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Stott, KJ;Christy, B;McCaskill, M;Benke, KK;Riffkin, P;O'Leary, GJ;Norton, R

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Integrating crop modelling and production economics to investigate multiple nutrient deficiencies and yield gaps

Kerry J Stott[1], Brendan Christy[2], Malcolm McCaskill[3], Kurt K. Benke[1], Penny Riffkin[3], Garry J O'Leary[4] and Robert Norton[5]

[1]*Agriculture Victoria, Centre for AgriBioscience, 5 Ring Road, Bundoora VIC 3083, Australia. Ph: 03 9032 7730 (B), 0457 707 620 (M), kerry.stott@agriculture.vic.gov.au,* https://orcid.org/0000-0002-2793-2866.

[2]*Agriculture Victoria, Rutherglen Centre, Rutherglen VIC 3685, Australia.*

[3]*Agriculture Victoria, Hamilton Centre, Hamilton VIC 3300, Australia.*

[4]*Agriculture Victoria, 110 Natimuk Road, Horsham, VIC 3400, Australia.*

[5]*Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Victoria 3010.*

Abstract

A method is described for integrating crop modelling and production economics to quantify optimum applications of multiple nutrients and yield gaps. The method is demonstrated for crop production in the high rain-fall zone of southern Australia. Data from a biophysical crop model were used to overcome the persistent problem of inadequate experimental data. The Mitscherlich function was expanded to accommodate four variable inputs - nitrogen, phosphorus, potassium and sulphur - and the expansion path was used to determine the economic optimum application of all four nutrients. Modelling revealed the state-contingent yield potential and the extent to which unrealised yield could be explained by profit-maximising behaviour and risk-aversion by growers. If growers and their advisors were guided by the methods described they would be better equipped to assess crop nutrient demands and limitations, predict yield potential, additional profits and the risks associated with high input systems in a variable climate. If scientists were more aware of the extra profits and the risks involved as well as the quantitative relationships between inputs and outputs when thinking about what to produce and how to do so, they would be more circumspect about the net benefits to be obtained from closing yield gaps.

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MS. KERRY JANIENE STOTT (Orcid ID : 0000-0002-2793-2866)

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1. Introduction

Field experimentation and crop simulation studies have demonstrated capacity to increase yield potential for wheat and canola crops grown in the temperate, high-rainfall zone (HRZ) of south-eastern Australia. These areas have an annual average rainfall exceeding 500 mm and generally abundant water for producing high yielding crops, though seasons vary from favourable to water-stressed during grain-filling. Recent studies suggest the long-term water-limited yield potential in the HRZ is 7-10 t/ha for wheat (Triticum aestivum), and 4-6 t/ha for canola (Brassica napus), provided cultivars best suited to the longer-cooler growing season are produced with sufficient fertilisers and other inputs required to express the superior yield potential (Riffkin and Sylvester-Bradley 2008, Acuña et al. 2011, Christy et al. 2013, Riffkin et al. 2016, Robertson et al. 2016, McCaskill et. al. 2019). However, yields reported in agricultural statistics are much lower, averaging 2.9 t/ha for wheat and 1.5 t/ha for canola (Hochman et al. 2019); which for wheat is a yield gap between actual and potential of about 5 t/ha, and for canola 2 t/ha.

A meaningful interpretation of yield gaps requires giving weight to both biological and economic realities of crop production (Beddow et al. 2014) (section 2.1). Biological factors limiting crop yields in the HRZ include poorly adapted germplasm (though this is being addressed by new cultivar releases), periodic waterlogging, soil acidity, disease and frost. A major limitation, and the focus of this paper, is lack of nutrition attributed to incomplete knowledge on the part of growers and their advisors about nutrient demands in crops with high yield potential, the high up-front costs, and the risk of nutrient usage in a variable climate (Christy et al. 2015a,b). Nutrient inputs in HRZ cropping are costly, amounting to about $20,600 per farm or 10% of all cash costs in 2018 (ABARES 2019). The payoff is uncertain and risk-increasing when assessed using a measure that reflects both the downside

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and upside aspects of risk (e.g. the standard deviation of income) (Roosen and Hennessy 2003, Rajsic et al. 2009, Gandorfer et al. 2011, Pannell 2017, Monjardino et al. 2019). Consideration of risk would decrease rather than increase a risk-averse farmer's rate of fertiliser application. Furthermore, the extent of the decrease would increase with the degree of risk aversion. Monjardino et al. (op cit.), for instance, found that the risk premium faced by Australian wheat producers was greater for higher N treatments compared to low N treatments, and more so in the riskier lower rainfall environments compared to high-rainfall environments.

The goals of this study were to (a) demonstrate to growers the yield potential for wheat and canola crops and economic optimum applications of nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) in the variable high-rainfall environment, (b) determine the extent to which yield gaps and foregone profits could be attributed to considerations of marginal returns and costs and risk aversion by the decision-maker, and (c) develop a bio-economic analysis framework that can solve this and other similar problems of multiple limiting factors when experimental data are lacking (section 2.2).

This paper addresses the above goals and contributes to method development in two ways. First, by extending the modified Mitscherlich response function of Gourley et al. (2017) for response to N in dairy pastures, and as applied by Stott et al. (2018), to accommodate four variable inputs: N, P, K and S (section 2.3). This allowed yield potential and economic optimum nutrient applications to be determined for multiple limiting factors using marginal analysis of production economics (Bishop and Toussaint 1958, Jauregui and Sain 1992) (sections 2.4).

Much has been written about nutrient response functions in cropping since Heady's (1957) seminal work, mostly with a singular focus on N (for example Godden and Helyer 1980). Regrettably, marginal analysis is seldom applied because of the lack of field observations with sufficient 'design points' to map out response functions that exhibit diminishing marginal returns (Borsen and Richter 2012) for the full range of potential weather outcomes. The second contribution of this paper was to overcome these data limitations by fitting the Mitscherlich function to yields generated from a process-level crop model calibrated for HRZ cropping - the Catchment Analysis Tool (CAT) (Christy et al. 2013) (section 2.5).

The framework was applied to two hypothetical case-study paddocks in the HRZ of southern Australia (defined in section 2.6). Estimates of optimum nutrient applications, and yield gaps due to biological and economic factors (section 3) were theoretically sound, precise estimates based on profit maximising principles, though perhaps presented with more implied precision than is required in practice given the general flatness of payoff functions in agricultural production (Pannell, 2016). Lastly, some general principles concerning the economics of nutrient application are confirmed and discussed (section 4).

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2. Methods

2.1. Conceptual framework

A stylised response function exhibiting diminishing marginal returns, and the biological and economic contributions to the yield gap when nutrients are used to produce a crop is shown in Figure 1. The agronomic maximum, or water-limited yield potential, with best technology for a crop fully supplied with nutrients is represented by point **a**. Hypothetical yields with 'marginal' or 'low' nutrient availability are represented by points **d** and **e**. The yield gap relative to the agronomic maximum is the difference in yield between these points and point **a**.

[figure 1 in here]

Because nutrient applications that maximise expected profit (point **b** in Figure 1) are less than those that maximise expected yield (Pannell 2006, Beddow et al. 2014), a portion of this yield gap can be attributed to economic factors. Economic optimum nutrient applications vary with the decision-maker's desired return on marginal capital (Anderson 1975, Anderson, Dillon and Hardacre 1977, Pannell 2006). If the desired rate of return on the marginal dollar invested in fertiliser includes a substantial risk premium (or high learning costs), say in the order of "2 to 1", the profit maximising yield decreases further (to point **c** in Figure 1), possibly substantially depending on the slope of the response curve in that region.

2.2. Building blocks

The analysis (Figure 2) accommodates both wheat and canola crops grown under continuous cropping or after recent pasture conversion and is tailored to soil conditions at sowing as defined by mineral N (0-60 cm), Colwell-P (0-10 cm), Colwell-K (0-10 cm) and KCl40-S (0-10 cm).

[figure 2 in here]

Modelling using CAT provided time-series data spanning 60 years for estimating nutrient response curves that exhibit the diminishing marginal returns necessary for economic analysis. CAT can replicate the high yields and N responses for wheat and canola in the HRZ (Christy et al. 2013, Christy et al. 2018). Figure 3 shows the performance of CAT with response to N fertiliser measured on 55 crops grown within the HRZ of south western Victoria. Crop application of N ranged from 12 kg N/ha at sowing up to 160 kg N/ha applied in-crop, and the supply of other nutrients was non-limiting (McCaskill et al. 2016). The modelled response shows no obvious prediction bias with typical root

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mean squared error of 0.57 t/ha. The CAT nitrogen model comprises four primary components: mineralisation, nitrification, volatilisation and denitrification of soil layers, and the corresponding allocation between pools of nitrogen concentrations using the functions described in Neitsch et al. (2001 p340). The model monitors five different pools of nitrogen within the soil, featuring two inorganic mineral pools and three organic pools. Organic nitrogen is then further partitioned into fresh organic nitrogen associated with crop residue, and humic organic nitrogen associated with active and stable pools. Plant use of nitrogen is estimated using the supply and demand approach (Williams et al. 1984). Daily plant demand is a function of plant biomass and biomass N concentration. Available nitrogen in the soil (within rooting depth) is supplied to the plant. When demand exceeds supply, there is a nutrient stress. For simulating the yield response to limitations of P, K or S supply, the biomass growth responses were scaled according to empirical functions based on trials collated into a national database, "Better Fertiliser Decisions for Cropping Systems in Australia" (Spiers et al. 2013).

[figure 3 in here]

For simplicity, no allowance was made for an experimental/modelled yield gap (i.e. the difference between the commercial yield achieved by farmers and the experimental yield achieved in controlled experiments). This could be in the order of 15% (Nigussie et al. 2018) but has been estimated as high as 30% for Victorian wheat crops (Davidson and Martin 1965).

Response functions were determined for four expected yield outcomes contingent on seasonal conditions. The four yield outcomes were 'very good', 'good', 'poor' and 'very poor', based on quartile years for yield. At the start of a growing season, each yield outcome is equally likely and has a probability of one-quarter. By late August, more is known about soil water levels and the climate models have better predictive performance for spring rainfall (GRDC 2005), so each outcome is no longer equally likely.

For calculating economic optimum nutrient applications, only those costs and returns that change with the nutrient treatment are considered. These include the expected farm-gate grain price and the 'as spread' cost of each nutrient. For simplicity, the small cost of soil testing (approximately $5/ha) was not included in the analysis.

The precise 'best bet' level of nutrient to use was determined using 'marginal analysis' of production economics. The profit-maximising decision rule is to apply the variable input up to where the revenue from an extra kilogram of nutrient applied just exceeds its cost. With multiple nutrients an additional rule is needed to equate marginal return from the use of all inputs simultaneously.

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Optimum rates were estimated for the growers desired return on marginal capital, which could simply be the cost of additional capital for fertiliser purchases (as represented by the overdraft rate for the period under consideration) or could be higher to include a more substantial risk premium.

It was assumed that fertiliser rates are calculated to manage nutrient supply for the current crop only, not for the following crop nor for building-up of soil reserves. Hence, the response functions were ‘conventional’ one-period nutrient response curves, not ‘maintenance curves’ that account for changes in fertiliser stocks in the soil as proposed by Godden and Helyer (1980).

2.3. The response function

There are many functional forms to choose from in production analysis (Griffin et al. 1987) and numerous statistical criteria (such as goodness-of-fit and general conformity to data) to aid selection. In this analysis, the Mitscherlich equation was chosen for its intrinsic properties: concavity and asymptotic convergence towards a maximum yield; and for its similarity to functions typically fitted to data in the national BFDC database (Dyson and Conyers 2013; Spiers et al. 2013). Concavity is important in the context of economic optimisation, because it enables input levels that maximize profit to be computed from the partial derivatives.

The classical Mitscherlich equation is often used to describe the yield response of a crop to an increase in a main factor limiting its growth. Harmsen (2000) introduced moisture-dependency in a Mitscherlich equation for crop response to N availability under rain-fed conditions. To address multiple limiting nutrients the constraint factors for each nutrient are multiplied together as proposed by Baule (1918). Multiplicative interaction among co-limiting nutrients has been found to be consistent with experimental evidence at constraint levels that apply in agriculture (Wallace 1990a b, Wallace and Wallace 1993). In our study, the Mitscherlich adaptation of Gourley et al. (2017) was generalised from a conventional single-variable (N) problem to multiple limiting nutrients (N, P, K and S). The 4-variable Mitscherlich equation is introduced as follows:

$$Y = \alpha \prod_{i} \left(1 - e^{(-b_i - c_i x_i)}\right) \tag{1}$$

where:

Y is the crop yield (t/ha)

α is the asymptotic yield (t/ha)

x_i are applied nutrients N, P, K and S (kg/ha)

b_i are implicit measures of initial soil nutrient status for each nutrient i

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c_i are the curvature coefficients for each nutrient i

i = 1, 2, 3, 4 for N, P, K and S, respectively.

2.4. Economic optimisation

2.4.1. Marginal products

The rate of change, also called the 'marginal product' (MP) for each input (i.e. the change in total output as one additional unit of input is added to production), is shown in Eqn (2):

$$\frac{\partial y}{\partial x_i} = \alpha c_i e^{(-b_i - c_i x_i)} \prod_{i \neq j} \left(1 - e^{(-b_i - c_i x_i)}\right) \tag{2}$$

where i, j = 1, 2, 3, 4, respectively, for N, P, K and S

The 'technical rate of substitution' between N and P, K and S, respectively, are described in Eqns. 3 to 5. In this situation, substitution should not be interpreted to mean that a wheat or canola plant is substituting nutrient P for nutrient N (for example) in a biological sense. Rather, it simply means that changes in yield are achieved by smooth changes in the proportion of nutrients (Jauregui and Sain 1992).

$$\frac{\partial n}{\partial p} = \frac{c_2 e^{(-b_2 - c_2 P)}\left(1 - e^{(-b_1 - c_1 N)}\right)}{c_1 e^{(-b_1 - c_1 N)}\left(1 - e^{(-b_2 - c_2 P)}\right)} \tag{3}$$

$$\frac{\partial n}{\partial k} = \frac{c_3 e^{(-b_3 - c_3 K)}\left(1 - e^{(-b_1 - c_1 N)}\right)}{c_1 e^{(-b_1 - c_1 N)}\left(1 - e^{(-b_3 - c_3 K)}\right)} \tag{4}$$

$$\frac{\partial n}{\partial s} = \frac{c_4 e^{(-b_4 - c_4 S)}\left(1 - e^{(-b_1 - c_1 N)}\right)}{c_1 e^{(-b_1 - c_1 N)}\left(1 - e^{(-b_4 - c_4 S)}\right)} \tag{5}$$

2.4.2. Unit prices

The unit price of the crop ($/kg) net of costs that vary with the volume produced (harvest costs, insurance, delivery to point of sale and any yield adjustment) is given by Eqn (6).

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$$p_y = \left(P_y - C_y\right)(1-g) \tag{6}$$

where P_y is the net price of the crop at point of sale, C_y is the cost net of marketing levies, insurance, harvesting and transporting grain, g is the experimental yield gap (set to zero for simplicity).

The bulk prices at point of sale for urea, muriate of potash (MOP), mono-ammonium phosphate (MAP) and sulphate of ammonia (SOA) were used to determine the unit prices of the four elements N, P, K and S. That is not to say that these elements cannot be supplied in other fertiliser blends.

The unit cost of the added N was derived as follows:

$$p_n = (P_u + t)/Pct_n \tag{7}$$

where P_u is the price of urea fertiliser, t is the cost of delivery and spreading and Pct_n is N content of urea (46%).

The unit cost of the added K was determined similarly. The unit prices for P and S were determined from the bulk prices of the compound fertilisers after considering the value of the nitrogen (DA 2018).

Three equal split applications were assumed in determining the spreading cost for N-type fertiliser.

Unit prices and costs were sourced mostly from the Rural Solutions SA Budget Guide (RS 2018).

2.4.3. Optimum N rate

According to conventional economics for continuously variable inputs, the economic optimum N rate (N^*, kg/ha) is the point on a response function where the last increment of N returns a yield increase just large enough to pay for the additional N given background P, K and S levels (Bishop and Toussaint 1958, Malcolm et al. 2005). This was determined by equating Eqn. (2) for N to the inverse price ratio and solving for N (Eqn. 8).

$$N^* = ln\left\{\frac{\alpha c_1 e^{-b_1}\left(1-e^{(-b_2-c_2P)}\right)\left(1-e^{(-b_3-c_3K)}\right)\left(1-e^{(-b_4-c_4S)}\right)\, p_y\, r}{p_n}\right\}/c_1 \tag{8}$$

To accommodate the decision-maker’s desired return on marginal capital, p_y is multiplied by the marginal B/C ratio, denoted by r. A marginal B/C ratio of 2:1 is equivalent to a rate of return of 100% where an investment is returned 12 months later but is higher for shorter intervals between expenditure and sale of the crop.

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2.4.4. Profit maximising combinations of nutrients

Least-cost combinations of N with P, K or S (the 'expansion path' in production economics) were determined from Eqns. 9 to 11, respectively.

$$P = ln\left\{\frac{c_2 e^{(-b_2)}\left(1 - e^{(-b_1 - c_1 N)}\right)p_n}{c_1 e^{(-b_1 - c_1 N)}\left(1 - e^{(-b_2 - c_2 P)}\right)p_p}\right\}/c_2 \tag{9}$$

$$K = ln\left\{\frac{c_3 e^{(-b_3)}\left(1 - e^{(-b_1 - c_1 N)}\right)p_n}{c_1 e^{(-b_1 - c_1 N)}\left(1 - e^{(-b_3 - c_3 K)}\right)p_k}\right\}/c_3 \tag{10}$$

$$S = ln\left\{\frac{c_4 e^{(-b_4)}\left(1 - e^{(-b_1 - c_1 N)}\right)p_n}{c_1 e^{(-b_1 - c_1 N)}\left(1 - e^{(-b_4 - c_4 S)}\right)p_s}\right\}/c_4 \tag{11}$$

where:

p_p is the unit price of P,

p_k is the unit price of K, and

p_s is the unit price of S.

A partial budget was used to determine the profit maximising combination of all four nutrients. N applications ranging from zero to 350 kg/ha were tabulated in Excel with the associated least-cost levels of P, K and S, and the predicted yield. The gross benefits were the modelled yield adjusted for any experimental yield gap multiplied by net price of the crop. Total costs were the costs of all four nutrients, as spread. The marginal returns (MR) and marginal costs (MC) were calculated. The profit maximising level of nutrient use was where the marginal returns just equal marginal costs. This is where the B/C ratio is 1 (Eqn. 12), or where the rate of return on marginal capital invested in fertiliser (ROI) is zero (Eqn. 13).

$$B/C = \frac{MR}{MC} = \frac{\Delta(Yp_y)}{\Delta(Np_n + Pp_p + Kp_k + Sp_s)} \tag{12}$$

$$ROI = \frac{Marginal\ net\ benefits}{MC} = \frac{MR - MC}{MC} \tag{13}$$

Note that the B/C ratio is for the marginal dollar invested in the last unit of applied nutrient. Every unit less would add more to profit. The B/C ratio averaged over all units of added nutrient would be higher.

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2.5. Calibrating the Response Function

The coefficients α, and c_i in Equation 1 were estimated satisfactorily for selected locations, crop types, paddock histories and yield quartiles by minimising the root mean squared error (RMSE) between predicted yields and simulated CAT yields. Parameter estimation was carried out using the Evolver option, which is an evolutionary programming algorithm in the Decision Tools Suite Ver 7.5 (Palisade Corporation, 2019). The b_i coefficients in Equation 1 were set prior to optimisation from the yield ratios in Eqn (14):

$$b_i = -\ln\left(1 - {Y_{i,0}}/{Y_{i,max}}\right) \tag{14}$$

where:

$Y_{i,0}$ is the average yield with zero added nutrient i other nutrients unlimiting, and

Y_{max} is the average yield with the maximum amount of added nutrient i other nutrients unlimiting.

CAT simulated 60 years of wheat and canola yields at selected locations using historical climate data. Scenarios for the wheat and canola crops comprised two levels of initial soil mineral N and three levels each of applied N, initial soil P, K and S. The two levels of initial soil N were: (1) 'low' (85 kg N/ha) for continuous cropping, and (2) 'high' (157 kg N/ha) for recent pasture conversions. N was applied as urea in split applications totalling 0, 90 or 250 kg N/ha. The three levels of soil P were ‘low’ (Colwell P; 10 mg/kg soil), ‘marginal’ (20 mg/kg) and ‘sufficient’ (30 mg/kg). Initial K soil levels were set at ‘low’ (Colwell K; 60 mg/kg soil), ‘marginal’ (200 mg/kg) and ‘sufficient’ (400 mg/kg). Initial S soil levels were set at ‘low’ (KCl-40; 3 mg/kg soil), ‘marginal’ (9 mg/kg) and ‘sufficient’ (12 mg/kg). Initial soil P, K and S values were converted into kilograms per hectare using soil factors reported by Gourley (2013) for a PBI range of 101-300. The CAT simulations were subsetted by location, crop type, paddock history and yield quartile for analysis with Evolver.

The response functions derived from the CAT data using Evolver exhibit diminishing marginal returns, asymptote towards a maximum yield (α), and intercept the Y-axis at a non-zero yield (b_i) (Fig. 4). At the lowest level of initial soil fertility there were strong responses in wheat to N, P and K, but not S (Fig 4b); however, canola had a much stronger response to added S (not shown).

[figure 4 in here]

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2.6. Application to crop production at Skipton and Bool Lagoon

Yield responses for wheat and canola and economic optimum nutrient applications were examined for two illustrative case studies (paddocks) located at Skipton and Bool Lagoon, in the HRZ of Victoria and South Australia, respectively. Assumptions regarding pre-sowing soil attributes, yield expectations, unit prices and costs, and the decision-maker's desired return on marginal capital are contained in Table 1.

[table 1 in here]

Soil tests and paddock histories provided the necessary information about the pre-sowing nutrient status of the paddock. The paddock history was either continuous cropping with mineral N of 85 kg N/ha or pasture conversion with mineral N of 157 kg N/ha. Both paddocks tested 'low' for soil P, K and S, respectively, 10, 80 and 6 mg/ha. Nutrient levels are well below 90% of relative yield reported in Christie et al. (2015) and strong yield responses were expected.

At sowing N application rates were for 'very good' yield outcome in the top quartile (4), the reason being that with uncertainty around the optimum rates, the profit losses from under- fertilising (yield penalty) are generally greater than those from over- fertilising (unnecessary fertiliser expense). To reduce up-front cost and risk, N input was minimised at sowing and the balance applied in split applications throughout the growing season depending on developments. For example, should the decision to apply the final top-dress be revised in late August and an El Nino event is forecast, then yield expectations would be revised down substantially (Table 2). At Skipton the yield potential was 11.1 t/ha in a 'very good' year but a more modest 7.3 t/ha in a 'poor' year. Potential yields were lower at Bool Lagoon in all seasons (Table 1).

[table 2 in here]

The N to wheat price ratio is 8.2. That is, about 8 kg of wheat is necessary to buy 1 kg of N – covering all the costs that vary and providing for any yield adjustment. The P to N price ratio is 2.5. That is, to buy, deliver and spread 1 kg of P costs 2.5 times more than it does for an equivalent amount of N.

The farmer's desired rate of return on the marginal dollar invested in fertiliser is 100% on an annual basis, equivalent to a '2 to 1' return. This is substantially higher than the cost of additional capital for fertiliser purchases which is in the order of 5% (real) - the average rate paid on business debt in the farming sector over the last 10 years (ABARES 2018) - or the return for investing in Australian equities of 9% (real) p.a. and reflects a high degree of risk aversion on the part of the decision-maker.

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3. Results

3.1. Economic optimum N applications

For both the pasture conversion scenario at Skipton, and the continuous cropping scenario at Bool Lagoon, unlimited P, K and S greatly increased the site N responsiveness, and hence the net value of adding N and the optimum N application rate (Figure 5).

The optimum N rate at Skipton determined for a marginal B/C ratio of 2:1 with unlimited P, K, & S and seasonal conditions conducive to a 'very good' yield outcome was 158 kg N/ha (Fig 5a). The expected yield was 10.6 t/ha, which was on the relatively flat part of the response curve, and in the range for the maximum potential yield of 11.1 (10.1 – 13.4) t/ha. With limited P, K, S the profit-maximising N rate for a B/C ratio of 2:1 fell to 24 kg N/ha for a yield of 1.7 t/ha. Optimum N rates and yields were lower at Bool Lagoon, reflecting the lower overall yield potential (Fig 5b).

[figure 5 in here]

Figure 6 shows how lower productivity due to poorer seasons reduced both the realised yields and economic N rate. Should the N-decision be revised in late August to reflect an expectation that yields are likely to be 'poor', then for a B:C ratio of 2:1 and unlimiting P, K, and S, the optimum N rate at Skipton would fall by 35% to 102 kg N/ha – confirming the wisdom of farmer practice to apply N in split applications to ameliorate production risk (Fertiliser Institute 2016). The expected yield falls 38% to 6.6 t/ha.

[figure 6 in here]

3.2. Economic optimum N, P, K and S applications

The optimum N application rate also decreased when the cost of adding P, K and S to a paddock deficient in these nutrients was considered. Least-cost combinations of added N, P, K and S for wheat grown at Skipton on soil with limiting fertility are shown in Figure 7. The profit maximising N rate for a marginal B/C ratio of 2:1 declined to 130 kg/ha from 158 kg/ha with unlimited P, K and S. The profit maximising P, K and S rates were, respectively, 26 kg/ha, 24 kg/ha and 0 kg/ha. The predicted yield associated with this level and combination of nutrients was 7.9 t/ha. Although no S was indicated for the wheat crop, this would not be the case for a canola crop grown at the same location (not shown).

[figure 7 in here]

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3.3. Yield and profit gaps

Predicted yields and additional profits when nutrients were applied to wheat and canola crops grown at Skipton in a ‘good’ (quartile 3) year are presented as heat maps (tables 3-5). Yield and profit outcomes are shown for both ‘low’ and ‘high’ crop prices, with the low prices being those used previously, and the high prices reflect those achieved in southern Australia during the recent drought. Wheat prices ranged from \$220/t to \$390/t and canola price ranged from \$480/t to \$550/t. Yield and profit gaps are expressed as percentages against a baseline.

Predicted yields (Table 3) for the various nutrient scenarios ranged from a high of 9.3 t/ha (conceptually point **a** in Fig 1) to a low of 1.7 t/ha for wheat in the paddock with ‘low’ initial soil fertility (point **e** in Fig 1) and low prices. For canola the range was 5.4 t/ha to 1.4 t/ha. By not addressing soil fertility and considering grower risk-aversion, represented by the 2:1 B/C ratio, the yield gap was as much as 82% for wheat and 74% for canola for the paddock with low fertility. It payed to apply more nutrients under the high-price scenario; yields at the lower end were higher, and the yield gaps were smaller.

Profit maximisation, represented by the 1:1 B/C ratio (point **b** in Fig 1), accounted for 6% of the total yield gap in wheat under the low-price scenario. High risk aversion, represented by the 2:1 B/C ratio (point **c** in Fig 1), accounted for a further 10% drop in yield; a similar outcome to the yield-depressing effects of growing crops in a paddock with ‘marginal’ fertility (point **d** in Fig 1).

[table 3 in here]

Additional profits and profit gaps are shown separately for paddocks starting with ‘marginal’ and ‘low’ levels of P, K, S (tables 4 and 5, respectively). For both paddocks, profits were maximised for the N, P, K and S applications that returned a B/C ratio of 1:1. Compared to this baseline, profit gaps were much smaller than yield gaps in percentage terms, provided growers addressed multiple nutrient constraints concurrently. Using high ‘hurdle rate’ (B/C ratio of 2:1), risk-averse growers would substantially reduce their input costs, but be no worse off in profit terms than if they had pursued a yield maximising objective.

[table 4 in here]

[table 5 in here]

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4. Discussion and conclusions

Our framework when applied to two hypothetical case-study paddocks in the HRZ of southern Australia considered both the biological and economic realities of crop production and provided sound estimates of optimum nutrient applications and yield gaps. Novel features and strengths of this study included the use of a four-dimensional Mitscherlich equation as the basis for the economic optimisation and a crop model with proven performance in the HRZ to overcome data limitations.

The analysis reported in this paper has confirmed some general principles:

a. Site responsiveness and optimum levels of applied N were higher in better seasons. For example, should yield expectations be downgraded from ‘very good’ to ‘poor’ during the growing season, optimum yields would fall by ~30%, confirming the common practice to apply N in split applications to ameliorate production risk.
b. Site responsiveness and optimum levels of applied N were also higher for higher levels of background soil fertility (i.e. initial P, K and S levels). Investing in N only at the expense of other nutrients (P, K and S), limits the optimum N rate and potential net benefits from N applications. The economic optimum N application rate decreases when the costs of adding other nutrients (P, K and S) were also considered.
c. Economic optimum nutrient applications varied with the decision-maker’s desired return on marginal capital. If the desired rate of return on the marginal dollar invested in fertiliser included a substantial risk premium (say a B/C ratio on the order of 2:1), the profit maximising amount of nutrients to apply and the realised yield would decrease, possibly substantially depending on the slope of the response curve at that point.

At the assumed unit cost of inputs and unit value of outputs used in this paper, the analysis also revealed that:

a. Profit maximisation that optimises one nutrient (N) to the exclusion of others (P, K, and S) involves a substantial decline in value and profit in crop production, especially for growers with high risk-aversion (as represented by a 2:1 marginal B/C ratio). For example, in a ‘good’ season, the agronomic yield gap could be as high as ~10-20% on soil with ‘marginal’ fertility, but a more extreme ~70-80% on a soil with ‘low’ fertility. The respective profit gaps could be as high as ~15-25% and ~90-95%. These figures compare to the yield gap due to sub-optimal N fertiliser management for Australia as a whole reported by Hochman and Horan (2018) of 40%. They are also consistent with Monjardino et al. (2015), who demonstrated for four dryland cropping sites spread across

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the southern wheat-belt of Australia that yield- and profit- maximising N rates are often quite similar, but can differ substantially from N rates influenced by risk and risk-aversion.

b. Multiple nutrient applications that maximise expected profit were generally less than those that maximise water-limited yield. By maximising profits (as represented by a 1:1 marginal B/C ratio) and sacrificing some yield, growers could reduce their input costs and be better-off in profit terms than by pursuing a yield maximising objective. Profit maximisation involving multiple nutrients accounted for ~5 percentage points of the total yield gap, suggesting that growers could profitably target yields of ~95% of the maximum. High risk aversion (as represented by a 2:1 marginal B/C ratio) accounted for a further ~10 percentage points of the total yield gap, suggesting a lower yield target ~85% of the agronomic maximum. These ~85%-95% ‘rule-of-thumb’ yield targets are higher than the ‘exploitable’ yield gap of ~80% from the work conducted by Lobell et al. (2009); the relatively benign impact on profits is consistent with the axiom of flat pay-off functions in agriculture (Pannell 2006).

This paper demonstrates how profit-maximising behaviour and risk-aversion by farmers contribute to unrealised potential for increased production of wheat and canola in the HRZ of southern Australia. The yield and profit gaps could be substantial if N usage is optimised without consideration of initial soil P, K and S levels, particularly for risk-averse growers. If crop growers and their advisors are guided by the methods presented in this study, they would be better equipped to assess crop nutrient demands, and predict yield potential, additional profits and the risks associated with high input systems in a variable climate[1]. If scientists were more aware of the extra profits and risks, as well as the quantitative relationships between inputs and outputs, when thinking about what to produce and how to do so, they would be more circumspect about the size of the net benefits from closing yield gaps.

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[1] The method described in this paper has been prototyped in MS Excel® and provided as supporting information.

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Table 1. Starting soil conditions, yield expectations and economic assumptions for wheat crops sown at Skipton and Bool Lagoon

Variable	**Skipton**	**Bool Lagoon**
Pre-sowing soil attributes		
Mineral N (0-60 cm) (kg/ha)	157 (pasture conversion scenario)	85 (continuous cropping scenario)
Colwell-P (0-10 cm) (mg/ha)	10	
Colwell-K (0-10 cm) (mg/ha)	80	
KCl40-S (0-10 cm (mg/ha))	6	
Expected yield potential for the quartile years (range)		
'Very good' (quartile 4) (t/ha)	11.1 (10.1 – 13.4)	8.8 (8.0 - 10.3)
'Good' (quartile 3) (t/ha)	9.3 (8.3 – 9.9)	7.1 (6.4 – 7.6)
'Poor' (quartile 2) (t/ha)	7.3 (6.1 – 8.1)	4.9 (3.7 – 6.1)
'Very poor' (quartile 1) (t/ha)	5.1 (2.9 – 6.1)	2.4 (0.5 – 3.6)
Wheat price ($/t)	220	
Contract harvesting cost ($/t)	20	
Freight costs (crop) ($/t)	20	
Unit price (net) ($/kg)	0.15	
Urea cost 46:0:0:0 ($/t)	480	
Fertiliser delivery costs ($/t)	20	
Contract fertiliser spreading costs ($/ha)	8.50	
Unit price for N (net) $/kg	1.20	
N/wheat price ratio	8.2	
Mono-ammonium phosphate (MAP) cost {10:22:0:0} ($/t)	660	
Unit price for P (net) $/kg	2.95	
P:wheat price ratio	20.1	
P:N price ratio	2.5	
Muriate of Potash (MOP) cost {0:0:50:0} ($/t)	490	
Unit price for K (net) $/kg	1.46	
K:wheat price ratio	9.9	
K:N price ratio	1.2	
Sulphate of Ammonia (SOA) cost {21:0:24:0} ($/t)	427	
Unit price for S(net) $/kg	1.09	
S:wheat price ratio	7.4	
S:N price ratio	0.9	
Desired return on marginal capital	B/C ratio of 2:1, or rate of return of 100% p.a. (75% for a 9-month growing season)	

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Table 2. Probable link between seasonal conditions prevailing at late August[‡] and yield expectations for a wheat crop grown at Bool Lagoon.

Yield expectations	Good moisture and no drought influence	Good moisture with drought influence	Low moisture and no drought influence	Low moisture with drought influence
Very poor (quartile 1)	15%	0%	50%	58%
Poor (quartile 2)	18%	63%	33%	17%
Good (quartile 3)	32%	13%	0%	25%
Very good (quartile 4)	35%	25%	17%	0%

Note:

‡ Four season-condition categories were based on the occurrence or otherwise of 'good' soil moisture and a 'drought influence': 'Good' moisture is growing season rainfall to end August in the 4th decile or above for the selected location. 'Drought influences' are an El Nino event or a positive Indian Ocean Dipole.

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Table 3. Heat map for wheat and canola yields (t/ha) under various nutrient and price scenarios in a 'good' year (quartile 3) at Skipton. The paddock was a pasture conversion with initial mineral N of 157kg /ha and either 'marginal' or 'low' soil P, K and S[†]. Percentage changes (in brackets) are relative to the maximum.

	Wheat		**Canola**	
Crop price[‡]	**Low**	**High**	**Low**	**High**
Nutrient scenario				
Maximum agronomic (water-limited) yield with best technology and 'unlimiting' N, P, K, S	9.3 (0%)	9.3 (0%)	5.4 (0%)	5.4 (0%)
Economic optimum multiple nutrient applications (N, P, K, S) for a B/C ratio of 1:1	8.7 (-6%)	9.3 (0%)	5.1 (-6%)	5.2 (-4%)
Economic optimum multiple nutrient applications (N, P, K, S) for a B/C ratio of 2:1	7.9 (-15%)	8.6 (-8%)	4.6 (-15%)	4.7 (-13%)
Economic optimum N for a B/C ratio of 2:1 with 'marginal' P, K, S	7.8 (-16%)	8.4 (-10%)	4.5 (-17%)	4.6 (-15%)
Economic optimum N for a B/C ratio of 2:1 with 'low' P, K, S	1.7 (-82%)	2.4 (-74%)	1.4 (-74%)	1.5 (-72%)

Notes:

† 'Marginal' soil P, K and S was 20, 110 and 10 mg/kg respectively. 'Low' soil P, K and S was 10, 80 and 6 mg/kg respectively.

‡ The wheat price range was \$220/t to \$390/t. The canola price range was \$480/t to \$550/t.

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Table 4. Heat map for additional profits ($/ha) for wheat and canola crops grown under various nutrient and price scenarios in a 'good' year (quartile 3) at Skipton. The paddock was a pasture conversion with mineral N of 157kg /ha and 'marginal'[†] soil P, K and S. Percentage changes (in brackets) are relative to the maximum.

	Wheat		**Canola**	
Crop price[‡]	**Low**	**High**	**Low**	**High**
Nutrient scenario				
Maximum agronomic (water-limited) yield with best technology and 'unlimiting' N, P, K, S	602 (-2%)	1468 (0%)	691 (-7%)	873 (-3%)
Economic optimum multiple nutrient applications (N, P, K, S) for a B/C ratio of 1:1	614 (0%)	1468 (0%)	742 (0%)	903 (0%)
Economic optimum multiple nutrient applications (N, P, K, S) for a B/C ratio of 2:1	590 (-4%)	1421 (-3%)	719 (-3%)	868 (-4%)
Economic optimum N for a B/C ratio of 2:1 with 'marginal' P, K, S	486 (-21%)	1241 (-15%)	562 (-24%)	698 (-23%)

Notes:

† 'Marginal' soil P, K and S was 20, 110 and 10 mg/kg respectively.

‡ The wheat price range was $220/t to $390/t. The canola price range was $480/t to $550/t.

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Table 5. Heat map for additional profits ($/ha) for wheat and canola crops grown under various nutrient and price scenarios in a 'good' year (quartile 3) at Skipton. The paddock was a pasture conversion with mineral N of 157kg /ha and 'low'[†] soil P, K and S. Percentage changes (in brackets) are relative to the maximum.

	Wheat		**Canola**	
Crop price[‡]	**Low**	**High**	**Low**	**High**
Nutrient scenario				
Maximum agronomic (water-limited) yield with best technology and 'unlimiting' N, P, K, S	845 (-6%)	2174 (0%)	1189 (-4%)	1489 (-2%)
Economic optimum multiple nutrient applications (N, P, K, S) for a B/C ratio of 1:1	900 (0%)	2174 (0%)	1239 (0%)	1518 (0%)
Economic optimum multiple nutrient applications (N, P, K, S) for a B/C ratio of 2:1	865 (-4%)	2105 (-3%)	1175 (-5%)	1456 (-4%)
Economic optimum N for a B/C ratio of 2:1 with 'low' P, K, S	36 (-96%)	237 (-89%)	86 (-93%)	128 (-92%)

Notes:

† 'Low' soil P, K and S was 10, 80 and 6 mg/kg respectively.

‡ The wheat price range was $220/t to $390/t. The canola price range was $480/t to $550/t.

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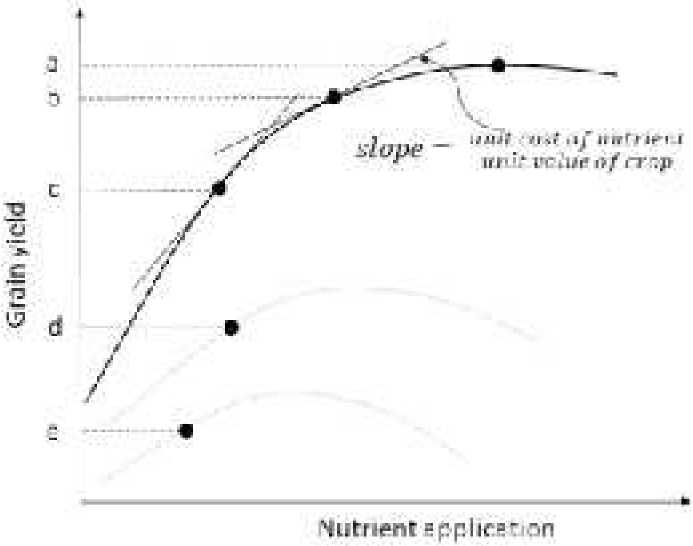

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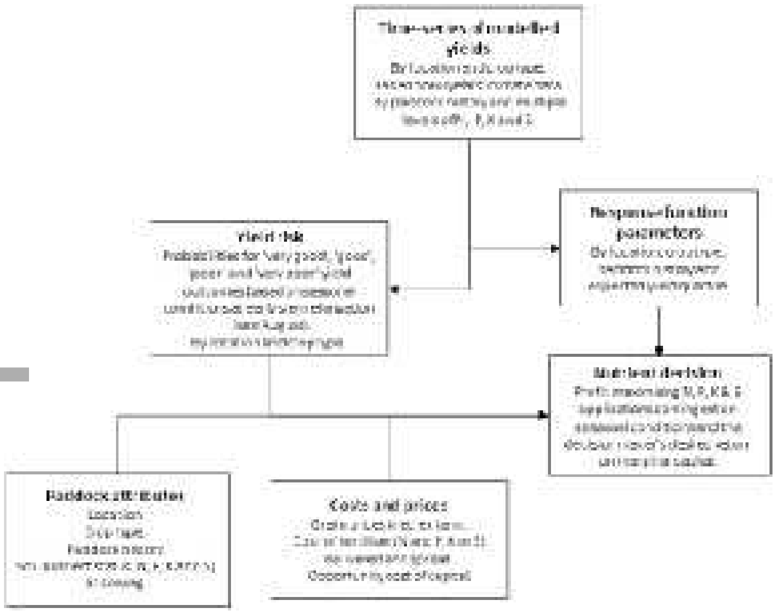

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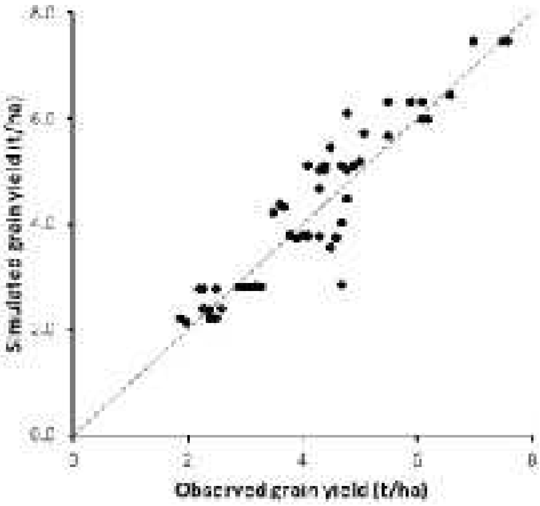

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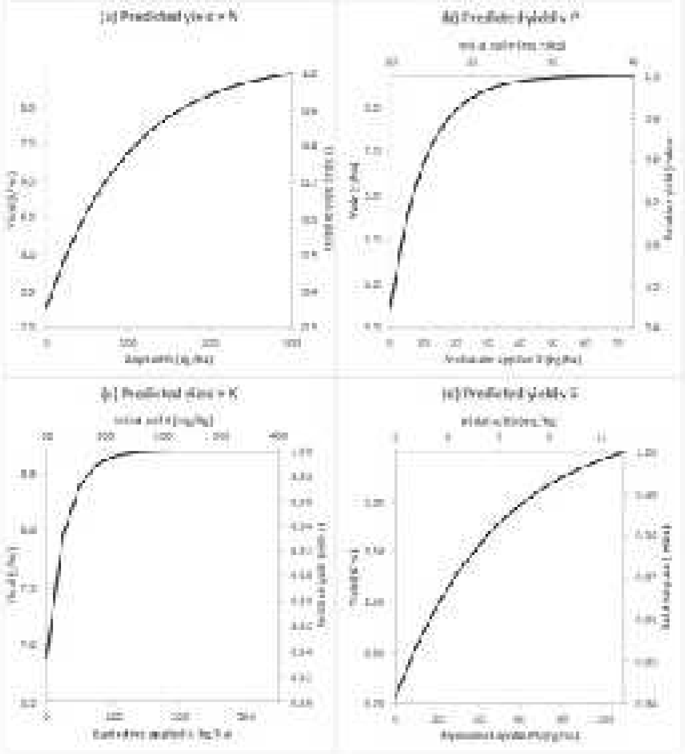

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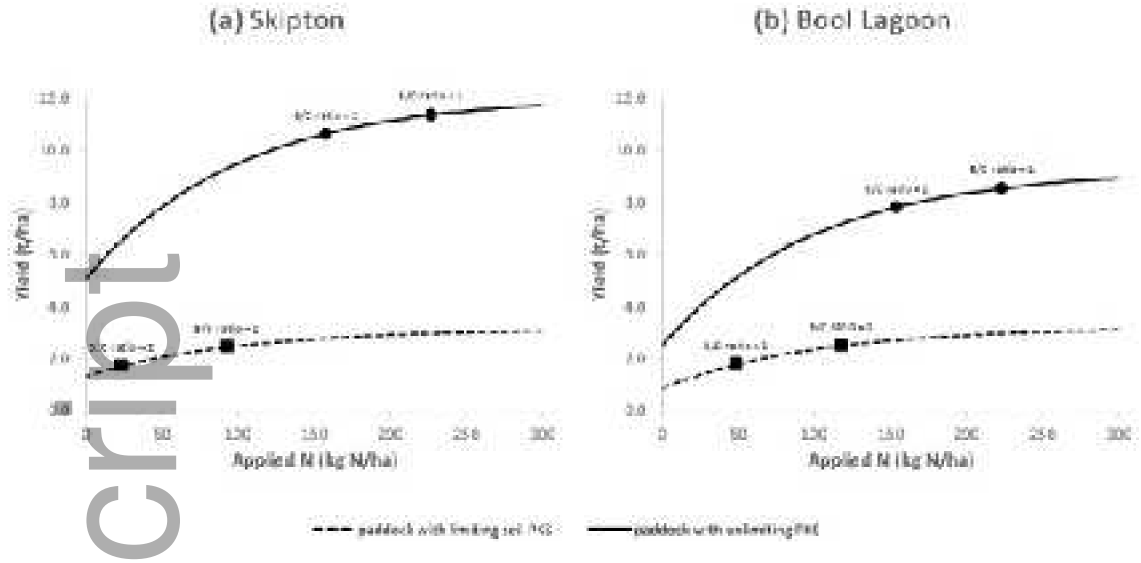

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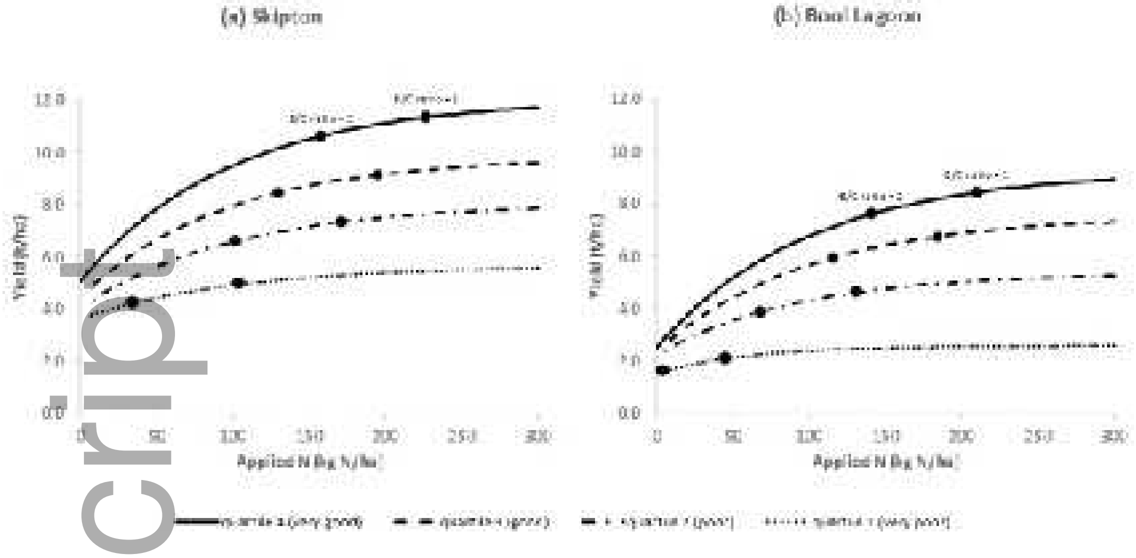

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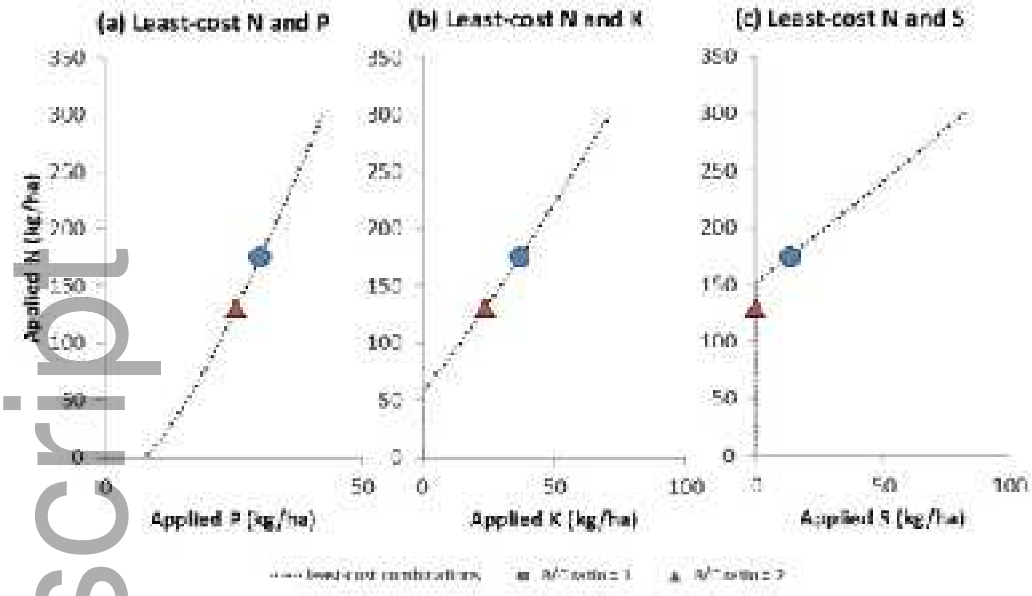

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