR	2029 (116)	6244 (331)	139 (7)	3 (0)	39 (4)	35 (4)	16 (1)	5304	738	189	85
CAR	2396 (151)	8063 (673)	177 (14)	9 (2)	65 (9)	55 (9)	25 (4)	1310	233	73	33
SAR	2369 (207)	7288 (635)	161 (13)	4 (1)	44 (8)	40 (7)	18 (3)	754	122	30	14
Mean	2168 (130)	6847 (0.4)	152 (8)	5 (1)	47 (6)	41 (4)	19 (2)				
Total								7368	1092	292	131
					Other grain legumes						
NAR	1738 (137)	4376 (454)	113 (7)	7 (1)	59 (6)	51 (7)	23 (3)	719	82	37	17
CAR	2169 (144)	6331 (29)	181 (13)	7 (0)	110 (7)	102 (7)	46 (3)	328	59	34	15
SAR	2453 (400)	8751 (1573)	273 (47)	2 (1)	184 (38)	181 (37)	81 (16)	421	115	77	34
Mean	2014 (204)	5872 (0.9)	167 (23)	7 (1)	101 (18)	94 (16)	42 (7)				
Total								1468	257	148	66

Table 9. Mean fertiliser N applied for all paddock-years, and legume N contributions, within the Northern Agricultural Region (NAR), Central Agricultural Region (CAR) and Southern Agricultural Region (SAR)

Fertiliser N applied is the mean for each region from the Focus Paddock database (Table 5). Area is total area of each region and overall from the Focus Paddocks database. Nfix, N derived from atmosphere (see Methods for description of modelling), RNfix, residual Nfix after N removal in legume grain; RNmin, RNfix in mineral form in following 3 years, estimated at 45% RNfix (30% year 1, 10% year 2, 5% year 3)

	Fertiliser applied			Legume N (all legumes) (t)			Ratio		
	N (kg/ha)	Area (ha)	Total (t)	Tot Nfix	Tot RNfix	Tot RNmin	Fert:Nfix	Fert:RNfix	Fert:RNmin
NAR	35	49 272	1722	838	245	110	2.1	7.0	15.6
CAR	31	28 458	875	485	299	135	1.8	2.9	6.5
SAR	34	27 180	919	465	335	151	2.0	2.7	6.1
Total		104 910	3516	1789	879	396	2.0	4.0	8.9

of 20.3 kg N/ha was contributed for the 19 582 ha (19% of total study area) dedicated to legumes, which totalled ~397 t RNmin for the study period (Table 9).

When the total amount of fertiliser N added was compared with that added by legumes across the area of the study, the ratio was 7.0 in NAR (7.0 times more N added by fertiliser than legumes), 2.9 in CAR and 2.7 in SAR (Table 9). Considering that only a proportion of residual fixed N (RNfix) is mineralised and used by subsequent crops or pastures, it was estimated that the ratio of fertiliser N to legume derived N in mineral form was 15.6:1 in NAR, 6.5 in CAR and 6.1 in SAR (Table 9).

Discussion

Sequence nutrient budgets

Nutrient management was not sustainable in all fields, with exports exceeding inputs (negative balances) for N in 60%, P in 20%, K in 90% and S in 32% of fields. This occurred despite annual soil analyses indicating that soil fertility was adequate for the crop or pasture being grown in the majority of instances. Most fields with a negative P and S budget had small losses; overall only 5% of fields returned losses >5 kg P and 7 kg S/ha over the period of 5 or 6 years. The negative K balance in many fields is a concern and is consistent with reports of K deficiency in WA becoming more frequent on course-textured soils as cropping has intensified (Bolland 2011). The finding that 54% of fields ran five or six consecutive non-legume years and 10% of fields had a net decline of >60 kg N/ha is consistent with reports of negative N budgets being common for dryland cereal and oilseed crops within Australia (Baldock 2019), and with estimates of ~45% depletion in total soil N in fields with ~20 years of crop since the use of a traditional legume pasture phase (Angus and Grace 2017). Within traditional ley farming systems, which were common from the 1950s through to the 1990s, short periods of negative N budgets from cropping were offset by legume pastures replacing soil N (Puckridge and French 1983;

Helyar *et al*. 1997; Angus 2001; Kirkegaard *et al*. 2011). We showed that the effect of a legume carried through for 3 years, similar to other studies (Evans *et al*. 2001; McNeill and Fillery 2008; Peoples *et al*. 2017), after which soil N concentration declined. Angus and Peoples (2012) estimated that a neutral soil N balance would be achieved within southern Australian crop–livestock farms with little mineral N input if ~40% of land area was dedicated to legume-dominant pasture. We estimated that two legumes in 5 years (40% legumes), with the addition of fertiliser at the rates observed, maintained a positive partial N budget in all regions of the survey. Furthermore, at ~20% legume inclusion, a positive partial N budget was still observed for NAR, whereas balances were negative within CAR and SAR. It is not surprising that a high proportion of CAR and SAR fields carried a substantial negative N balance at this legume inclusion rate, considering the greater amount of fixed N foregone from the legume year and higher yields of cereals and canola than in NAR. Indeed, for NAR the low N input of pastures, lower crop yield potential and lower soil N banks simplify calculations of N balances, which may explain the higher proportion of positive N balance years within this region.

The low N balance compared with P and S balances observed may impede C sequestration rates from C-rich residues. In similar cropping systems, Kirkby *et al*. (2016) calculated a requirement for ratios of N:P ~3:1 and N:S ~4:1 to attain humification rates that achieved a positive C balance. Overall, our N budget results suggest that N management in many of the fields surveyed was not sustainable, and this is more of an issue within CAR and SAR than NAR.

It is likely that actual N balances over the crop sequences in this survey differ from the partial N balances estimated here. Leaching may lead to N balances with a greater deficit than those reported. For example, simulation modelling showed that the leaching losses of N from a wheat crop following a lupin crop grown near Moora (Region H2 in Fig. 1) ranged from 0 to 116 kg N/ha and that there was a 50% probability of N leaching exceeding 53 kg N/ha over a growing season where summer rainfall had occurred (Asseng *et al*. 1998). Similarly, N was leached from a wheat crop grown after lupin in field studies conducted near Moora at rates of 59 kg N/ha in 1995 and 42 kg N/ha in 1996 (Anderson *et al*. 1998*b*). To date, no studies have measured loss pathways of fertiliser N in WA cropping soils, which is a significant knowledge gap due to the increasing dependence on fertiliser N for grain production in WA. Therefore, the high frequency of negative partial N balances that we report provides impetus for research into quantifying these losses of N in order to gain a better understanding of the longer term implications of current N management on soil N supply.

Annual nutrient budgets

Inspection of annual nutrient budgets showed that the mean amount of fertiliser P and S applied to each land use was more than what was extracted, except for S on canola crops, although some field-years were negative, which accounts for the small percentage of fields with negative P and S sequence balances. The increasing positive balance of P in long wheat sequences is a result of additional P applied as compound fertiliser with N and will contribute to the build-up of soil P that has occurred in WA soils (Weaver and Wong 2011). There was a negative K balance in all crops and sequences of wheat, consistent with the large proportion of fields with negative K sequence budgets.

The mean annual Nfix of pasture predicted (46 kg N/ha) is below or at the lower end of previously reported ranges: 50–125 kg N/ha for sites of 300–600 mm annual rainfall in south-west WA (Bolger *et al*. 1995), 29–162 kg N/ha in south-west WA (Anderson *et al*. 1998*a*), and 2–284 (Peoples and Baldock 2001) and 22–87 kg N/ha (Angus and Peoples 2012) across southern Australian mixed farming systems. This is due to the low mean legume biomass observed in our study. However, pasture legume biomass ranged widely from 2 to 7252 kg/ha such that the range of Nfix was 0–276 kg N/ha. The large variability in legume DM, and consequently Nfix, from self-regenerating pastures is to be expected as pasture years become less frequent and seed reserves of pastures are depleted by weed control actions undertaken throughout long cropping phases (Gill 1996; Heap 2000; Walsh and Powles 2007; Walsh and Powles 2014; Harries *et al*. 2020). These findings reinforce reports of declining productivity of pastures on Australian dryland farms since the early 1990s (Heap 2000; Angus and Peoples 2012). Furthermore, we found substantial differences in the N contribution of pastures among regions; in NAR, 8.5% of N input from legumes was derived from pastures compared with 62% in CAR and 68% in SAR.

Lower pasture productivity is expected within NAR than regions further south because of lower rainfall, higher temperatures and shorter growing seasons; additionally, key constraints to pasture productivity including herbicide-resistant weeds, long cropping sequences and soil acidification (Loi *et al*. 2005) have become widespread within the NAR (Owen *et al*. 2007, 2014; Walsh *et al*. 2007; Harries *et al*. 2015). In the present study, pasture legume shoot DM included aboveground DM in spring and did not include an estimate of grazed biomass because stock movements were not recorded accurately enough to facilitate this. This is likely to be of little consequence in NAR, where plant densities measured in autumn and spring were low, and only 6.6% of plants observed in pasture fields were legumes (Harries *et al*. 2020). Hence, the large regional differences in N contribution from pastures that we estimated are likely a consequence of differing agronomic practices and inherent productivity, as discussed above, rather than overly intensive grazing practices in NAR. However, further studies measuring ungrazed legume DM would be useful for better defining total fixed N_2, particularly within CAR and SAR.

Similar to pastures, the N contributions per ha from lupin, the most frequently grown grain legume, have declined with the increased harvest index of adopted cultivars. Unkovich *et al*. (1994) reported a residual N balance of 107 kg N/ha when using cv. Illyarrie (released 1979), which had a harvest index, calculated from aboveground biomass, of 0.11 in this study. Evans *et al*. (2001) predicted the N balance for lupin by relating shoot DM to yield for a dataset with a harvest index of

0.23, compared with 0.31 for the Focus Paddocks dataset, which comprised 80% cv. Mandelup (released 2004). Applying the equations in Evans *et al*. (2001), 10.2 t/ha of shoot DM is required to produce the mean lupin yield of the Focus Paddocks dataset (2.2 t/ha), compared with the 6.9 t/ha of shoot DM measured here. The higher harvest index of the Focus Paddocks dataset equated to an estimate of Nfix that was 70 kg N/ha lower than estimated by Evans *et al*. (2001). Although our results highlight large differences among cultivars, we recommend further research to quantify more accurately the changes in N contributions per ha among lupin cultivars. This requires detailed assessments including underground biomass, as per the methodology of Unkovich *et al*. (1994).

Cereal and canola production resulted in negative annual N balances, consistent with Baldock *et al*. (2018). This is in part because cereals grown after legumes received less fertiliser N, but it should be noted that Nmin from preceding legumes crops was not adequate to offset the losses. Also the lower legume N inputs per ha that we measured relative to previous studies, due to low pasture legume content and high harvest index in lupin, are possibly not being incorporated by farmers/farm advisors within N budgeting for the first crops after the legume phase. In a longitudinal survey assessing farmer attitudes to the benefits of break crops, conducted in 2008 and 2014 as a part of our Focus Paddocks study, the proportion of respondents who considered provision of N to the following wheat crop as a moderate/major benefit of the break crops declined from 84% to 65%, showing that farmers were aware of the reduced biological N input due to their land use changes (Carmody 2015); however, they did not compensate with enough fertiliser N in many of the fields that we monitored. Further research is required to determine whether N contributions of legumes have changed, and if so, whether this is being incorporated into N budgeting. By the third and fourth wheat year, the amount of fertiliser N applied increased to compensate for the lack of legume N. Furthermore, our analysis of the amount of N fertiliser applied by length of sequence without a legume indicated the amount of N applied increased by 160–200%, depending on region, by the fifth year without a legume.

Fertiliser

Mean fertiliser N application in our study was similar to the 45 kg N/ha reported as an Australian average for dryland cereals and oilseeds (Angus and Grace 2017). The amount of fertiliser N applied was adjusted in response to seasonal starting conditions and rotation. Less N was applied in years with later starts and lower autumn rainfall. The greater amount of fertiliser applied to the third and fourth years of wheat sequences improved balances of all nutrients, but yield and fertiliser efficiency also declined, from 14.6 kg fertiliser N/t grain in the first wheat crop to 24.4 kg fertiliser N/t grain in the fourth wheat crop. This finding is in line with global estimates that increased N fertiliser use since 1961 has resulted in a decline in the proportion of the fertiliser N applied that is converted to grain, from ~68% to 47–59% (Liu *et al*. 2010; Lassaletta *et al*. 2014).

The production area of cereals and oilseeds increased in south-west WA over the period 2000–16: from 4.4 to 5.1 Mha for wheat, from 1.0 to 1.3 Mha for barley, and from 0.5 to 1.2 Mha for canola (ABS 2016). Conversely, area of grain legume declined; from 1.0 to 0.4 Mha for lupins, and from 0.17 to 0.04 Mha for pulses combined (ABS 2016). Based on these cropped areas and mean fertiliser inputs observed in our study, we estimate that changes in N applied by land use from 2000 to 2016 were +24 756 t for wheat, +10 149 t for barley, +34 472 t for canola, and –890 t for all grain legumes, a net increase in N fertiliser of 68 487 t N/year. Hence, with increased reliance on N fertilisers in south-west WA, it is crucial to improve understanding of fertiliser use efficiency so that balances can be accurately assessed. Applying the same changes in cropping hectares to mean P, K and S amounts applied in our study provided estimates of net annual increases in applied fertiliser P of 10 824 t, K of 1822 t and S of 9885 t in south-west WA.

Legume versus fertiliser N

Applying the calculated Nfix to the reduction in grain legume area (0.73 Mha) across south-west WA over the 2000–16 period, we estimated reductions of ~93 885 t N fixed by lupin and 19 969 t fixed by pulse crops, resulting in a reduction of ~41 108 t RNfix after grain harvest in 2016 compared with 2000. This does not account for the reduction in pasture N contribution, previously estimated to provide 60 kg N/ha.year in southern Australia (McDonald 1989; Angus and Peoples 2012). It is impossible to calculate accurately the reduction of biological N input from pastures because of the poor records of area covered by legume pasture and the lack of time-series data on legume content. However, to appreciate the magnitude of this change, we should consider that under ley farming practices in the 1960s it was estimated that for every kg fertiliser N applied per ha, ~20 kg/ha was supplied from pasture as biologically fixed N (Reeves 2020). This contrasts with our findings of 4 kg/ha of fertiliser N to 1 kg/ha of legume fixed N added to the soil, which concurs with Reeves (2020) estimation of a 4:1 ratio in southern Australian dryland crop and pasture farms. In the NAR, where lupin was the main biological N supply, the ratio of fertiliser N to RNfix was higher (7.0:1), due to a substantial amount of fixed N being harvested as grain.

Soil N and C dynamics

Soil mineral N concentration in autumn was influenced by summer rain, soil organic matter content and temperature, consistent with previous studies (Angus *et al*. 1998; Hoyle *et al*. 2016; Peoples *et al*. 2017). This highlights that measuring soil N concentrations annually, before sowing, is not an accurate way to assess the impact of land use changes on long-term N balance. Organic matter content was greater with higher annual rainfall and lower temperatures, in line with previous WA research (Hoyle *et al*. 2011, 2016). The climate of south-west WA has altered in recent decades, with reductions in May–July precipitation of ~20% since 1970 (BOM 2018), and reductions in May–October rainfall of 17% (50 mm) contrasted by additional summer rainfall of

39 mm (68%) in CAR post-2000 (Scanlon and Doncon 2020), with projections for continuing reductions in rainfall and increasing temperatures (BOM 2018). Temperature and rainfall are major drivers of soil C and N dynamics; therefore, the relationships that we quantified within the regression tree for summer rainfall, organic C and mineralised N in autumn may need periodic examination.

Luo *et al*. (2010) estimated that agricultural cultivation in Australia over the past 40 years has led to a 51% loss of C in the 0–10 cm soil layer, with large reductions in soil N also resulting from tillage (Russell 1980; Brennan *et al*. 2013). The uptake of minimum tillage (Llewellyn *et al*. 2012) has increased the liable soil C fractions (Roper *et al*. 2010) and reduced decline of soil C in recent decades in WA (Wang *et al*. 2013). However, due to the tight coupling of soil N and C, less frequent use of legumes is likely to have the opposite effect (Blair and Crocker 2000; Batlle-Aguilar *et al*. 2011; Kumar *et al*. 2018), although we did not detect this over the period of our study. This has led to the suggestion that rotations with more legumes need to be combined with modern technologies to move towards more sustainable farming systems, a key measure of sustainability being the building of soil C and N (Baldock 2019; Reeves 2020). Indeed, the move away from biological N fixation and rapid increase in fertiliser use in south-west WA is at odds with a key principle of sustainable intensification: to rely less on external inputs while engaging ecological processes to supply nutrients (Cassman and Grassini 2020).

Conclusions

Despite increasing amounts of fertiliser being used in south-west WA in recent decades, and farmers altering fertiliser inputs based on land use and rotations, N inputs in 60% of fields and K inputs in 90% of fields were inadequate to balance exports. When two legumes were grown in 5 years, N balances were positive in all regions. At the level of legume inclusion observed (20%), N budgets were negative in the central and southern regions, which over the long-term will result in declines in soil fertility from the levels built up over the last half of the 20th Century. Within the northern region, positive N balance at 20% legume inclusion was achieved by using around twice as much fertiliser N to legume N as in the other regions. Across all regions the ratio of fertiliser N to legume-fixed N added to the soil was ~4.0:1, a major change from estimates of 1:20 under ley farming systems.

Consequently, we suggest that land managers need to reassess K fertiliser inputs and estimate legume biomass and harvest index rather than assume N supply from residues based on previous data. Researchers designing and modelling farming systems also need to be aware of these issues and factor in the large regional differences in N supply from legumes that we observed.

Further quantifications of the effects of changing farming systems on nutrient balances are required, particularly reduced N contributions per hectare from legumes and losses of N in current grain production systems.

Conflicts of interest

The authors declare no conflicts of interest.

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