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AmaizeN: A decision support system for optimizing nitrogen management of maize

F.Y. Li [a,b,*], P.R. Johnstone [a], A. Pearson [c], A. Fletcher [a], P.D. Jamieson [a], H.E. Brown [a], R.F. Zyskowski [a]

[a] New Zealand Institute for Plant & Food Research, Private Bag 4704, Christchurch, New Zealand
[b] AgResearch – Grasslands Research Centre, Tennent Drive, Private Bag 11008, Palmerston North 4442, New Zealand
[c] Foundation for Arable Research, P.O. Box 80, Lincoln, New Zealand

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ABSTRACT

AmaizeN is a decision support system to help maize growers schedule nitrogen (N) fertilizer applications for site-specific maize crops. It forecasts crop yields and N-fertilizer application rates for potential yield and best economic returns, and predicts the consequences of user management decisions. It takes into account both crop production and environmental impact. In this article we describe the system functionality and underlying crop models, and the system validity and effectiveness evaluated in 16 field trials covering a wide range of weather and soil conditions. At each trial site crops received either two or four N-fertilizer application rates, including one rate recommended by AmaizeN. The AmaizeN-predicted maize yields matched field measurements well ($r^2 = 0.77$; $p < 0.001$ for silage, and $r^2 = 0.55$; $p < 0.001$ for grain), and gave a reasonably good indication of silage crude protein content ($r^2 = 0.28$; $p < 0.001$) and silage harvest date ($r^2 = 0.71$; $p < 0.0006$). The system was also capable of estimating N-leaching during the cropping season and predicting residual soil mineral-N at the end of the season ($r^2 = 0.47$; $p < 0.001$), but more effort is needed to improve the accuracy of some predictions. In all instances the AmaizeN-recommended N-fertilizer strategy was more efficient than the growers' practice. Recommended N-fertilizer rates were on average 85 kg ha^{-1} less than conventional application rates across 10 crops, with no yield reduction. Its recommended higher-than-conventional application rate at another crop brought about a significant yield increase. System development was guided by an industry user group who requested the decision support system interface to be 'simple and easy to use'. To ensure user adoption of the system some compromises in system prediction accuracy were required. Local agricultural production conditions were also incorporated.

1. Introduction

Maize is a cost-effective supplementary feed for livestock in New Zealand, enabling farmers to increase profitability from traditional pasture-based systems [1]. Maize crops respond strongly to nitrogen (N) supply, and N-rich fertilizers are routinely applied to ensure adequate N availability. While this practice ensures high yields, it also increases the risk of nitrate leaching and groundwater contamination. To achieve economic profitability and environmental sustainability, New Zealand environmental management authorities have developed resource management rules that require farmers to provide nutrient management plans for fertilizer applications based on nutrient management planning tools [2]. A decision support tool for N-fertilizer management in maize production is required by the New Zealand maize industry.

Many crop models exist for simulating maize growth and development [3–5], and some have been incorporated into crop system simulation models or decision support systems (DSSs), such as APSIM [6] and DSSAT [7]. These models or systems have been widely used to investigate crop growth and environmental impact under a wide range of environments. Although many of them have versatile functions, they typically require a large number of parameters to be specified. Ultimately, this complexity constitutes an impediment for their uptake by farmers. Simple and easy to use DSSs with limited but clearly defined functions are highly sought after by specific groups of users. We have developed such an easy to use system for New Zealand's maize growers. The system (AmaizeN) is mainly for (1) forecasting crop yield and N-fertilizer requirements, and (2) planning N-fertilizer and irrigation applications for site-specific maize crops. Both crop yield and environmental impact are taken into account when planning management applications.

* Corresponding author at: AgResearch – Grasslands Research Centre, Tennent Drive, Private Bag 11008, Palmerston North 4442, New Zealand. Tel.: +64 6 3518190; fax: +64 6 3518032.
E-mail address: frank.li@agresearch.co.nz (F.Y. Li).

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This paper outlines the system development processes, describes system functionality and underlying crop models, reports its adequacy in predicting crop yield, crop quality and N-leaching risks against measurements from field experiments, and evaluates its effectiveness in recommending N-fertilizer rates against existing maize growers' practice. It also presents the principles or approaches built in the system for increasing usability, including an appropriate compromise between system accuracy and convenience of use, and the incorporation of regional agricultural production conditions.

2. Materials and methods

2.1. The system development process

An iterative system development process was followed during a 3-year period. A user group was formed at the start to ensure the DSS was simple and easy to use. The user group consisted of maize growers, fertilizer consultants, environment management officers, and crop researchers. Development included software development, field maize experiments, and database preparation. A system prototype with complete graphical user interface (GUI) was developed and primarily tested against measurements collected from field crops at the end of the first year, and delivered to the user group for feedback. Both the GUI and system functionality were modified during the second year, based on this feedback, and the system functionalities were validated against field experiments. The system was modified further following extensive interactions with potential users at maize field days held in key maize-growing regions during the second year. This change included reducing system functionality and simplifying system inputs to increase its usability. Two major changes were made: (1) removing the system function that generates irrigation schedules (because >90% of the maize crops in New Zealand are rainfed), and (2) reducing the sampling depth for determining soil mineral-N from 1.2 to 0.6 m. This simplification resulted in a 'light' version of the AmaizeN system, referred to as AmaizeN Lite, which deployed fewer functions and was much easier to use. All the functions of the AmaizeN system are described below, but with more details on the major functions deployed in AmaizeN Lite.

2.2. The AmaizeN system

2.2.1. System functions and database

The major function of AmaizeN is to recommend N-fertilizer and irrigation application schedules for a site-specific maize crop, and to predict crop yield and nitrate leaching risks of either system-generated or user-specified management strategies. The system can also be used to help farmers select the appropriate maize varieties, sowing date and harvest date in accordance with local weather and site-specific soil conditions.

AmaizeN is a Windows application, deployed with a database of local weather stations, general soil types and maize varieties. The weather data include: daily maximum and minimum temperatures, rainfall and solar radiation. The actual weather records of 42 stations in maize-growing areas were included, together with their 'average' weather data generated on the basis of long-term (30 years, or all years if the period of observation was shorter than 30 years) meteorological records. Up to date weather data can be added to the system during the cropping season. The system switches to the average weather from the date when actual weather data become unavailable. The general soil type data contain parameters describing soil moisture retention characteristics and soil organic matter content, which are derived from the National Soil Database of New Zealand [8]. Users may set up soil

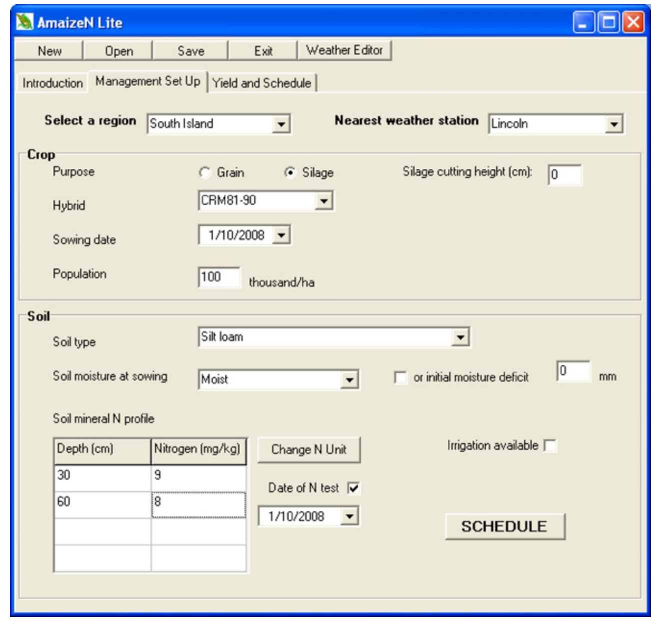

Fig. 1. Interface for management set up of the AmaizeN Lite decision support system.

profile descriptions for site-specific soil types using their knowledge and measurements. Maize variety information includes plant leaf number, and thermal time requirement of maize growth and development. New varieties are expected to be updated. If a variety is not available in the system, users may select a 'variety category' according to the CRM (comparative relative maturity ratings) range of that variety, or simply select a category variety of long, medium or short-season as an approximation.

2.2.2. System operation and outputs

When using the system, a user selects a weather station, specifies a variety, and enters sowing date and plant population, as well as the purpose of the crop (silage or grain) on the 'Management Set Up' page (Fig. 1). The user also selects the soil type, specifies initial soil moisture status, and enters the measured mineral-N content of the soil profile and the date of the soil-N test. A guide to collecting soil samples for soil mineral-N determination is deployed with the system. The user needs to specify whether irrigation is available for the field and the irrigation application rule if available. The irrigation application rule is specified in the format of applying x mm of water when soil moisture deficit reaches y mm. No irrigation application rule can be specified on AmaizeN Lite; instead, a tick on 'irrigation available' means no water deficit will be encountered during the season.

Clicking on the 'Schedule' button (Fig. 1) initiates the system simulation from the earlier date of sowing or soil mineral-N test. The simulation re-directs a user to the interface for management planning and prediction reporting ('Yield and Schedule' page of AmaizeN Lite, Fig. 2). The system outputs are:

(1) N-fertilizer and irrigation requirement and schedules: two N-fertilizer application rates are generated, one for reaching potential yield and the other for the best economic return. The costs of N-fertilizer application ($ per kg N per ha) and the price of products (cents per kg DM silage, or $ per ton of grain with an industry standard moisture content of 14%) are required for recommending the most economic rate. The N required for reaching potential yield is calculated as the difference between plant-N uptake assuming an ample N supply and the actual soil-N conditions at testing. The predicted N-fertilizer rate is split

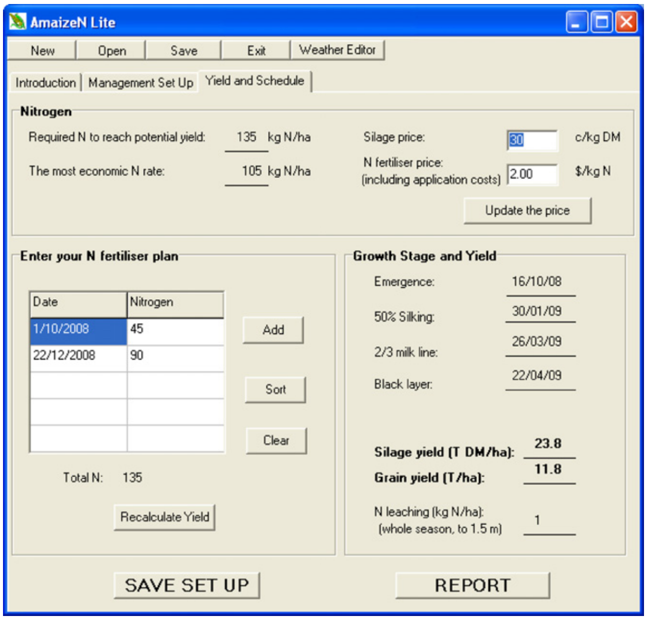

Fig. 2. Interface for management planning and prediction reporting of the AmaizeN Lite decision support system.

into two applications, one at sowing and the second approximately 6–8 weeks after sowing (V6 stage, i.e., when at least 50% of the plants show the 6th leaf collar [9]). Irrigation demand is scheduled according to user-specified application rules, and cost of irrigation application ($ per mm per ha) is also specified for calculating its economic effects.

The system allows the user to adjust N-fertilizer and irrigation application schedules according to his management experience and to investigate the likely consequences of those adjustments.

(2) Grain and silage yields, N uptake and silage quality. Crude protein content (%CP) of maize silage is estimated according to model-predicted crop-N uptake (N, kg ha^{-1}) and biomass (B, kg ha^{-1}) at an appropriate maturity for silage harvest (%CP = 6.25 × N/B).

(3) The dates of plant development stages, including the date for silage harvest. The time for silage harvest is estimated based on relationships between maize yield, dry matter content and nutritional values [10,11]. Maturity differences among maize varieties are mainly associated with development differences during the vegetative period, whereas the length of the grain-filling period is rather consistent [12]. Thus, the thermal time from silking (850 degree days; base temperature = 0 °C) is used to predict the date when the milkline is 1/3 along the kernel from the dent (1/3ML date) or 2/3 towards the cob (the date is shown as 2/3 milkline on the user interface according to the preference of maize growers, but is referred as 1/3ML date throughout this text). The predicted 1/3ML date is used to indicate the time to start assessing plant dry matter content (DM%) for silage harvest. The ideal range for ensiling silage in New Zealand is 32–37% DM.

(4) N-leaching and the end of season residual soil-N. N-leaching during the cropping season is calculated using the method of Addiscot [13], and the residual N in the soil profiles is estimated based on the measured initial status and input and output from the soil during the cropping season.

The user may save the management set up for a specific crop, view or print out a report on the management plan and associated predictions, and, on the full version, examine crop system dynamics (daily changes) in terms of plant canopy development, biomass accumulation, and soil mineral-N and soil moisture changes.

2.3. The crop system models

2.3.1. Plant model

The core of the AmaizeN system is a daily time step simulation model of plant–soil systems in response to variable weather conditions and different management scenarios. The plant model is an extension of the maize potential growth model of Muchow et al. [4] and Wilson et al. [14]. In the model a maize variety is defined by its number of leaves, the area of its largest leaf, and the thermal durations of various phenological stages. Canopy development was calculated according to the leaf area of each leaf and leaf appearance rate multiplied by plant population. Biomass accumulation was the product of the canopy intercepted solar radiation and radiation use efficiency (RUE), which is affected by temperature. Biomass is partitioned to grain in the reproductive stage with a linear increase of harvest index [4,14].

The changes to the original potential growth model were detailed in Li et al. [15]. Briefly, they include the estimation of the leaf area of the largest leaf of a variety (previously an input), the addition of plant population effects on plant leaf area, and the addition of a root system. Mechanisms to quantify crop water and N demand and the effects of water and N limitations were added to the potential growth model. Plant-N uptake was allocated into four pools [16,17]: structural N, leaf-N, labile N, and grain-N. Plant-N demand was calculated as the sum of the N demand for various plant tissue components. During the vegetative development phase, N uptake was allocated to the N pools in a priority order of structural N, leaf-N, and labile N. Under N limitation, the daily green area index increment (ΔGAI) was reduced to what the N could support after meeting the needs of structural growth. Under extreme N deficiency, leaf-N was remobilized and re-allocated, resulting in a GAI reduction. During the grain-filling period, N movement was driven by the demand of grain growth, and N in vegetative tissue was remobilized and redistributed into grain. If N was insufficient, labile N stored in the stem was remobilized to the grain rather than new mineral-N taken up from the soil. When labile N was exhausted and soil-N uptake was insufficient, leaf senescence was accelerated to release more N for grain growth. This would result in a loss of GAI and a subsequent reduction of biomass accumulation.

2.3.2. Soil moisture

Soil moisture and mineral-N dynamics were simulated using the same method as in the Sirius wheat model [18], and are similar to those in the CERES-Maize model [3]. Briefly, the amount of soil moisture in the root zone was calculated as the balance between water input (precipitation and irrigation) and output (evapotranspiration and drainage). Evaportranspiration was calculated using the Priestley–Taylor method, and water percolation in the soil profile was simulated using the method of Addiscot [13]. Within any soil layer, water is present in three phases: unavailable (below the lower limit of extraction), available immobile (between the lower limit of extraction and the drained upper limit) and mobile (between the drained upper limit and saturation). Plant available water holding capacity per layer was defined as the capacity of the available immobile phase, whereas actual plant available water was the sum of available immobile and mobile phase in the root zone. Moisture-stress effects on plant growth were modelled by reducing daily leaf expansion, accelerating leaf senescence, and reducing RUE.

2.3.3. Soil mineral-N

Simulation of soil mineral-N dynamics included the mineralization of soil organic-N, N-leaching coupled with water percolation,

Table 1
Field crops with variable N-fertilization rates.

Site	Crop	Variety	Sowing date	Plant pop ($\times 10^3$ ha^{-1})	Initial N[a] (kg ha^{-1})	N-fertilizer rate (kg ha^{-1})[b]			
						Low	Amaize	Farmer	High
2005–2006 season									
Bay of Plenty	B05	N59Q9	15/10/05	92	55	36	121	174	256
Gisborne	G05	38P05	10/09/05	95	93	36	136	169	336
Hamilton	H05	34D71	07/11/05	102	80	78	140	203	300
Manawatu	M05	38P05	19/10/05	93	115	45	140	203	300
TeAwamutu	T05	33J24	10/10/05	97	134	(189)[c]	119	257	399
2006–2007 season									
Bay of Plenty	B06	33J24	07/10/06	80	36	–	232	174	–
Gisborne	G06	N4187	23/09/06	103	63	–	175	221	–
Hamilton	H06	34D71	19/10/06	110	65	122	242	159	361
Huntly	HL06	38P05	17/10/06	92	340	–	54	169	–
Hastings	HS06	36H36	21/10/06	90	78	–	165	–	–
Manawatu	M06	38P05	23/11/06	93	122	–	82	174	–
Northland	N06	36B08	15/10/06	87	91	–	152	198	–
Opiki	O06	38P05	15/10/06	105	95	(278)[d]	220	174	335
Taranaki	TR06	36M28	19/10/06	105	228	–	128	266	–
Waikato	W06	36M28	14/10/06	97	114	–	73	188	–
Chertsey[e]	C06	Prinz	31/10/06	113	69	24	79	134	224

[a] Soil mineral-N content in a soil profile of 1.2 m prior to planting.
[b] Four N treatments: AmaizeN's recommendation, farmer practice (Farmer), low N and high N.
[c] Since AmaizeN's recommendation is lower than the farmer's starter N-fertilizer application, another N rate between Amaize N and Farmer N was set, but not used as low N treatment in the analysis.
[d] Farmer applied rate on all the sites, eliminating the possibility of low rate, so a rate between Amaize and high rates was decided in its place.
[e] The crop on the experimental farm received full irrigation and four N-fertilizer rates (the N rate in column 'Farmer' was not decided by farmers). The data set was used in [15] for comparing different approaches in quantifying crop-N demand and N-deficit effects.

N-fertilizer application and estimation of gaseous N loss and plant-N uptake [18]. Plant-N uptake was driven by demand, but limited by soil mineral-N availability. To accurately simulate soil mineral-N dynamics, determining the initial mineral-N content in the soil profile to a depth of 1.2 m is required. The mineral-N amount (kg N ha^{-1}) in each soil layer was calculated according to the tested mineral-N content (ppm) and soil bulk density. Whereas the importance of measuring mineral-N content in deep soil layers was well recognized, using the system without testing deep soil-N content was favoured by potential users. To achieve this an approach was incorporated in the system for estimating soil mineral-N content in the whole soil profile when only topsoil-N is determined. The estimate was done using the general pattern of soil mineral-N profile as well as actual measurements of topsoil-N. The general pattern of the soil-N profile (median values of the soil mineral-N in each layer) was drawn from an independent soil mineral-N data set from a survey of 63 maize fields across major maize-growing regions of New Zealand [19].

2.4. Field experiments

The system was initially tested against four field-grown maize crops [20]. In the present study a data set of 16 maize crops grown across a wide range of weather and soil conditions that received different N-fertilizer treatments were used to validate the predictions and examine the effectiveness of the AmaizeN system (Table 1). Most of the crops (except C06 and HS06) were grown on farmers' fields and managed by farmers using their own standard practice, except for N-fertilizer application at side-dressing. The system was designed to recommend applying all N-fertilizer required by a crop in two applications, one at sowing and one in the V6 stage as side-dressing. This approach is due to two factors. Firstly, N uptake by maize from emergence through to the V6 stage only represents about 5% of the total plant-N uptake and rapid N uptake takes place between the V8 stage and silking [9]. Secondly, plant height after the V6 stage makes it difficult to apply fertilizer with tractor-mounted spreaders. Accordingly, different N rates were tested in the field experiments by manipulating the amount of N applied as side-dressing. At 7 of the farmers' sites (Table 1), 20 plots were marked out in a randomized complete block design for an N-application experiment with 4 treatments and 5 replicates. The treatments were: (1) AmaizeN-recommended N-application (designated AmaizeN), (2) farmer practice N (FarmerN), (3) low N, and (4) high N. At the remaining seven farmers' sites, two N-fertilizer treatments, AmaizeN or FarmerN, were compared by designating two AmaizeN strips within the otherwise farmer-managed field. Plant and soil measurements were taken on six paired comparisons of the two N treatments. Crops HS06 and C06 were on experimental farms. Crop C06 (at Chertsey) was a randomized complete block design for an N-application experiment with four treatments and four replicates, whereas HS06 (at Hastings) received only one N-fertilizer rate as per AmaizeN recommendation (six replicates). Crop C06 was fully irrigated, but the other 15 crops were rainfed only. Side-dressed N was applied as granulated urea. N-application rates are summarized in Table 1.

2.4.1. Soil measurements

Soil samples were taken at each site prior to sowing and applying the starter fertilizers. The soil samples to determine mineral-N were taken to a depth of 1.2 m in 30-cm increments. Five samples were taken at each site. Total soil mineral-N (NO_3-N and NH_4-N) was determined colorimetrically following 2 M KCl extraction [21]. An additional composite sample of twenty 0–15 cm cores was collected from each site to determine basic soil fertility properties (soil pH, P-Olsen, exchangeable cations, soil organic matter, total C and total N), using standard methods. Following the grain harvest at the end of the season, soil mineral-N was measured again using the same method on a composite sample collected from the plant row and the mid-row in each N-treatment plot at each site.

2.4.2. Crop measurements

Standing biomass and its N content at the time of silage harvest and grain harvest were determined. The plants in two adjacent rows of 2.5 m length were counted and harvested; 10 plants were retained and divided into live leaves, dead leaves, stem and ear, which were subsequently weighed. To calculate dry matter content a mulched subsample of each component was weighed fresh and oven-dried at 70 °C until constant weight was reached. N content of each subsample was determined using the Dumas combustion method [22]. Total N was converted into crude protein content (%CP) using the standard conversion factor 6.25.

2.5. Simulation control and data analysis

Actual crop management information, site-specific soil descriptions, and weather data recorded during the season were provided to AmaizeN for simulating all the treatments over the 16 crop sites. Soil profiles were described based on the general soil type but adjusted using the pre-season measurements. Weather data were obtained from on-site or the closest weather stations (mostly within 40 km from the experimental sites).

System predictions were compared with actual measurements from these crops, in terms of crop yield (silage and grain), silage %CP and harvest date, as well as the end of season residual mineral-N content in the soil profiles. N-leaching during the cropping season was not measured; AmaizeN yields N-leaching data during the cropping season using the soil model tested for N-leaching under other crops [13,23].

A one-way ANOVA was used to analyse the measured crop yield and the residual mineral-N in the soil profiles of each crop under the different N treatments, and examine the effects of the N treatments. Linear regression and root mean square deviation (RMSD) were used to compare AmaizeN predictions with measurements. All statistical analyses were done using GenStat 8 [24].

3. Results

3.1. Validity of AmaizeN predictions

3.1.1. Crop yield

Measured standing biomass at silage harvest ranged from 15.1 to 27.2 t DM ha^{-1}, and grain yields ranged from 7.9 to 14.5 t DM ha^{-1}. The effects of N fertilization on both silage and grain production were statistically significant for 5 of the 14 measured crops (B05, G05, H05, B06 and TR06; Table 2). Effects could not be tested for the two crops HL06 and HS06, the first one having no silage harvest, the second one having received only one N-fertilizer application. The silage (S) and grain (G) yields predicted by the system matched well with the corresponding measured values (M) (Fig. 3). The regressions $S = 2.7 + 0.91 \times M$ ($r^2 = 0.77$; $p < 0.001$; RMSD = 1.7 t ha^{-1}) and $G = 2.5 + 0.79 \times M$ ($r^2 = 0.51$; $p < 0.001$; RMSD = 1.3 t ha^{-1}) were not significantly different (F.pr. > 0.2) from the regressions with a forced slope of 1. The system slightly overestimated silage yield (0.7 t ha^{-1} on average) but not grain yield.

3.1.2. Crop N uptake and silage crude protein content

The model-predicted (P) crop-N uptake was significantly correlated with measurements (M) ($P = 75.6 + 0.702 \times M$, $p < 0.0001$), but the prediction had a large deviation ($r^2 = 0.32$, RMSD = 39 kg ha^{-1}). Results from the first year [20] showed that measured plant %CP at silage harvest increased significantly with higher N-fertilizer application rates, and that model-predicted plant-N uptake and biomass accumulation can be used to predict %CP of maize silage. Over the whole data set of 16 crops, the model-predicted maize %CP at silage harvest was also significantly correlated with %CP calculated from measured plant biomass and N content ($p < 0.001$), but its predictability was weak with a large deviation ($r^2 = 0.28$; RMSD = 0.73%).

3.1.3. Silage harvest dates

The AmaizeN-predicted 1/3ML dates, actual silage harvest dates and the DM% of harvested silage are shown in Table 2. For most of the crops, DM% was in the range suitable for silage use. Three crops, C06, M06 and TR06, harvested earlier than the 1/3ML date, had a low silage DM%. Crop O06 was harvested markedly later than the 1/3ML date, with a high DM% (Table 2). On the whole, DM% increased with the number of days (D) harvesting was delayed beyond the predicted 1/3ML date (DM% = $34.1 + 0.27 \times D$, $r^2 = 0.71$; $p = 0.0006$; excluding one outlier measured at T05). This relationship suggests that the predicted 1/3ML date is a reasonably good indication for the time to determine DM% for silage harvest.

Table 2
Standing biomass at silage harvest under various N applications, and silage harvest date compared with 1/3 milkline date predicted by the model.

Crop	Yield (t DM ha^{-1})				Diff.[a] F.pr.	LSD$_{0.05}$ (d.f.)	1/3ML date	Harvest date	Days diff.[b]	DM %
	Low	Amaize	Farmer	High						
2005–2006 season										
B05	21.4	24.7	27.2	26.8	0.004	3.2 (12)	09/03/06	14/03/06	5	37
G05[c]	18.2	22.2	22.4	22.4	0.001	1.8 (12)	–			
H05	17.9	20.2	23.3	21.8	0.380	6.2 (12)	02/04/06	04/04/06	2	33
M05	16.7	20.5	20.5	21.9	0.070	4.1 (12)	19/03/06	21/03/06	2	37
T05	20.8	20.3	21.2	20.7	0.980	4.7 (12)	17/03/06	24/03/06	7	30
2006–2007 season										
B06	–	24.5	22.2	–	0.010	1.5 (5)	09/03/07	15/03/07	6	38
G06	–	26.3	26.2	–	0.960	2.7 (5)	17/02/07	22/02/07	5	35
H06	26.6	27.0	27.0	24.6	0.247	2.9 (12)	25/03/07	27/03/07	2	34
HL06[d]	–	–	–	–	–	–	–	–		–
HS06	–	23.9	–	–	–	–	13/03/07	06/03/07	−7	31
M06[e]	–	17.6	18.4	–	0.339	1.8 (5)	30/04/07	17/04/07	−13	31
N06[c]	–	21.3	22.7	–	0.520	5.9 (3)	–			
O06	20.1	18.7	20.3	21.1	0.104	1.9 (12)	30/03/07	17/04/07	17	37
TR06	–	23.2	24.0	–	0.089	1.0 (5)	30/03/07	26/03/07	−4	31
W06	–	24.6	23.6	–	0.608	4.5 (5)	19/03/07	27/03/07	2	36
C06[e]	17.1	16.5	15.7	16.5	0.574	2.2 (9)	28/04/07	12/04/07	−16	30

[a] Statistical significance of the difference among N treatments (F-test probability).
[b] Days diff.: number of days between the predicted 1/3ML date and the actual date for silage harvest. A negative number indicates actual harvest before the predicted date.
[c] No silage harvest on crop G05 and N06. The silage yield was estimated from the crop biomass at grain harvest (harvest index = 0.5).
[d] Only grain yield was determined on crop HL06, with no statistically significant difference between AmaizeN and farmer's rate (7.8 and 7.9 t ha^{-1}, respectively).
[e] Harvest of crop M06 and C06 was early to avoid frost.

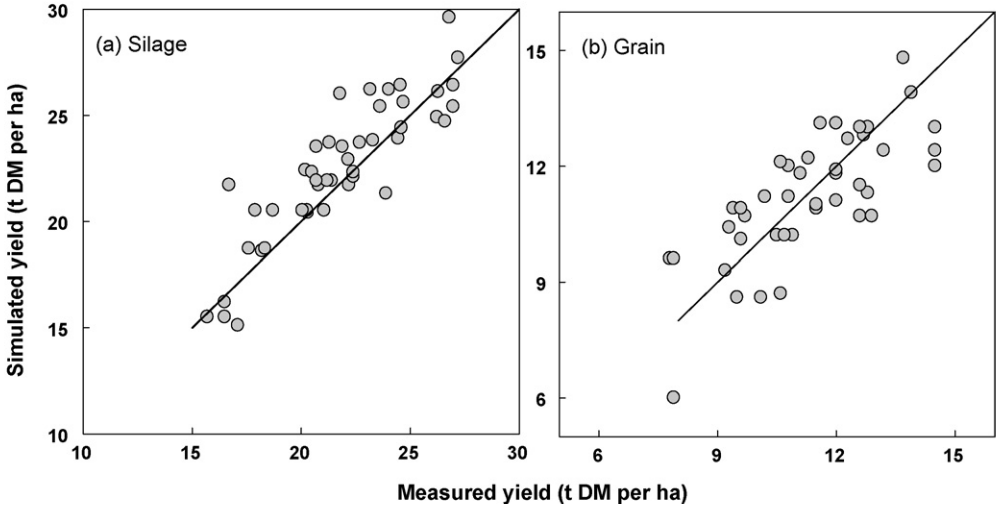

Fig. 3. Comparison of mean measured silage (a) and grain (b) yield with yields predicted by the AmaizeN for 16 maize crops under different N treatments.

3.1.4. *N-leaching and the end of season soil mineral-N*

More N-fertilizer generally resulted in higher residual soil mineral-N contents at the end of the cropping season (Table 3). The differences in residual soil mineral-N between the HighN and LowN treatments were statistically significant (i.e., <$LSD_{0.05}$) for five of the eight crops that received four N treatments (B05, G05, H05, H06, and O06; Table 3). However, the differences between AmaizeN and FarmerN treatments were not statistically significant (i.e., >$LSD_{0.05}$), except at two sites (H06 and O06). These non-significant differences between AmaizeN and FarmerN might partly be related to the higher plant-N uptake and the increased N emission and leaching under the higher N-fertilizer rates. In addition, the number of soil samples may have been insufficient to account for soil heterogeneity and possible unevenness of applied N-fertilizer (as shown by the large standard errors in Fig. 4).

Prediction of the total amount of residual soil mineral-N at harvest was more important than prediction of N-leaching during the cropping season, because most drainage and N-leaching in New Zealand's major maize-growing regions occurs during winter time when precipitation exceeds potential evapotranspiration [25]. Using the measured pre-planting soil mineral-N profile, the AmaizeN-predicted soil mineral-N profile at the end of the cropping season matched the end of season measurements (Fig. 4). There was a statistically significant linear correlation between the predicted and measured values ($r^2 = 0.47$; $p < 0.001$), but the prediction had a large deviation (RSMD = 51 kg ha^{-1}). This deviation might have reflected inherent within-field variability and inevitable model compromises with actual crop conditions. The model predicted that the soil mineral-N distribution profile under different N-fertilizer rates also matched field measurements reasonably well [19].

AmaizeN also gave an estimate of N-leaching (passing beyond a depth of 1.5 m) during the cropping season. No N-leaching data were collected in the experiments. The model-predicted N-leaching showed that statistically significant N-leaching during the maize cropping season occurred under a few crops only (Fig. 5), which was related to stormy-rainfall events (e.g., G05 and O06), or to a high soil mineral-N content, especially in the deeper soil layers (e.g., TR06 and HL06) at the beginning of the cropping season. N-leaching of crop C06 in the early season might be related to the irrigation applied to this crop. It was also suggested that N-leaching occurred mainly early in the maize cropping season when rainfall exceeded evapotranspiration, nitrate was already in the soil profile, and the crop roots were shallow and not yet able to recover all the N. Except during a heavy-rain event, N-fertilizer applied as side-

Table 3
Residual soil mineral-N contents (kg ha^{-1}) in the profile to a depth of 1.2 m under different N treatments at the end of crop season.

Crop	Low	Amaize	Farmer	High	F.pr.	$LSD_{0.05}$ (d.f.)
B05	34	44	49	51	0.061	13(11)
G05	62	63	72	124	0.057	50(12)
H05	55	52	73	110	0.001	14(12)
M05	81	87	92	94	0.757	27(12)
T05	166	120	159	182	0.593	99(12)
B06	–	35	32	–	0.394	9(5)
G06	–	44	86	–	0.146	63(5)
H06	108	219	138	265	0.021	102(12)
HL06	–	180	213	–	0.172	59(3)
M06	–	167	120	–	0.084	55(5)
N06	–	68	85	–	0.173	28(5)
O06	(104)	114	82	158	0.084	27(12)
TR06	–	150	225	–	0.261	154(5)
W06	–	50	82	–	0.098	41(5)
C06	57	77	61	75	0.467	34(9)

Note: Pre-planting N (in Table 1) is the same across all N treatments at a site, so it is not included in the analysis. No mineral-N measurements at site HS06, and the measurement at C06 was only to 90 cm.

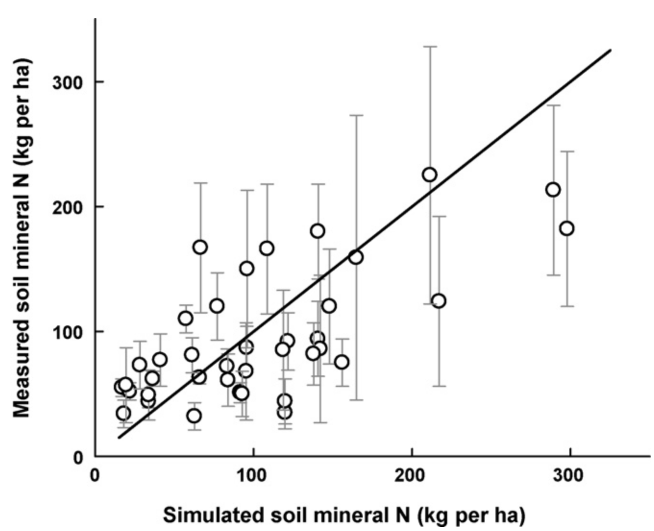

Fig. 4. Comparison of simulated and measured mineral-N contents in the soil profile to a depth of 1.2 m at the end of the season. The vertical bars are one standard deviation, and the diagonal is the 1:1 line (the results on the peaty soil sites are excluded).

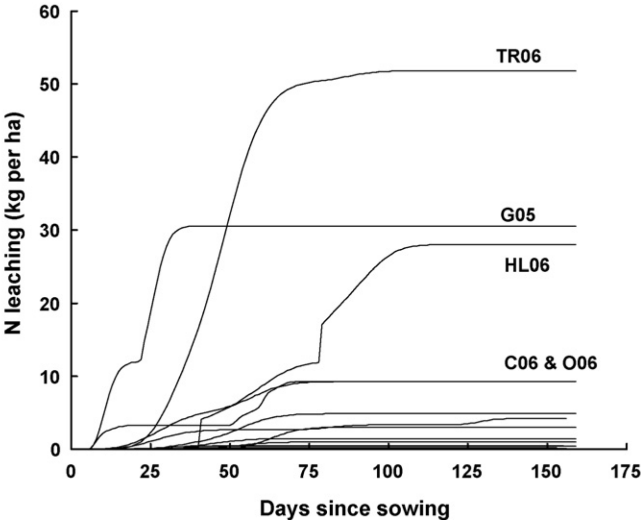

Fig. 5. Simulated N-leaching dynamics under the experimental crops. Except for the five labelled crops, the leaching was <5 kg N ha^{-1}.

dressing to the rainfed maize crops studied would not have leached beyond a soil depth of 1.5 m, but would increase the N retained in the soil profile at the end of the season, thereby increasing the N-leaching risks in winter.

3.1.5. Effectiveness in recommending N-fertilizer applications

The AmaizeN-recommended N-application rate was higher than the farmer's rate (FarmerN) in three crops: B06, H06 and O06 (Table 1). This higher N rate resulted in a significantly higher yield of crop B06, but not of crops H06 and O06, which were on peaty soils (Table 2). For crop N06, the AmaizeN-recommended rate was the same as FarmerN (152 kg N ha^{-1}), so in that case a higher N rate was applied on the experimental strips (198 kg N ha^{-1}), which gave no yield increase as expected. For the remaining 10 crops on farmers' properties, AmaizeN-recommended N rates averaged 85 kg N ha^{-1} less than FarmerN, but caused no statistically significant yield reductions ($p > 0.05$ for the 10 crops, Table 2). The effectiveness of AmaizeN in calculating N-fertilizer demand was shown clearly in two crops: W06 and TR06. These received 115 and 138 kg N ha^{-1}, respectively, as side-dressings, using farmer management, but received none in the experimental strips according to AmaizeN recommendations. No difference was found in crop yield between the two N treatments in these two crops (Table 2).

4. Discussion

4.1. The plant–soil system model

N-deficit effects on maize growth were modelled by reducing GAI, similar to the methods used in the wheat models of Sinclair and Amir [16] and Jamieson et al. [17]. Experimental measurements have shown that both GAI reduction and specific leaf-nitrogen (SLN) dilution occur under N limitation, but maize was more sensitive to SLN dilution [26,27]. However, model-predicted crop yield and N uptake were insensitive to the methods used for quantifying N-deficit effects, either by reducing GAI only or by reducing both GAI and SLN, because the effects of GAI reduction and SLN dilution on biomass compensate for each other [15].

AmaizeN slightly overestimated the silage yield, but not the grain yield. It appears that the harvest index (HI) was higher than the value of 0.5 that was assumed in the model [4]. For all crops with measurements of silage, grain and final biomass, the pooled average HI was 0.52. The model-predicted 1/3ML date based on thermal time gave a reasonably good indication to farmers of the time for preparing for silage harvest, but incorporating in-season weather factors (e.g., rainfall or soil moisture conditions) in the forecasting processes would improve the prediction, because wet and cool weather may slow down the crop dry-down rate [12].

The different N-fertilizer application rates had only statistically significant effects on the yield of 5 of the 14 crops studied. The non-significance suggests that more than required N-fertilizer had been applied on many crops. For crop sites that received only two N-fertilizer rates (AmaizeN and FarmerN) the yield differences were mostly statistically significant (except for crop B06, Table 2), providing evidence that AmaizeN was effective in recommending N-fertilizer application rates since most of AmaizeN rates were lower than Farmer's rates.

The results show that the AmaizeN system did not work well on peaty soils. The estimated reference mineralization rate of soil organic-N appeared to be biased in these instances when using the semi-mechanistic model of N mineralization [18,28]. More research is needed on the N processes in peaty soils for application of the system in these situations.

4.2. Balance accuracy and convenience

To turn a simulation model into a model-driven decision support system, accurate simulation of the soil dynamics and crop growth is only one aspect. An appropriate compromise between accuracy and convenience of use is necessary. The prediction of the AmaizeN system was very sensitive to soil parameters, especially those describing soil-water retention characteristics. This matched the results of the simulation research of Lawless et al. [29]. Using an accurate description of the soil profile based on measurements at a given site, including measuring pre-planting soil mineral-N to a depth of 1.2 m, will give the most accurate predictions of yield and environmental impact, but is laborious. In response to the requests of users to reduce the number of soil measurements required to set up soil profile descriptions, generalized soil types were deployed within the system. Additionally, a general pattern of soil mineral-N profiles in maize-growing regions was built into the system; these were used to estimate soil mineral-N in the subsoil (below 30 or 60 cm) if only N in the topsoil (to 30 or 60 cm) was determined [19]. The estimation using this method was reasonably good. For the 15 field sites (one site was excluded where N was measured to 90 cm), when soil mineral-N was measured to a depth of 30 cm, the estimated soil mineral-N for a profile of 1.2 m matched well with measured values at the 12 sites (RSMD = 23 kg N ha^{-1}, RSMD/mean = 19%); when measured to a depth of 60 cm, the match was improved (RSMD = 16 kg N ha^{-1}, RMSD/mean = 13%). The larger deviation of the estimated compared with the measured soil mineral-N content at the three other sites was due to significant differences in their soil mineral-N profiles from the 'median' pattern. More accurate estimates of soil mineral-N deep in the soil profile may be achievable by incorporating soil types and previous land use history into the estimation methods [19]. The reduction of system parameter inputs, which was requested by users, did sacrifice some accuracy but was expected to increase user adoption of the system.

4.3. Simple user interface

The user interface and functionalities of the AmaizeN system evolved during its development, culminating in two versions. All the system functions of the light version (AmaizeN Lite) are accessible in the full version. However, users strongly prefer the light version, which provides a simple interface and a limited number of functions. One of the major functions of the AmaizeN system is to simultaneously generate N-fertilizer and irrigation application schedules during the cropping season, using up to date weather data and incorporating up to date management applications. Users can let the system generate N-fertilizer application schedules for a cropping season by specifying 'schedule for nitrogen' only, 'irrigation unavailable', and 'new schedule' (meaning a schedule for the whole cropping season, and not for the period from a date during the cropping season). But these operations and the grid used for irrigation schedules on the interface were considered complex and redundant for users who grow rainfed maize crops.

Another function of the AmaizeN system is allowing user to adjust plant silking date. That is, user may adjust the silking date during the season to align system prediction with reality. This is important for the prediction of crop maturity for silage harvest, especially if the variety information is not complete (e.g., using a CRM range to approximate the variety). But this function is not favoured by most of the users who are interested only in N-fertilizer application schedules. Deployment of limited functions on a simple user interface has enhanced the uptake of this technology.

5. Conclusions

The AmaizeN-predicted maize silage or grain yields matched measured yields well, and gave reasonably good prediction of silage crude protein content and silage harvest date. The system was also capable of estimating N-leaching during the crop season and predicting residual soil mineral-N at the end of the season, but more research is required to improve the accuracy and precision of some predictions. Using the tool to quantify crop N-fertilizer requirement resulted in more efficient and environmentally sound N-fertilizer management. A reasonable compromise between system prediction accuracy and convenience of use, and incorporation of local agricultural production conditions are necessary for effective user adoption of the system.

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