AmaizeN: developing a decision-support tool to optimise nitrogen management of maize

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Abstract

A decision-support system (DSS) for optimising nitrogen management is being developed for maize crops. The tool (AmaizeN) incorporates a mechanistic model of maize growth and development including the response of maize to water and N deficit. It simulates the daily dynamics of the plant-soil system, including the nitrogen and water flows, according to user-input site-specific weather and soil conditions, and traits of maize hybrids. The tool then outputs nitrogen fertilisation recommendations plus associated economic and environmental consequences. The interactive interface allows users to test various management scenarios before and during the crop season, and to examine the outcomes to inform their decisions.

During the 2005-06 maize growing season, crops at five sites in the North Island were managed using either AmaizeN (version 0.9) or conventional best management. Crop phenological and leaf area development were monitored, silage and grain yield and quality were measured, together with soil mineral N status at the beginning and the end of the season. Comparisons were made between observations and AmaizeN simulations for all treatments. AmaizeN prediction on silage production, silage protein contents and grain yields matched measurements well for four of the five trial crops. At the other site, yields were well below potential, both in terms of the simulations and in comparison with the other sites. The reason for the low yields is discussed in terms of effects of plant population and soil properties, but further investigation is required to determine the causes. Overcoming the constraint could lead to substantial production gains.

Additional keywords: decision-support system, grain yield, silage yield, crude protein.

Introduction

Increasingly, crop management aims at optimising economic returns while minimising environmental problems. Decision support systems (DSS) are being developed to calculate or predict the consequences of different crop management scenarios and for recommending the best management. Following the development and deployment of two crop calculators to improve N management in wheat and potato crops (Jamieson *et al*., 1998; Jamieson *et al*., 2003; Armour *et al*., 2004), we have developed a new tool, the AmaizeN Calculator, for optimising N management of maize crops for both silage and grain. The effectiveness and accuracy of AmaizeN is being evaluated on farms as part of a Sustainable Farming Fund project.

In this paper we report the results of the first year of this project. This includes a description of the AmaizeN system and its embedded crop-soil models, the scenarios that the system uses, and the performance of AmaizeN-managed crops compared with those managed conventionally in five maize crops in the North Island during the 2005-06 season. Our intention is to use these results to update the AmaizeN Calculator, and another objective is to identify constraints to production that are not specifically addressed by AmaizeN.

Description of the AmaizeN calculator

Simulation models

The AmaizeN Calculator is a model-driven DSS. The core of the system is the day-time step simulation model of maize growth and development, driven by solar radiation and interacting with soils. The maize simulation model is an extension of the maize potential production model of Muchow *et al,* (1990) as modified for cooler conditions by Wilson *et al*. (1995). The extension was to include dynamic plant-soil interactions under variable water and N conditions as in the Sirius Wheat model (Jamieson *et al*., 1998), with allocation of N among tissue categories within the crop based on the allocation mechanism described for wheat by Jamieson & Semenov (2000). For maize, we assume that N is allocated to leaf according to a constant specific leaf N concentration of 1.5 g N/m^2, of which 0.4 g N/m^2 is structural that will be retained in leaf after senescence. Similarly, structural N in stem is a constant proportion of stem biomass (2.5 g N/kg biomass), and labile N storage in stem fluctuates between 0 and 12.5 g N/kg biomass. Minimum N concentration in grain is 11 g N/kg biomass, but can reach 16 g N/kg biomass when N is not limited. Shortages of N result in reduced leaf area compared with potential, and in accelerated leaf senescence as N is used up by transfer to structure and grain. During grain-filling, labile N in stems is deemed easier to use by grains than N from soil. The soil model also simulates soil moisture dynamics that affect crop growth directly, but also indirectly by affecting soil N turnover and movement. The model differs from an earlier Maize Calculator reported by Reid *et al*. (1999) that used an empirical N-response curve for optimising N application. In addition, the effects of plant density on maize production were incorporated in the model based on published experimental data (Zoltan and Lap, 2004).

System inputs

A maize crop is defined by its hybrid and planting variables. The hybrid parameters include the number of the leaves (L), the thermal durations from sowing to emergence (GDM), from last leaf to silking (GDS) and from silking to start of grainfill (GDLAG). The original maize potential model needs to specify the leaf area of the largest leaf (Muchow *et al.,* 1990), whereas the leaf area of the largest leaf in our model is calculated from the number of the leaves of the hybrid using a regression relation built on the data of 28 hybrids.

The planting variables include sowing date and population, as well as weather and soil conditions. Weather inputs are daily solar radiation, rainfall, and maximum and minimum temperature. Soil parameters include soil organic N content, initial mineral N in the soil profile, soil water-holding capacity, water permeability, and initial water deficit. As one of the calculator series developed by Crop & Food Research, the AmaizeN uses the same soil description as the Sirius Wheat Calculator and the Potato Calculator.

User interface and use scenarios

The calculator uploads weather and soil description data directly from weather and soil databases, and a user-friendly graphical user interface is built for users to specify the crop and soil parameters with more variable characteristics, such as maize hybrid, sowing date and population, the initial soil mineral N contents, fertilizer price, etc. The AmaizeN has two user cases, as follows. (1) Recommending the N application schedule for a best yield based on up-to-date weather and soil conditions, as well as the specification of the crop management, and giving the associated financial and environmental impact analysis. Previous research showed that N application method had no effects on maize yield when the N amount was sufficient (Pearson *et al*., 2004), but might have different environmental effects. Currently, the latest time of N application is set at the V8 stage of maize crop for practical purposes. (2) Advising yield and environmental impact for any user-specified N application schedule based on their crop management experience and actual availability of labour and time. The calculator also outputs a series of graphs showing crop canopy development, biomass and grain yield accumulation, and soil N and moisture dynamics to support users in informed decision-making.

Experimental crops

Crops on the five sites in the North Island were managed using AmaizeN (version 0.9) or by conventional best management during the 2005-06 maize growing season to validate and calibrate the AmaizeN calculator. The five trial sites were on five farmers' crops and their planting variables are summarised in Table 1. All crops were sown at an intended population of around 90,000 plants/ha, with starter fertilisers, and managed by farmers according to their management decisions, except for N application in the designated experimental blocks.

In each farmer's crop, a trial site of 20 blocks was arranged in a randomised complete block design (four N treatments × five replicates). The block size was 15 m ×11 rows for crops at Hamilton, and 10 m × 8 rows for crops at the other four sites.

Table 1. Hybrids, sowing dates and starter fertiliser application of the five experimental crops.

Site	Code	Hybrids	Plant date	Starter fertiliser type and rate(kg/ha)
Bay of Plenty	B	Corson N59-Q9	15/09/2005	DAP@200
Gisborne	G	Pioneer 38P05	10/09/2005	Cropmaster20@186
Hamilton	H	Pioneer 34D71	7/11/2005	12N:10P:10K@200
Manawatu	M	Pioneer 38P05	19/10/2005	15N:10P:10K:6S@300
Te Awamutu	T	Pioneer 33J24	19/10/2005	DAP@150

The pre-planting soil mineral N contents were measured to a depth of 1.2 m at each trial sites (Table 2), which was used to calculate the amount of additional nitrogen needed by the crops before the maize growing season, assuming that the crop would experience average weather conditions. The weather data used are from the closest weather stations, managed by either FAR or NIWA.

Table 2. Soil types, organic matter content (SOM, to 30 cm), C:N ratio (to 30 cm) and mineral N contents (to 120 cm) at five maize trial sites

Crop	Soil type	SOM(%)	C:N	N(kg/ha)
B	Paroa silt loam on peat on grave	8.4	11.0	55
G	Waihirere heavy silt loam	4.3	8.5	93
H	Te Rapa peaty loam	24.0	23.2	80
M	Kairanga fine sandy loam	3.2	9.2	115
T	Ohaupo silt loam	8.6	9.5	134

The four N treatments in the trial represent the AmaizeN calculator recommended N application (AmaizeN), the farmers' best conventional N application (FarmerN), and low and high N applications. Actual amounts of fertiliser varied among sites in response to initial soil mineral N tests (Table 3), but in all cases, AmaizeN recommendations were for less N to be applied than was planned by the farmers. The total N applications were split into two - one at planting and the other at the V8 stage as a side-dressing.

Table 3. Total N application on the five experimental crops (kg N/ha).

Treatment	B	G	H	M	T
LowN	36	36	78	45	189
AmaizeN	121	136	140	125	119
FarmerN	174	169	203	188	257
HighN	256	336	300	225	399

Crop phenological development and leaf area were monitored, and silage and grain yield were measured, together with soil mineral N status, at the beginning and end of the season. These observed or measured results were compared with the predictions of the AmaizeN Calculator using the actual parameters of the hybrids, soil and weather conditions.

The efficiency of the AmaizeN-generated management schedules was assessed by comparing the crop performance managed by AmaizeN with that under conventional management. The validity of the AmaizeN calculator, as well as of its embedded crop-soil model, was examined by comparing the AmaizeN prediction with the measurements.

Results

Validity and efficiency of the AmaizeN Calculator

Measured silage and grain yields

Measured silage yields ranged from 16.7 to 27.2 t/ha. The significant effects of N application on silage yield were observed in crops B and G, and also in crop M with less significance (Table 4). Measured grain yields ranged from 9.0 to 15.8 t/ha. Yield was also significantly increased by N application for the three crops B, G and H, but was not significantly changed for two other crops.

The grain and silage yields were not significantly higher under FarmerN than AmaizeN management, though more N was applied.

Table 4. Silage yield (t/ha, dry matter) and grain yield (t/ha, with 14% moisture as per industry standard) under the four N applications on the five experimental maize crops.

Crops	B		G		H		M		T	
N treatment	silage	grain	silage[1]	grain	silage	grain	silage	grain	silage	grain
LowN	21.4	12.1	18.2	10.5	17.9	9.0	16.7	10.6	20.8	11.1
AmaizeN	24.7	14.5	22.2	13.1	20.2	11.6	20.5	12.3	20.3	10.9
FarmerN	27.2	15.8	22.4	13.1	23.3	13.7	21.9	12.3	20.3	10.9
HighN	26.8	15.6	22.4	13.7	21.8	14.6	20.7	12.1	20.7	10.9
F pr	0.004	<0.001	<0.001	<0.001	0.380	0.01	0.070	0.209	0.98	0.812
$LSD_{0.05}$(d.f.=12)	3.2	1.4	1.8	1.4	6.2	3.2	4.1	1.9	4.7	0.9

[1]No silage measurement for crop G, so the total biomass (dry matter) measured when harvesting grain is used here. The measured biomass when harvesting grain was not significantly different from the silage yield measured across the other four sites (grand mean = 19.9 t/ha for silage, and 19.0 t/ha for the end-of-season biomass, F pr.=0.19, l.s.d. = 1.4, d.f. = 158).

AmaizeN prediction of silage and grain yields

AmaizeN predicted grain yields matched well with the measurements for the four crops B, G, H and M, but the measured yields were lower than predicted for crop T (Figure. 1a). The prediction of silage production was also similar to the measured values except for crops T, but AmaizeN systematically overestimated by approximately 1.9 t/ha on average, and the measured silage production for crop T was also lower than AmaizeN predicted (Figure. 1b). The systematic difference between simulated and measured silage yield is partly because the simulation is of total above ground biomass, where silage is cut at some distance above the ground.

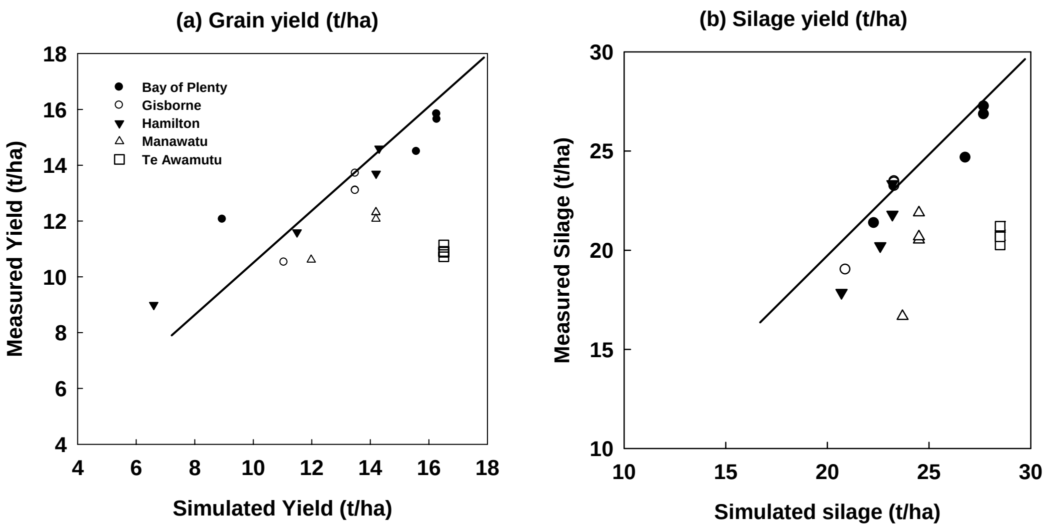

Figure 1. Comparison of mean measured grain (a: at 14% grain moisture content) and silage (b) yields with that predicted by the AmaizeN Calculator from five maize crops grown in the North Island.

Protein contents in silage

Silage quality was measured for the experimental crops, including contents of crude protein, acid detergent fibre and neutral detergent fibre, digestibility, energy and soluble sugar. Only crude protein contents were significantly increased by the N application at all trial sites (Table 5). Silage crude protein content (P) was closely related the soil N-supplying capability (N: sum of pre-planting mineral N in soil profiles and N fertiliser). The relation is shown in Figure. 2, and could be described as P = 6.916*(1-exp(-0.0099*N)), n=20, r^2 = 0.582, p<0.0001.

Table 5. Protein contents in silage under the four N applications on the four experimental maize crops.[1]

N treatment	B	H	M	T
LowN	4.32	4.96	6.50	6.98
AmaizeN	5.64	5.10	7.08	5.98
FarmerN	5.64	6.26	7.10	6.86
HighN	5.98	6.50	7.38	6.88
F pr.	<0.001	0.013	0.060	0.072
$LSD_{0.05}$(d.f.=12)	0.67	1.03	0.63	0.83

[1]No silage quality measurement for crop G (Gisborne).

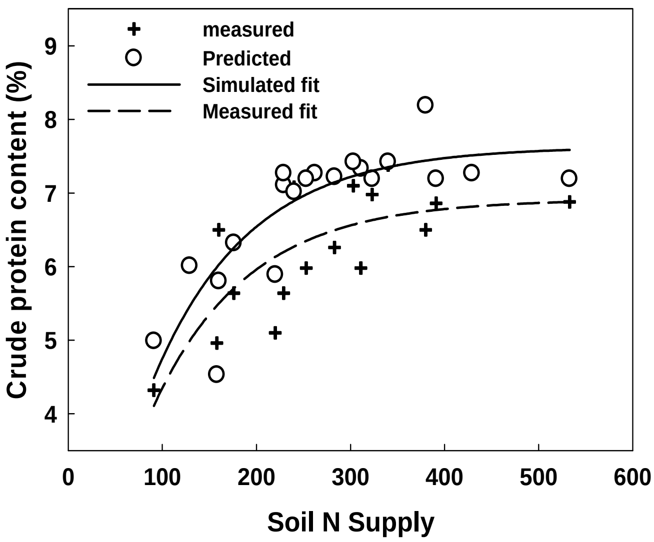

Figure 2. Measured and simulated crude protein content (%) in maize silage in relation with soil N-supplying capability (sum of pre-planting mineral N in soil profile and fertiliser N).

AmaizeN predictions of protein contents in silage

The AmaizeN Calculator can predict the N contents in maize silage and in grains. The predicted crop N contents were converted into crude protein (multiplied by 6.25) for comparison purposes. The predicted protein contents (P) significantly increased with increase in soil N supply (N), which was similar to that shown in field experiments ($P = 7.628 * (1-\exp(-0.0097*N))$; n=20, $r^2 = 0.695$, $p<0.0001$; Figure. 2). The increase of crude protein content with soil N increase towards an asymptote reflected the fact that crop N contents had a maximum value, which was set in the mechanistic simulation.

Figures 2 and 3 shows the predicted crude protein contents match well with the measurements, including their changing pattern in response to soil N supplies. The model predicted crude protein content for crop T varies little, while measured values do have some variations, which was related to a discrepancy between measured and predicted yield.

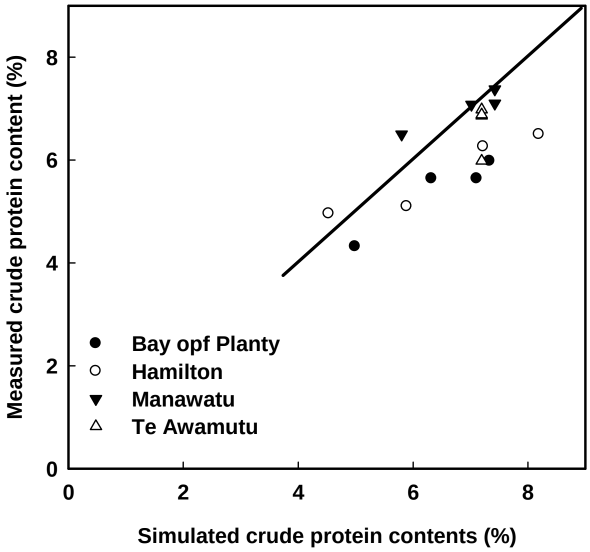

Figure 3. Measured versus simulated protein contents in maize silage.

Soil mineral N contents at the end of maize growing season

At the end of maize-growing season, the soil still contained a significant amount of mineral N (Table 6), especially under crop T. The effect of N application on soil mineral N was significant at the trial sites of crops H, and less significantly at the sites of crop B and G.

Table 6. Soil mineral N contents at the end of maize-growing season under four N treatments on the five experimental crops (kg/ha).

Site	Pre-planting N	N Treatments				Effects of N treatments on the end-of season N content[1]	
		LowN	AmaizeN	FarmerN	HighN	F pr.	$LSD_{0.05}$ (d.f.)
B	55	34	44	49	51	0.061	13.1 (11)
G	93	62	63	72	124	0.057	49.5 (12)
H	80	55	52	73	110	<0.001	14.2 (12)
M	115	81	87	92	94	0.757	26.9 (12)
T	134	166	120	159	182	0.593	99.1 (12)

1. Pre-planting N is same across all N treatment sites, so not involved in the analysis

Discussion

The AmaizeN calculator (version 0.9) predicted well the grain yield and silage production as well as the silage crude protein content associated with different N applications for four monitored crops, but its predictions did not match well with actual measurements from the crops in Te Awamutu. It is important to understand the causes of the lower-than-predicted yield at this site to identify the limiting factors that were not considered by the crop-soil model. It is also useful to analyse other possible reasons for the discrepancy between measurements and simulation. This will allow the AmaizeN Calculator to be updated, and will help farmers to adjust their management to improve their crop yield.

Population

In the crop model, the effects of low plant population on total biomass could be compensated for to some extent by the increase in per-plant biomass. Table 7 shows that the crop T has a good population establishment, the low-than-predicted yield of this crop is mainly the result of the smaller per-plant yield, and that the effects of N application on the yield is insignificant.

The crop H was sown in variable row spacing and variable spacing between plants of different rows. The sampling was done on the narrow rows, which had relatively smaller per-plant silage and grain yield, but higher density, in comparison with crops at other sites (Table 7). Sampling both the narrow and wide spaced rows will be worthwhile in the future for improving the accuracy of measurements.

Table 7. Per-plant silage yield (g, dry matter) and grain yield (g, with 14% moisture as per industry standard) under the four N treatments on the five experimental maize crops.

Crops	B		G		H		M		T	
Population[1]	92		95		102		93		97	
N treatment	Silage	grain	silage[2]	grain	silage	grain	silage	grain	silage	grain
LowN	230	133	189	109	172	86	190	108	216	110
AmaizeN	269	163	230	136	215	110	221	130	222	119
Farmer N	300	172	242	142	218	129	222	131	217	113
HighN	297	177	236	145	214	138	228	126	201	122
F pr.	0.002	0.001	0.001	0.001	0.322	0.014	0.171	0.057	0.624	0.340
$LSD_{0.05}$(d.f.=12)	33	18	17	13	59	30	38	20	36	15

[1]Population (thousand plants/ha) differs significantly among the 5 sites, F pr.<0.001, $LSD_{0.05}$ =4.1(d.f.=91);

[2]No silage measurement for crop G, total biomass at harvest grain is used here.

Soil properties

The significant differences in per-plant yield in crop B, G and H across the N applications, which were significantly lower under LowN treatment than under HighN treatment, suggested that the low per-plant yield was the consequences of N deficits. Although the soil still had some mineral N left at the end of maize-growing season (Table 6), the crop might have suffered from N deficits during growth and development. The end-of-season soil mineral N was significantly lower under the treatments LowN and AmaizeN than under HighN for these three crops.

Crop H was on a peaty soil with an extremely high organic matter content (24%) and a high C:N ratio (23.2, Table 1). Under such a soil condition, the mineralisation rate of the soil organic N could be very low, and even the applied mineral N might be immobilised. The current yields reported here for crop H was predicted assuming the net mineralisation rate being around zero. Our earlier simulation experiment, ignoring the property of peaty soil and using a mineralisation rate similar to other soils, had predicted a sufficient soil N supply in this site under all the 4 N treatments. While soil description and soil organic matter processes in soil model needs to be improved, the N processes in peat soil and their effects on crop growth deserve further investigation.

Other factors

The reason for a lower-than-predicted yield in crop T is uncertain, thought the above analysis showed the lower yield is mainly the consequences of smaller per-plant yield. N fertilisation (120-400 kg N/ha) was higher than the crop requirement predicted by the AmaizeN calculator (93 kg N/ha) based on a pre-planting soil mineral N of 134 kg/ha, for a climatic attainable production of 14 t/ha grain or 28 t/ha dry matter. Crop production was not significantly different among N applications, which meant that the actual effects of N were similar for all the N applications at this trial site. There was plenty of mineral N retained in the soil profile (120-180 kg/ha) at the end of the maize-growing season (Table 6), which seemed also to confirm the absence of N limitation. In addition, the soil at this site had very similar soil organic matter and C:N ratio (Table 1) to crop B, so the lower-than-predicted production might be related to other factors. The only difference in soil measurements was a low Olsen P (15 mg/L in top 30 cm) at site T in comparison with the other sites (49 mg/L average), but we are not sure that this factor is significant because 150 kg/ha DAP were applied at planting. In addition, four different hybrids were planted in the five experimental sites, which might also have brought about some differences in crop performance across the sites. Thus, the reason for lower production at this site also deserves further investigation.

Upgrading the AmaizeN calculator

Based on the experimental results, more work is needed to look at the quantitative relations between plant population density and silage and yield production, to understand the effects of soil properties on N supply to plants, and to examine the traits of different maize hybrids.

The effects of N deficit on crop growth were estimated mainly by limiting the expansion of leaf area or accelerating the leaf senescence in the current model, which in turn led to a yield decrease, whereas the most recent research (Vos *et al*., 2005) confirmed that the effects of N deficit on maize production were better understood by reducing leaf N content and radiation use efficiency than by adapting the size of leaf area. The current model predicted well the effects of N deficits on maize growth, but implementing the alternative mechanism is worthwhile to see whether it can improve the accuracy of prediction.

Pearson *et al*. (2005) found that while very high irrigation rates shortly after sowing could alter the distribution of N in the soil, the total N available to the maize crop (at 0-180 cm, the unimpeded rooting depth of maize) was the same as in un-irrigated maize. More efforts are needed to validate and calibrate N-leaching processes in the AmaizeN Calculator.

More information on silage yield and quality (crude protein content) also needs to be added into the user interface.

Conclusions

The AmaizeN Calculator worked well in the maize-growing area in North Island. Its prediction of grain yield, silage yield and silage crude protein contents matched closely with actual measurements under different N applications where other constraints to crop growth were unimportant, and its recommended N application was always lower than farmers but gave no significant yield penalty. The AmaizeN also diagnosed the sites with major yield constraints. If these constraints can be identified and overcome, then substantial yield benefits may be gained. To improve the accuracy of the AmaizeN calculator in forecasting N requirements and predicting yield and quality, further field experiments and simulations are needed to examine the effects of plant population density, soil property, and the different traits of maize hybrids.

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