CROP SIZE AND SUGARCANE NITROGEN FERTILISER REQUIREMENTS: IS THERE A LINK?

By

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Abstract

THE AUSTRALIAN SUGARCANE industry is under pressure to reduce nitrogen (N) fertiliser applications and hence N losses to the environment. One pathway suggested to reduce N applications is to match yield targets in N fertiliser recommendations to the yields achieved by farmers. This seems a sensible strategy: smaller crops generally grown by farmers (relative to current yield targets) 'should' need less N. Is it really that simple? We collated over 150 N response curves for ratoon crops from past experiments to investigate the amount of N (N_{opt}) needed to achieve 95% of maximum sugarcane yield (Y_{95}). There was little correlation between Y_{95} and N_{opt}. For example, low yields (e.g. <50 t/ha) occurred at both low (<50 kg/ha) and high (>200 kg/ha) N_{opt} values. The low correlation was also seen in individual experiments and thus the results were not an artefact of amalgamating data from different locations. At one experiment, for example, across five years the N requirement varied three-fold. Given that soil and management were consistent across the years, the variation showed the climatic influence on N requirement. The results also showed that there was variation among sites and crops in **both** yield potential and the amount of N required to grow a tonne of cane. Rather than trying to improve N recommendations by changing concepts around target yields, we suggest it would be more beneficial to develop ways to predict N_{opt} directly. We simulated N responses with the APSIM model for one of the better characterised experiments in the database and derived N_{opt} from the response curves. Simulated N_{opt} was generally within the range of N_{opt} at the experiment. We conclude that direct prediction of N_{opt} through application the APSIM model, in combination with seasonal climate forecasts could be the basis of a future decision support system to define optimum N rates.

Introduction

Nitrogen (N) losses to the environment from crop production along the coastal lands of north Queensland need to be reduced to meet government water quality targets for protecting the health of Great Barrier Reef ecosystems (Kroon *et al*., 2016). As N losses from agriculture (including sugarcane) are stimulated by increased applications of N fertiliser (Thorburn *et al*., 2013), close matching of N applications to crop N requirements is an important component of reducing N losses.

Nutrient balance principles are a common basis for determining crop N requirements. The amount of N required is the product of (1) a yield target and (2) the amount of N needed to produce that yield, less (3) the amount of N supplied from organic sources (e.g. decomposing soil organic matter or residues of legume crops). The Australian sugarcane industry has a well-developed program, SIX EASY STEPS (6ES, Schroeder *et al*., 2014), for determining application rates of

N that are consistent with this general approach. The yield term is the district yield potential (DYP, tonnes of cane per hectare), the amount of N needed to produce a tonne of cane (the cane N requirement) is constant (equal to 1.4 kg N/t cane for yield less than 100 t/ha) and there are guidelines to account for the amount of N supplied from decomposing soil organic matter and legume residue. It should be noted that the DYP was never intended to be used as an actual yield value but rather as district discriminator (Schroeder *et al*., 2018).

For ratoon crops at a given location (site and soil), the DYP and soil organic matter terms of the N requirement equation are constant in 6ES. This relationship, together with the substantial farm-to-farm and year-to-year variability in yields of rainfed sugarcane crops in Australia (Schroeder *et al*., 2010) have led to suggestions that DYP in the 6ES system be replaced with the productive potential of management zones, e.g. cane fields or even within-field zones (Bell and Moody, 2014; Bramley *et al*., 2017).

Although this suggestion seems to make intuitive sense, it begs the questions: 'Is it really that simple?' What is the evidence relating crop size to the amount of N needed to achieve near-maximum sugarcane yield? These are important questions in the search for methods to improve N management.

To examine these questions, we collated results from Australian sugarcane N response experiments to investigate the relationship between the optimum N application (N_{opt}), defined as the amount of N fertiliser required to achieve 95% of the maximum yield (Y_{95}), and Y_{95}. We focussed on ratoon crops to avoid the complexities of the effect of fallows on plant crop N responses, as details of fallows management were generally not available.

There was little relationship between N_{opt} and Y_{95}, Thus, we also explored (1) the reasons for the poor relationship using data from a comprehensive N rate experiment and (2) other ways in which N_{opt} could be recommended without relying on assumptions of crop size.

Methods

Data sources

Data were collated from N response experiments (e.g. Allen *et al*., 2010; Anon., 2016; Catchpoole and Keating, 1995; Chapman, 1982 and 1994; Hurney and Schroeder, 2012; Schroeder *et al*., 2014; Skocaj, 2015; Thorburn *et al*., 2003; Vallis *et al*., 1994) conducted in all the major sugarcane regions in Queensland, from Rocky Point to the Wet Tropics. Experiments with less than four N rate treatments were discarded, as were experiments where there was relatively little difference (e.g. 20 kg N/ha) between N treatments.

Plant crop responses were omitted because the conditions preceding planting have a large effect on the N response of plant crops, and there was no information on these conditions in most experiments. The collation resulted in 154 N responses for ratoon crops.

As much metadata as possible were collected for each experiment. Extensive metadata (such as precise location, detailed soil and management information) were available for only a limited number of experiments (e.g. Hurney and Schroeder, 2012; Skocaj, 2015; Thorburn *et al*., 2003). More commonly, metadata were limited to region, year of harvest, crop class and (for 57% of experiments) soil organic carbon (SOC). Of the experiments with SOC data, 87% had SOC between 0.4 and 1.6 %. For some sources (Chapman, 1982 and 1994) the regional identification was broad, i.e. the 'Wet Tropics' rather than 'Tully' or 'Herbert'. For these experiments no attempt was made to determine a more specific region.

Data on rainfall, solar radiation and maximum and minimum temperature were derived for each experiment from the Silo database (https://www.longpaddock.qld.gov.au/silo/). Given that information on precise location, crop start and harvest date were generally unavailable, climate data were obtained for a central location in the region for a 12 month period (September to September). As well as climate parameters in the year of the experiment, the variation of the parameter from the long-term mean (expressed as % of the mean) was derived.

This was done to separate systematic (e.g. Tully having higher rainfall than Bundaberg) from inter-annual variation.

For each experiment, the N response was emulated by a second degree polynomial equation fitted to N response data (e.g. Figure 1). The value of Y_{95} was derived from the emulated response and then the value of N_{opt} calculated. Thus, each experimental N response curve was represented by a single value of Y_{95} and N_{opt}. Note: a range of other equations were tested as emulators (following Thorburn *et al*, 2017), but they had little effect on the results (data not shown).

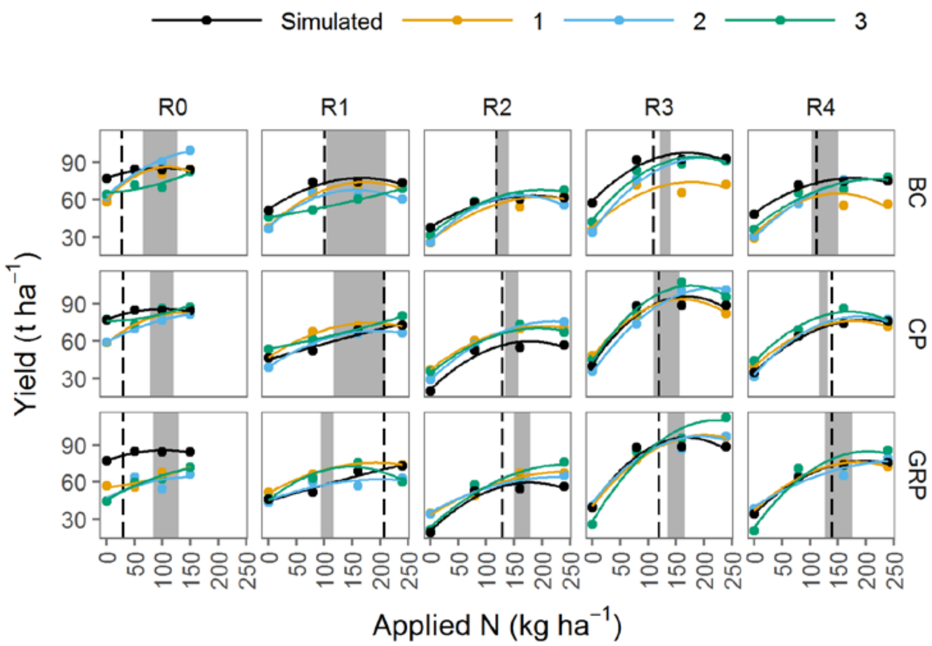

Fig. 1—The variation in yield at different rates of N fertiliser in an experiment on a Coom soil in Tully (Hurney and Schroeder, 2012). The experiment included five sugarcane crops (plant = R0, 1st ratoon = R1, etc.) grown under three management systems (BC: burnt cane, conventional cultivation plant and ratoons. CP: GCTB, conventional cultivation plant crop, zero cultivation ratoons. GRP: GCTB, zonal or row tillage plant crop, zero cultivation ratoons). Coloured dots show the measured data for three replicates and the black dots are simulated values. The solid lines show the second degree polynomial equation fitted to the data. The grey shaded area shows the range of the optimum N (i.e. N rate at 95% of maximum yield) values for the three replicates and the dashed line is the optimum N value for the simulated data.

Simulation of N responses and N_{opt}

We explored the reasons for the poor relationship between N_{opt} and Y_{95} through simulation of experimental N responses with the APSIM-Sugar model (Holzworth *et al*., 2014; Thorburn *et al*., 2017; Keating *et al*., 1999). We also investigated whether N_{opt} could be predicted with the model. We undertook this latter activity because, while sugarcane N responses have been previously simulated (Thorburn *et al*., 2017), the derivation of N_{opt} requires additional steps, i.e. simulating yields at different N rates, emulating the N response curve, deriving N_{opt}. The accuracy of this 'chain' of calculations has not been tested.

We simulated the experiment conducted on a Coom soil in Tully (Hurney and Schroeder, 2012) with APSIM v7.7. This experiment was selected because of the wealth of soil and management information available to specify model parameters and represent the experiment in the model, and the large number of crops (5 years x 3 tillage treatments x 4 N rates) it contained. The model configuration and application followed that described by Thorburn *et al*. (2017). Briefly, the model was configured with models for soil N and C, soil water, sugarcane growth and sugarcane residue.

Parameter values in these models came from three sources: (1) either standard values within the model, or some variation of those developed in previous studies; (2) measured or derived values of state variables at the site (mainly parameters describing the soil in the experiment); or (3) in a small number of cases, calibration against measured values.

Management of the experiment (e.g. dates of harvesting, fertiliser application, tillage, etc.) and the preceding fallow were specified in the model. Simulations were performed at the same N rates as applied in the experiment. The accuracy of simulation of yields was assessed by a range of methods (Bellochi *et al*., 2010): the correlation, regression and Root Mean Square Error between simulated and measured yields; and the Nash-Sutcliffe Efficiency (range –∞ to 1, high value is 'good') and Index of Agreement (range 0 to 1, high value is 'good') model performance metrics.

Outputs from the simulations included losses of N to the environment and the amount of N contained in cane. These are the two paths by which N was lost, or removed from the site and were used to calculate the cane N requirement.

The simulated N response was emulated by a second degree polynomial equation fitted to N response data, and the Y_{95} and N_{opt} values derived in the same way as for the experimental data.

Results

Relationship between observed yields and optimum N rate

For the ratoon crop N response curves, the value of N_{opt} (the N rate corresponding to 95% of maximum yield, Y_{95}) varied from 0 to 253 kg/ha and Y_{95} varied from 40 to 186 t/ha (Figure 2). There was no evidence that values of N_{opt} and Y_{95} differed significantly (P < 0.001) between crop class (Table 1), except between the first and second ratoons.

There was no significant correlation (r = 0.01, P = 0.91) between N_{opt} and Y_{95}: Low values (e.g. <80 t/ha) of Y_{95} occurred at N_{opt} both >200 and <50 kg/ha. Conversely, higher Y_{95} values (>130 t/ha) occurred at N_{opt} between 100 and 225 kg/ha. If the five responses where N_{opt} equalled 0 were removed, the correlation between N_{opt} and Y_{95} the correlation was stronger (r = 0.19, P = 0.02) but still had low explanatory and predictive power, with Y_{95} explaining less than 4% of the variation in N_{opt}.

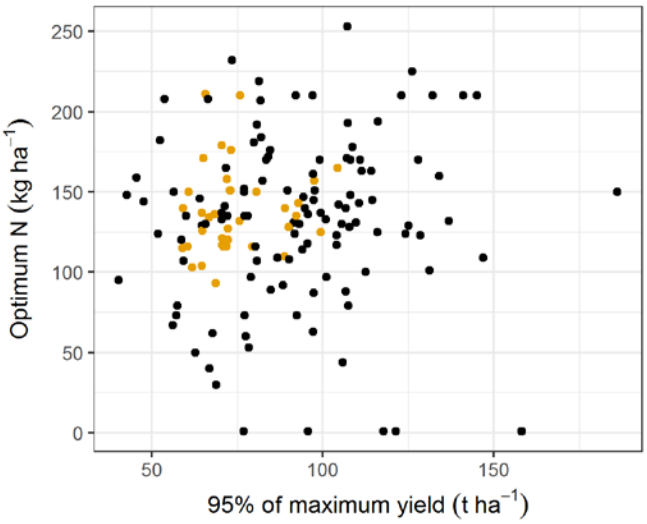

Fig. 2—The relationship between 95% of maximum yield and the N rate corresponding to that yield (Optimum N) derived from 154 ratoon crop N response experiments. The Tully-Coom experiment is identified in orange.

Table 1—Number of experiments for the different ratoons, and the average values for 95% of maximum yield (Y_{95}, t/ha) and the N rate corresponding to that yield (N_{opt}, kg/ha) for each ratoon. Different superscripted letters identify significantly (*p* <0.05) different means.

Ratoon number	Number of experiments	Average Y_{95}	Average N_{opt}
1	61	96^{a}	118^{a}
2	47	81^{b}	148^{b}
3	30	91^{ab}	135^{ab}
4	16	82^{ab}	136^{ab}

To assess whether the results were caused by aggregating data from experiments performed under different conditions (regions, soil types, etc.), we analysed data from the Tully-Coom experiment (highlighted in Figure 2).

For these data the correlation between N_{opt} and Y_{95} was weak (r = 0.11, P = 0.52). Low values (~65 t/ha) of Y_{95} occurred at N_{opt} both >200 and <100 kg/ha. N_{opt} values of approximately 160 kg/ha occurred in crops with Y_{95} from about 60 to 110 t/ha. N_{opt} did not vary significantly (P > 0.05) in the different treatments or crops in this experiment.

Simulation of the Tully-Coom experiment

Overall, cane yields from the Tully experiment were well simulated (Figure 3), with values of R^2 (0.71) and the Root Mean Square Error (10.4 t/ha), similar to those obtained for the original model calibration data (Keating *et al*., 1999). Other model performance metrics (Nash-Sutcliffe Efficiency = 0.65; Index of Agreement = 0.91) indicated the model had good prediction skill. One issue with the simulated yields was the over prediction of yield at low N rates in the plant cro

This result suggests too much soil N was being mineralised in the simulations, a problem likely to be caused by uncertainties in the prior management of the experimental sites, and thus the assumptions that needed to be made initialising parameters in the model.

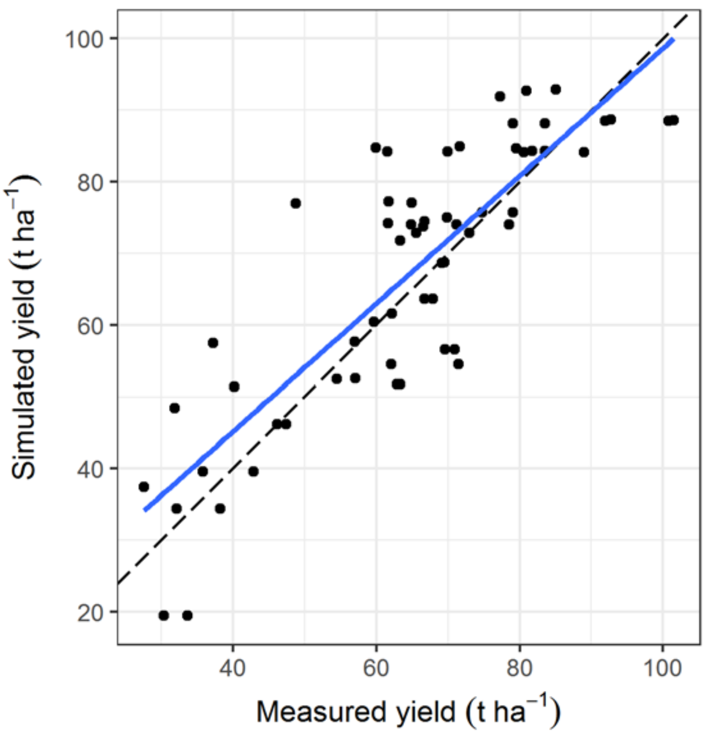

Fig. 3—The relationship between cane yields simulated with APSIM and measured in the experiment for all crops (plant and four ratoons) shown in Figure 1. The dashed line is the 1:1 line, and the solid line the regression.

Exploring the poor relationship between Y_{95} and N_{opt}

Simulated cane yields varied by 33 t/ha (or +/– 23% of the mean yield) across the five crops in the Tully-Coom experiment (Table 2). The variability in yields was poorly correlated (R^2 = 0.05) with total rainfall received by each crop.

Simulated N in cane varied from approximately 1 to 1.2kg N/t in the ratoon crops and was 0.64 kg N/t in the plant crop (Table 2). The simulated amount of N lost to the environment was more variable, varying by an order of magnitude across the five crops. Cane N requirement, i.e. the sum of the amounts of N taken up by the crop and lost to the environment, varied across the crops by a factor of three.

Table 2 – Simulated yields, N in cane, N lost to the environment (combined losses through denitrification, leaching and runoff), and Cane N requirement (the sum of N in cane and N lost) for a plant (P) and four ratoon (R1, etc.) crops in the Tully-Coom experiment (described above). Data are averaged over the tillage treatments in the experiment. Note that the N-related terms are expressed on a cane weight basis (not per hectare).

Crop	Rainfall (mm)	Yield (t/ha)	N in cane (kg/t cane)	N lost (kg/t cane)	Cane N requirement (kg/t cane)
P	3129	84	0.64	0.81	1.5
R1	4136	70	0.97	0.13	1.1
R2	3769	56	1.21	1.76	3.0
R3	3955	90	1.01	0.95	2.0
R4	4421	74	0.98	0.86	1.8

Simulation of Optimum N

The values of N_{opt} derived from the simulated data were generally within, or close to the range of N_{opt} between the replicates in the experiment (Figure 1). The exceptions were the plant crops (because of the over prediction of yields at low N rates noted above) and the first ratoon of the GRP treatment.

The wide range of N_{opt} in the first ratoon crops of the BC and CP treatments of the experiment were caused by the high N_{opt} value in Replicate 3 of these treatments in the experiment, where crops had an almost linear yield response to applied N. The simulated N response of the CP treatment in the first ratoon crop was also nearly linear, resulting in a simulated N_{opt} at the upper end of the range in this treatment. The situation was reversed in the BC treatment, with the simulated N response and N_{opt} being like those in replicates 1 and 2 of the experiment.

Discussion

Is crop size related to N fertiliser requirements of sugarcane?

This study set out to address a clear question – is crop size related to N fertiliser requirements of sugarcane? We have clearly shown that across N response curves from numerous experiments there is little correlation between near maximum yield (Y_{95}) and the N rates (N_{opt}) needed to achieve that yield (Figure 2). This result has important implications for sugarcane productivity: small crops may need as much N as large crops to reach their yield potential. Thus while lowering the yield target in the 6ES recommendations will lower recommended N application rates, which in turn will increase NUE (Bell *et al*., 2014) and lower environmental N losses (Thorburn *et al*., 2013), it may also reduce yields.

There has been evidence of the poor relationship between Y_{95} and N_{opt} for some time. Schroeder *et al*. (2005) showed results for two ratoon crops from an experiment in the Herbert region, each with a similar N_{opt} (approximately 160 kg/ha) but a 20 t/ha difference in the yield (114 and 134 t/ha) at N_{opt}. Also, Thorburn *et al*. (2017) consistently found results similar to those in Figure 2 in a large-scale simulation study of cane N responses. What we have done in this study is to show how wide-spread the phenomenon is in field experiments.

What causes the disconnection between Y_{95} and N_{opt}?

Addressing this question is helped by using a framework similar to that described for crop N requirements in the Introduction; i.e. N_{opt} is the product of (1) Y_{95} and (2) the cane N requirement, less (3) the amount of N supplied from organic sources. The second term in the framework has two components (following Thorburn *et al*., 2011): (a) the N concentration in cane, and (b) the amount of N lost to the environment, both expressed as kg N per tonne cane. For Y_{95} and N_{opt} to be well related, terms 2a, 2b and 3 in the framework need to be (relatively) constant. What do we know about their variation, or lack thereof?

Starting with term 3 in the framework, the amount of N supplied from organic sources, we might hypothesise that the crops with low N_{opt} (Figure 2) came from sites with high SOC and thus high N mineralisation potential. However, in the experimental data (Figure 2) there was no significant relationship between N_{opt} and SOC (results not shown), although there were no SOC data for many of the response curves analysed. Perhaps more telling is the variation in Y_{95} and N_{opt} in successive crops at a single site, i.e. the Tully-Coom experiment (Figure 2). The amount of organic matter should not change substantially in five successive crops at a site (unless there are changes in, say, trash management), so the variation in Y_{95} and N_{opt} across the experiment suggests that variation in N supplied from organic sources was not a significant factor in determining N_{opt}.

Unlike N supplied from organic sources, cane N concentrations can vary considerably. For example, they varied from 0.5 to 1 kg N/t cane in two successive ratoon crops at the site BK-2 of Thorburn *et al*., (2011). Similar variations in cane N concentrations in the N response curves analysed would contribute to the disconnection between Y_{95} and N_{opt}.

A third factor that may cause the disconnection between Y_{95} and N_{opt} would be variations in losses of N to the environment. N can be lost to the environment through various pathways; denitrification, leaching below the root zone and in runoff. Unfortunately there are no experiments in the Australian sugarcane industry (or any other industry to our knowledge) where losses through all these pathways have been measured. However, where losses through one of the pathways have been measured in successive, similarly managed crops, there has been substantial crop-to-crop variation (Thorburn *et al*., 2011; Webster *et al*., 2012; Rohde *et al*., 2013; Armour *et al*., 2013). So variations in environmental losses may contribute to the disconnection between Y_{95} and N_{opt}.

In the absence of comprehensive experimental data, simulations with a model such as APSIM can provide insights into the relationship (or lack thereof) between Y_{95} and N_{opt} because, in simulating crop growth and soil and crop N dynamics, the model 'calculates' crop-to-crop variation in cane N concentration, N lost to the environment and, hence, cane N requirement. In simulations of the Tully-Coom experiment (Table 2), cane N concentration varied by a factor of two between crops, N lost to the environment by more than a factor of 10 and, as a result, cane N requirement varied by a factor of three. These simulation results, together with the foregoing discussion, show clearly that there can be substantial variation in the terms 2a and 2b in the framework that relate N requirements to the yield achieved. Thus the disconnection between Y_{95} and N_{opt} should be expected, rather than a surprise.

Can we predict N_{opt}?

We have shown that crop size is not useful in predicting N_{opt}, so what is? A process-based model, like APSIM, synthesises soil and crop physiological processes, and their interactions with climate and management. These are the factors the influence N_{opt}, as discussed above. The model has been shown to accurately reproduce N responses in sugarcane (Thorburn *et al*., 2017), as well as many other crops (Holzworth *et al*., 2014). Here we showed that it can directly predict N_{opt} (Figure 1). Thus, in places where the soil, crop and management factors are adequately specified, predictions of N_{opt} will be possible. In addition, the crop-to-crop variability in cane N requirement in controlled experiments (Table 2) shows the importance of climate in determining cane N requirement, and thus N_{opt}. The importance of climate in determining cane N requirement means that a prediction of the forthcoming climate is also necessary for predicting N_{opt}.

The logic we have outlined above provides the basis of a decision support system to define optimum N rates based on process model, which could be a valuable tool in improving N fertiliser management. Developing such systems would complement other endeavours in understanding cane N management.

Conclusions

We found that there was little correlation between N_{opt} and Y_{95} in past N response experiments, and provide evidence that the result was likely due to variation in both yield potential and the amount of N needed to grow a tonne of cane.

Further, this variation is likely to be caused by year-to-year variation in climate. An implication of this result is that focussing solely on yield potential is likely to be an ineffective means of improving N management recommendations, and further, doing so could result in sugarcane yield reductions. A more fruitful means of improving N management recommendations is to predict N_{opt} directly without reliance on assumptions of yield targets.

We showed that N_{opt} could be predicted with the APSIM model. We conclude that application of this model in places where the soil, crop and management factors are adequately specified, in conjunction with forecasts of seasonal climate will be the basis of a future decision support system to better define optimum N rates.

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