Kasetsart J. (Nat. Sci.) 44 : 991 - 1003 (2010)

Growth and Yield Responses in Maize to Split and Delayed Fertilizer Applications on Sandy Soils Under High Rainfall Regimes

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ABSTRACT

The yield of maize (*Zea mays* L.) on sandy soils with high rainfall regimes is generally low due to poor nutrient use efficiency. Split and delayed basal fertilizer applications are possible strategies to improve the crop yield and reduce nutrient loss through leaching in sandy soils, but their effectiveness under high rainfall regimes to produce a maize growth response needs further investigation. The aim of the study was to determine the effect of fertilizer application methods on the growth, yield and agronomic characteristics of maize on a sandy soil with approximately 1,350 mm of rainfall during crop growth. Field experiments were conducted on Oxic Paleustults (Korat series) with a low cation exchange capacity (CEC) of 2–4 cmol kg^{-1}. Three to four split applications of the fertilizer increased the grain yield from 2.7 to 3.3–4.5 Mg ha^{-1}. There was a greater crop growth rate (CGR) and relative growth rate (RGR) with the split applications of fertilizer during 30–60 d after emergence (DAE). The highest agronomic efficiency (AE) resulted from a three-split application. However, application of fertilizer later than 45 DAE had only a low effective rate. Delaying the basal fertilizer application to 7–15 DAE increased the grain yield to 3.5–3.7 Mg ha^{-1}, whereas a pre–planting application produced a yield of 2.7 Mg ha^{-1}. Delaying the basal fertilizer application to 7–15 DAE improved the CGR, RGR and AE. These results indicated that fertilizer applications to minimize nutrient loss increased the growth and nutrient use efficiency of maize on sandy soil in a high rainfall regime.

Keywords: maize, fertilizer strategies, growth, agronomic efficiency, sandy soils

INTRODUCTION

The area under maize production in Northeast Thailand covers 200,000 ha, but the yield is low compared to other areas of Thailand (Office of Agricultural Economics, 2005), since 70% of the soils in the Northeast are sandy and have low nutrient use efficiency. In general, coarse-textured soils have a high risk of nutrient leaching that limits plant nutrient uptake, fertilizer use efficiency and yield (Sitthaphanit *et al*., 2009). Nyamangara *et al*. (2003) reported NO_3^- leaching losses of up to 56 kg N ha^{-1} y^{-1} with a rainfall of 1,395 mm. Kamukondiva and Bergstrom (1994)

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Received date : 31/03/10 Accepted date : 17/06/10

reported up to 39 kg N ha^{-1} y^{-1} loss through leaching in a tropical sandy soil. Eghball *et al.* (1996) reported that phosphorus (P) from inorganic fertilizer can be leached to below 1.1 m soil depth in sandy loam soils with an application rate of 80 kg P ha^{-1}. Loss of 19 kg K ha^{-1} has been reported with a rainfall of 480 mm in a 7–month period in sandy soils (Alfaro *et al.*, 2004)

Not only are most soils in Northeast Thailand sandy, but there is also high intensity rainfall in the rainy season, with 1,000 to 2,300 mm of rain falling in a 6-month period. The combination of the sandy soil and high rainfall regime results in nutrients from any fertilizer being highly vulnerable to leaching. In general, N is lost easily by leaching. However, P and K leaching can occur in sandy soils and the problem of leaching is accelerated by frequent and heavy rainfall events (Sims *et al.,* 1998; Sitthaphanit *et al.*, 2009). Many strategies have been developed to mitigate nutrient leaching and improve the nutrient use efficiency (NUE). Nitrification inhibitors, which slow the oxidation of NH_4, have been used to reduce N leaching (Di and Cameron, 2002). In addition, slow- and controlled-release fertilizers have the potential to decrease N leaching (Shoji and Kanno, 1994; Baligar *et al.*, 2001). Furthermore, soil management practices, such as incorporating straw with a high C:N ratio and minimum tillage can reduce N leaching (Meek *et al.*, 1995; Thomsen and Chistensen, 1998). Phosphorus in a slowly soluble form can reduce leaching in sandy soils under high rainfall conditions (Bolland *et al.*, 1995).

While the above strategies based on alternative fertilizer types can be effective in reducing leaching, the extra cost of such products often makes them prohibitive for use by small holders in rainfed environments. The timing of any fertilizer application is another low-cost strategy to reduce nutrient leaching, so that nutrient supply is synchronized with plant nutrient demand (Gehl *et al.*, 2005; López–Bellido *et al.*, 2006). However, in high rainfall areas, any period of heavy rainfall after planting on sandy soils can have the greatest risk of nutrient leaching to depth (Sitthaphanit *et al.*, 2009). Split applications and delayed basal application are effective fertilizer strategies to reduce nutrient leaching (Sitthaphanit *et al.*, 2009) and can be adopted readily by farmers with minimal cost. Growth analysis can be used to provide insight into any crop response to a fertilizer application design and to the climate and its ultimate affect on yield. The objective of the current study was to determine the effect of fertilizer application methods on the growth, yield and NUE of maize grown in sandy soil in a high rainfall regime.

MATERIALS AND METHODS

Experimental site and treatments

In 2005, two field experiments were conducted in Sakon Nakhon province, Thailand, (17°08′ N, 104°04′ E), on an Oxic Paleustult (Korat series). Experiment 1 consisted of five methods of fertilizer application: 1) no fertilizer (control); 2) basal application at the rate of 28 kg N ha^{-1} 12.2 kg P ha^{-1} and 23.3 kg K ha^{-1} followed by top dressing with 86.3 kg N ha^{-1} at 30 DAE (recommended practice); 3) split all N, P and K into three applications, with basal (20%), 30 DAE (40%), and 50 DAE (40%); 4) split all N, P and K into three applications, with basal (20%), 30 DAE (40%) and 45 DAE (40%); 5) split all N, P and K into four applications, with basal (20%), 30 DAE (20%), 40 DAE (40%) and 60 DAE (20%).

Experiment 2 was conducted to examine the effects of delayed basal fertilizer application. Fertilizer applications were at the same rates as for treatment 2 in Experiment1. Treatments were: 1) no fertilizer (control); 2) pre-planting (pre-plant); 3) delayed basal application until 7 DAE (7 DAE); 4) delayed basal application until 15 DAE (15DAE); 5) delayed basal application until 21 DAE (21 DAE). Nitrogen side-dressing with urea was applied at 30 DAE in all treatments. A randomized complete block experimental design was used with four replicates.

The plot size was 6 × 8 m. The maize cultivar Syngenta brand NT72 at 53,000 plants $ha^{-1}$was used. Maize seed was hand planted at a depth of 5 cm, with a spacing of 25 × 75 cm. Carbofuran granules were applied (12 kg ha^{-1}) at the time of planting for insect management. Weeds were controlled by hand removal at 30 DAE at the same time as the fertilizer application.

Soil characteristics and rainfall conditions

Soil samples were taken at depths of 0-15, 15-30, 30-60 and 60-100 cm before planting for nutrient analysis (NO_3 and NH_4 by the distillation method on 2 *M* KCl extracts, P by Bray II extraction and K by NH_4 acetate extraction). The analysis results are shown in Table 1. The soil in Experiments 1 and 2 was a loamy sand from 0-15 cm depth, a sandy loam from 15-30 cm depth and a sandy clay loam from 60-100 cm depth. The initial soil analysis showed NO_3+NH_4 was in the range 9-12 mg kg^{-1}, Bray II P was in the range 3-12 mg kg^{-1}, exchangeable K was in the range 17-27 mg kg^{-1} and the cation exchange capacity (CEC) was in the range 2–4 cmol kg^{-1}. The cumulative rainfall during the cropping period was 1,368 and 1,349 mm for Experiments 1 and Experiment 2, respectively. During the period from planting to 7 DAE, 120 and 170 mm of rainfall was recorded for Experiment 1 and Experiment 2, respectively (Figure 1). The highest rainfall intensity during the experimental period was 133 mm d^{-1}, but it occurred close to harvesting time. A second period of heavy rainfall of 300 mm was observed from 32 to 41 DAE in Experiment 1 and 26 to 35 DAE for Experiment 2, followed by an 18-day period of relatively gentle rainfall.

Sample collection and analyses

Maize nutrient uptake analysis was determined from six plants for total N, P and K. The samples were taken four times at: 30 DAE, 60 DAE, 90 DAE and at harvest on 110DAE. Whole shoots were dried at 60-70°C until constant weight, ground to pass a 0.2–mm sieve, and analyzed for total N by the micro Kjeldahl method, for P by colorimetry (Murphy and Riley, 1962) and for K by flame emission spectroscopy. The grain yield was determined from an area of 8 m^2. The maize grain yield was adjusted to 15% moisture content, shelled and then oven dried to determine the dry matter.

Table 1 Soil analysis results of Experiment 1 and Experiment 2 at Sakon Nakhon province in 2005.

	NO_3+NH_4 (mg kg^{-1})	P-Bray II (mg kg^{-1})	K–exchangeable (mg kg^{-1})	CEC (cmol kg^{-1})	Soil texture class
Experiment 1					
Soil depth (cm)					
0-15	10.9	10.6	19.9	2.14	Loamy Sand
15-30	11.7	11.8	22.9	2.24	Sandy Loam
30-60	10.6	4.7	26.6	3.19	Sandy Loam
60-100	11.1	2.9	21.6	3.92	Sandy Clay Loam
Experiment 2					
Soil depth (cm)					
0-15	10.4	10.3	20.4	2.02	Loamy Sand
15-30	9.8	12.1	18.0	2.16	Sandy Loam
30-60	9.1	7.0	18.8	3.08	Sandy Loam
60-100	9.7	6.0	17.0	3.52	Sandy Clay Loam

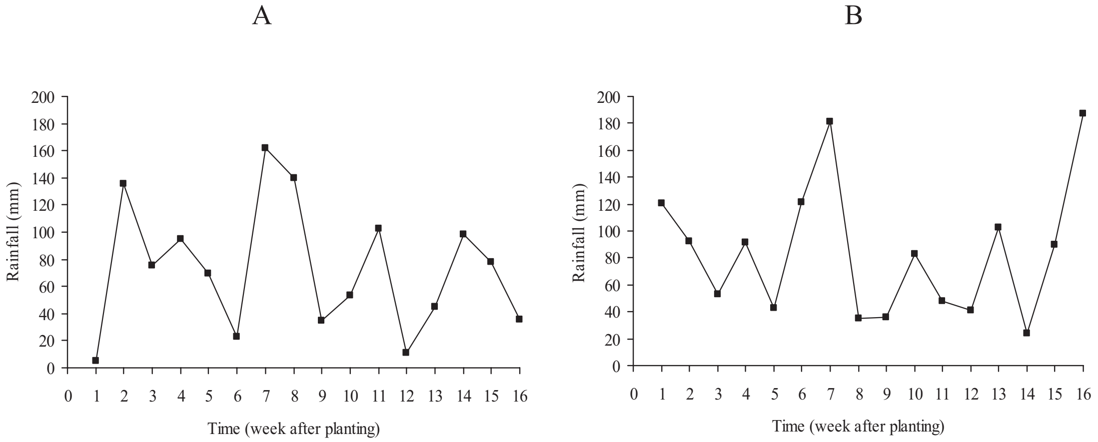

Figure 1 Weekly rainfall in field experiment during the gro wing season in 2005.
A) Split fertilizer application experiment; B) Delayed basal fertilizer experiment.

Growth analysis and nutrient use efficiency estimation

The crop growth rate (CGR), relative growth rate (RGR), harvest index (HI) and agronomic efficiency (AE) were calculated using equations 1-4, respectively:

$$CGR = (W_2 - W_1)/(t_2 - t_1) \quad (1)$$

where: W1 and W2 = dry weight at time t_1 and t_2, respectively.

$$RGR = (ln\ W_2 - ln\ W_1)/(t_2 - t_1) \quad (2)$$

where: W1 and W2 = dry weight at time t_1 and t_2, respectively.

HI = economic yield/biological yield (3)

AE = (yield F–yield C)/Quantity of nutrient applied (4)

where: yield F = yield of fertilized maize (kg),
yield C = yield of the control maize (kg).

The program STATISTIX (version 8) was used to conduct one way analysis of variance (ANOVA) for each experiment. The F-tests for analysis of variance were considered significant at the 0.05 probability level. Means were separated by least significant difference at $\alpha = 0.05$.

RESULTS

Split-application fertilizer (experiment 1)

No significant differences were observed in grain yield and total shoot dry matter between the fertilizing split into three and four applications. However, they attained greater yield and total dry matter than the other treatments (Table 2). The control treatment showed lower HI than the other treatments, but there were no significant difference in HI among the fertilizer application treatments.

Crop growth rates from splitting treatments from 30-90 DAE were significantly higher than the recommended treatment (Table 3). However, during the early period of growth (0-30 DAE), the CGR of the recommended fertilizer application was not different from the split applications. After 30 DAE, the CGR of all treatments increased sharply until 90 DAE. The CGR values of the split treatments were 36-55% greater than for the recommended rate at 30-60 DAE and 20-29% higher at 60-90 DAE. The maximum CGR of 125 kg $ha^{-1}day^{-1}$ was found with applying the fertilizer in four applications during the period 60-90 DAE.

The recommended fertilizer rate had a higher RGR than the control treatment, but was not significantly different to the split treatments from planting to 30 DAE (Table 4). However, the RGR from 30-60 DAE for the split treatments was 16% greater than for the recommended rate. The

Table 2 Effect of split fertilizer applications on mean grain yield, total dry matter and harvest index (HI) of maize during the rainy season in 2005.

Application treatment	Grain yield (Mg ha^{-1})	Total shoot dry matter (Mg ha^{-1})	HI
Control	0.44 d	1.15 d	0.38 b
Basal + N top dress at 30DAE	2.17 c	4.63 c	0.47 ab
Split 3 times (0, 30, 50 DAE)	3.33 b	6.18 b	0.55 a
Split 3 times (0, 30, 45 DAE)	4.46 a	7.70 a	0.58 a
Split 4 times (0, 30, 40, 60 DAE)	4.25 a	7.31 a	0.59 a
CV (%)	16.5	12.5	20.3

a-d = means labelled with the same letter in each column are not significantly different as determined by LSD ($P < 0.05$).

Table 3 Effect of split fertilizer applications on mean crop growth rate (CGR) of maize during the rainy season in 2005.

Application treatment	CGR (kg $ha^{-1}day^{-1}$)			
	Planting to 30 DAE	30 DAE to 60 DAE	60 DAE to 90 DAE	90 DAE to harvest
Control	2.4b	12.2d	26.7d	–4.5b
Basal + N top dress at 30DAE	5.7a	61.5c	97.1c	–14.9b
Split 3 times (0, 30, 50 DAE)	5.1a	84.0b	116.6b	0.4b
Split 3 times (0, 30, 45 DAE)	5.6a	94.7a	117.2b	58.9a
Split 4 times (0, 30, 40, 60 DAE)	5.1a	82.9b	124.8a	46.4a
CV (%)	13.6	22.3	19.8	25.5

a-d = means labelled with the same letter in each column are not significantly different as determined by LSD ($P < 0.05$).

Table 4 Effect of split fertilizer applications on mean relative growth rate (RGR) of maize during the rainy season in 2005.

Application treatment	RGR (kg $kg^{-1}day^{-1}$)			
	Planting to 30 DAE	30 DAE to 60 DAE	60 DAE to 90 DAE	90 DAE to harvest
Control	0.143b	0.060c	0.035a	–0.004a
Basal + N topdress at 30DAE	0.171a	0.082b	0.030a	–0.003a
Split 3 times (0, 30, 50 DAE)	0.168a	0.095a	0.028a	0.001a
Split 3 times (0, 30, 45 DAE)	0.171a	0.096a	0.026a	0.008a
Split 4 times (0, 30, 40, 60 DAE)	0.168a	0.095a	0.029a	0.007a
CV (%)	3.2	1.8	2.2	11.2

a-b = means labelled with the same letter in each column are not significantly different as determined by LSD ($P < 0.05$).

highest RGR was found from 30-60 DAE (0.096 kg $kg^{-1}day^{-1}$) in the split treatments with three and four applications.

Differences in N, P and K uptake among the split fertilizer applications were not significant. However, they had greater nutrient uptake than the control and recommended treatments (Table 5). The split applications had increased N and K uptake relative to the recommended fertilizer application rate by 27-39% for N and 18-30% for K. The apparent AE increased also by 67-131% for N, P and K with split applications of fertilizer when compared with the recommended treatment. The shoot N, P and K concentrations among fertilization treatments at 90 DAE were not significantly different (Table 6). The control treatment attained P and K concentrations significantly higher than the fertilization treatments (3.3 and 17.2 g kg^{-1}, respectively). However, the control showed significantly lower N concentration than the others.

Delay basal application fertilizer (Experiment 2)

Pre–plant application of fertilizer increased markedly the grain yield and shoot dry matter relative to the unfertilized control (Table 7). However, further grain yield and shoot dry

Table 5 Effect of split fertilizer applications on nutrient uptake of maize shoots and agronomic efficiency for N, P and K at 90 DAE during the rainy season in 2005.

Application treatment	Total N uptake	Total P uptake	Total K uptake	Agronomic efficiency		
		kg ha^{-1}		N^a	P^b	K^c
Control	10.4c	3.4b	15.5c	–	–	–
Basal + N top dress at 30DAE	44.2b	12.2a	50.1b	15.2	142	74
Split 3 times (0, 30, 50 DAE)	55.7a	13.0a	59.3ab	25.4	237	124
Split 3 times (0, 30, 45 DAE)	58.6a	13.6a	63.0ab	35.3	330	173
Split 4 times (0, 30, 40, 60 DAE)	58.4a	13.8a	65.3a	33.4	312	164
CV (%)	22.4	19.8	24.7			

[a] = agronomic efficiency for N (kg crop yield per kg N applied).
[b] = agronomic efficiency for P (kg crop yield per kg P applied).
[c] = agronomic efficiency for K (kg crop yield per kg K applied).
a-c = means labelled with the same letter in each column are not significantly different as determined by LSD ($P < 0.05$).

Table 6 Effect of split fertilizer applications on nutrient concentration of maize shoots at 90 DAE during the rainy season in 2005.

Application treatment	N concentration (g kg^{-1})	P concentration (g kg^{-1})	K concentration (g kg^{-1})
Control	6.2b	3.3a	17.2a
Basal + N top dress at 30DAE	9.2a	2.5b	10.1b
Split 3 times (0, 30, 50 DAE)	9.0a	2.2b	9.7b
Split 3 times (0, 30, 45 DAE)	9.0a	2.1b	9.7b
Split 4 times (0, 30, 40, 60 DAE)	9.2a	2.2b	10.1b
CV (%)	22.0	21.2	15.4

a-b = means labelled with the same letter in each column are not significantly different as determined by LSD ($P < 0.05$).

matter significantly increased with the 7-day and 15-day delay in basal application. There was no significant difference in the HI values among the pre–planting treatments, but they had significantly greater HI values than the control treatment.

Delaying application by 7-15 DAE and pre-plant application gave a higher CGR with the 30 DAE than with the 21 DAE application and the control (Table 8). Delaying application to 15 DAE produced a higher CGR during the period 30-60 DAE (46% greater than the pre-plant treatment). There was no significant difference in the CGR values of fertilized treatments in the period 60-90 DAE, but they were significantly higher than the control. After 90 DAE, the delayed application to 7 DAE had the highest CGR, whereas the others showed no significant difference in CGR.

The fertilizer application treatments had higher RGR values than the control treatment during the period from planting to 60 DAE, but pre-plant and the delay to 15 DAE were not significantly different in RGR from planting to 30 DAE (Table 9). Delaying the application until 15-21 DAE had the highest RGR (19% greater than pre-plant at 30-60 DAE). For periods beyond 60 DAE, the RGR was not significantly different among treatments.

An increase in the nutrient uptake was found to result from delaying the basal fertilizer application from 7 to 15 DAE, with 30% N, 22% K and 24% P greater than pre–plant rates (Table 10). Higher P and K uptakes were found with the 15- and 21-DAE basal applications, compared to the control and pre–plant treatments. Postponing the basal application to 7-15 DAE gave a greater

Table 7 Effect of delayed basal fertilizer application on grain yield, total dry matter and harvest index (HI) of maize during the rainy season in 2005.

Application treatment	Grain yield ($Mg\ ha^{-1}$)	Total shoot dry matter ($Mg\ ha^{-1}$)	HI
Control	0.29 c	0.96 c	0.30 b
Pre-plant	2.73 b	5.05 b	0.54 a
7 DAE	3.47 a	6.36 a	0.55 a
15DAE	3.68 a	6.58 a	0.56 a
21 DAE	2.48 b	5.58 b	0.44 ab
CV (%)	17.73	13.76	31.08

a-d = means labelled with the same letter in each column are not significantly different as determined by LSD ($P < 0.05$).

Table 8 Effect of delayed basal fertilizer application on crop growth rate (CGR) of maize during the rainy season in 2005.

Application treatment	CGR ($kg\ ha^{-1}\ day^{-1}$)			
	Planting to 30 DAE	30 DAE to 60 DAE	60 DAE to 90 DAE	90 DAE to harvest
Control	1.6c	9.2c	14.1b	10.4b
Pre-plant	11.1a	79.0b	69.3a	13.3b
7 DAE	10.1a	96.5ab	64.1a	61.8a
15DAE	10.3a	115.2a	71.1a	34.3b
21 DAE	8.5b	92.8ab	74.5a	15.1b
CV (%)	10.6	21.02	11.7	33.7

a-c = means labelled with the same letter in each column are not significantly different as determined by LSD ($P < 0.05$).

AE than the pre-plant treatment, with an increase of 30% N, 39% P and 39% K.

The highest N concentration in the aboveground plant parts was found with the 7-DAE basal application, but this concentration was not significantly different to the application made 15-21 DAE and the pre-plant application (Table 11). However, the control treatment had higher P and K concentrations in the shoots at 90 DAE compared with the fertilization treatments.

DISCUSSION

Grain yield response to fertilizer management

Both the split and delayed basal fertilizer applications improved the maize grain yield, growth pattern and nutrient use efficiency. Moreover, nutrient uptake was highest when fertilizer was split into three applications or with a delayed basal application 7-15 DAE. Timing fertilization according to crop demand can increase crop grain yield and nutrient use efficiency (Gehl *et al.*, 2005). The current study found that reduced and delayed basal fertilizer applications did not affect either the CGR or RGR during the first 30 d when compared with the control, whereas from 30-60 DAE, the split and delayed fertilizer applications improved the growth rate over the

Table 9 Effect of delayed basal fertilizer application on relative growth rate (RGR) of maize during the rainy season in 2005.

Application treatment	RGR (kg kg^{-1} day^{-1})			
	Planting to 30 DAE	30 DAE to 60 DAE	60 DAE to 90 DAE	90 DAE to harvest
Control	0.129c	0.063c	0.028a	0.012a
Pre-plant	0.193a	0.070b	0.019a	0.003a
7 DAE	0.191a	0.078ab	0.016a	0.011a
15DAE	0.191a	0.083a	0.015a	0.006a
21 DAE	0.185b	0.083a	0.018a	0.003a
CV (%)	2.1	2.3	4.2	6.5

a-c = means labelled with the same letter in each column are not significantly different as determined by LSD ($P < 0.05$).

Table 10 Effect of delayed basal fertilizer application on nutrient uptake of maize shoots and agronomic efficiency for N, P and K at 90 DAE during the rainy season in 2005.

Application treatment	total N uptake	total P uptake	total K uptake	Agronomic efficiency		
		(kg ha^{-1})		N[a]	P[b]	K[c]
Control	5.3d	2.5c	10.9c	–	–	–
Pre-plant	44.7c	7.8b	50.5b	21.4	200.0	104.7
7 DAE	62.1a	9.0ab	58.8ab	27.9	260.7	136.5
15DAE	62.3a	10.1a	65.3a	29.7	277.9	145.5
21 DAE		56.8b	10.1a	55.8ab	19.2	179.5
94.0						
CV (%)	15.6	15.6	17.4			

[a] = agronomic efficiency for N (kg crop yield per kg N applied).
[b] = agronomic efficiency for P (kg crop yield per kg P applied).
[c] = agronomic efficiency for K (kg crop yield per kg K applied).
a-c = means labelled with the same letter in each column are not significantly different as determined by LSD ($P < 0.05$).

control and the recommended practice. For maize, less than 20% of N and P uptake occurred in the first 40 d of growth, followed by rapid uptake during the period of middle vegetative growth and maximum uptake was found near silking for N and P and V12-V18 for K (Richie *et al.*, 1993). Growth analysis suggested that a delayed basal application during the period of low nutrient requirements, and reducing the amount of fertilizer supplied when the plant was small were effective in increasing fertilizer use efficiency. Sainz Rozas *et al.* (2004) found that maize can recover 43-53% of total N fertilizer application at planting compared to 62-74% when applied at the V6 stage. Several reports showed that split fertilizer applications could improve the yield and nutrient recovery. In sandy irrigated soil, Gehl *et al.* (2005) found that splitting 250 kg N ha^{-1} into two applications provided greater grain yield than a single application of N at the same rate. By contrast, Rasse *et al.* (1999) reported similar corn grain yields among N treatments that included a single pre-plant application of 202 kg N ha^{-1} and split N applications of 101 kg N ha^{-1} in sandy loam soils. Sitthaphanit *et al.* (2009) reported that split applications of fertilizer and a postponed basal application reduced nutrient loss through leaching. In a column experiment, increased soluble NO_3 and NH_4 downward transport was found with a single application, compared to split applications of N in sand (Sitthaphanit *et at.*, 2009). Moreover, split applications reduced total N leaching (Nakamura *et al.*, 2004). Sainz Rozas *et al.* (2004) reported 405 kg N ha^{-1} fertilizer applied at planting for maize had twice as much leaching compared with fertilizer applied at the V6 stage. For soybean, Kolar and Grewal (1994) reported that split applications of K were more beneficial than applying the full amount of K at the time of planting. However, in other studies, split applications did not improve crop yields. For instance, in a dry region, the wheat grain yield with N applied in three applications was not significantly improved compared with an equivalent single application (López–Bellido *et al.*, 2006). In the present study, a grain benefit of 1-2 Mg ha^{-1} was obtained with split applications or a delay in basal fertilizer application, when compared with the recommended practice. The low efficiency of nutrient use of the recommended fertilizer practice was attributed to the loss of fertilizer during the high intensity rainfall episode after fertilizer application (120 mm rainfall in the first two weeks after planting in both experiments). The economic benefit from increased grain yield should make either strategy worthy of adoption by farmers, even though an increase in labor costs would be associated with both strategies.

Table 11 Effect of delayed basal fertilizer application on nutrient concentration of maize shoots at 90 DAE during the rainy season in 2005.

Application treatment	N concentration (g kg^{-1})	P concentration (g kg^{-1})	K concentration (g kg^{-1})
Control	7.1b	3.3a	14.6a
Pre-plant	9.4ab	1.6b	10.6b
7 DAE	12.1a	1.7b	11.5b
15DAE	10.6a	1.7b	11.1b
21 DAE	10.8a	1.9b	10.6b
CV (%)	22.8	21.9	14.5

a-d = means labelled with the same letter in each column are not significantly different as determined by LSD ($P < 0.05$).

Enhancement of nutrient use efficiency in sandy soil

In general, The NUE in plant production is a function of plant interaction with the environment, comprising factors, such as soil, rainfall, temperature, solar radiation, diseases and insects (Baligar *et al*., 2001). However, plant production in tropical sandy soils commonly has a low NUE, caused by low soil fertility and physical constraints. Sandy soils in tropical zones with high rainfall regimes may trigger nutrient loss by leaching that in turn decreases NUE. Mitigation of nutrient leaching by management practices, such as synchronizing plant nutrient uptake with demand in sandy soils can improve the NUE (Jokela and Randall, 1997; Gehl *et al*., 2005). Other strategies have been reported to increase NUE in sandy soils, including clay amendment (Croker *et al*., 2004) and using controlled release fertilizer (Amberger, 1989; Serna *et al*., 2004). Tillage practices influence the plant NUE by improving soil organic matter and water holding capacity. Kong *et al*. (2009) reported that the N uptake in maize with minimum tillage was greater than under conventional tillage. By contrast, increased soil macropores in conservation tillage may affect leaching of nutrient. In corn-soybean production, Nissen and Wander (2003) reported no NUE advantage in no–tillage when compared with conventional tillage and found twice as much macropore leaching under no–tillage.

Delaying the final application from 45 to 50 DAE decreased the yield and shoot dry matter when the fertilizer was split into three applications. Even though the maximum maize nutrient uptake occurs near silking (Richie *et al*., 1993), the final fertilizer application at 50 DAE seemed too late for plant uptake and ultilization to produce grain yield. In the current study, maize was in the V16 growth stage at 50 DAE and was tasseling at 55 DAE. Binder *et al*. (2000) reported that late application of N fertilizer in the V16 growth stage decreased maize grain yield when compared with earlier application in the V6 stage. The late application at 50 DAE did not stimulate late growth or nutrient uptake. This suggests that either root activity declined at this stage and was less effective in nutrient uptake, or else the delay in fertilizer application to 50 DAE caused a temporary deficiency before tasseling, which impeded subsequent growth (as reflected in the lower CGR in the last 20 d) and N uptake. Hence, while splitting fertilizer applications was beneficial, the results suggested that all of the fertilizer needed to be applied by 45 DAE, a few days before tasseling.

The present recommended fertilizer rates were based on basal application of all the P and K, and 25% of the N, followed by 75% of the N at 30 DAE. However, it is unclear whether this is the optimal application rate for splitting into three applications, as proposed in the current study. All split applications absorbed more N, P and K than the recommended application, suggesting that higher rates may be needed. Indeed all split applications produced about the same N concentration in shoots at harvest, despite different N uptake levels. This suggests that all treatments reached the concentration of maximum dilution (Witt *et al*., 1999), and that higher N would increase yield potential with 3 applications of the N fertilizer.

Strategies of split application and delaying the basal application affected nutrient uptake and nutrient concentration in maize. An increase in total nutrient uptake was found with fertilization treatment. However, the nutrient uptake in the split and delayed basal fertilizer treatments was greater than in the recommended and pre–plant treatments. Likewise, shoot N concentration was higher in the split and delayed treatments than in the control. In contrast, the highest P and K concentration in the control was due possibly to less N uptake. The maximum dilution of nutrients is the result of environmental conditions and a lack of other nutrient uptake may have limited plant growth (Witt *et al*., 1999). Climatic factors, such as rainfall also affect the NUE in sandy soils. Heavy rainfall shortly after the basal fertilizer application increased nutrient leaching (Sitthaphanit *et al*., 2009). Avoiding any period of high intensity rainfall could improve the NUE. Crop varieties with rapid root growth can improve their NUE by reducing nutrient leaching in sandy soils. Liao *et al*. (2004) reported that wheat, as an early vigor breeding line, has double the N uptake when compared with other commercial cultivars. Garnett *et al*. (2009) concluded that early root system development would seem to increase the NUE. Fertilization using split applications and by postponing the basal application can increase the nutrient use efficiency by spreading the risk of leaching in the early stage of growth and in particular, reducing the amount of nutrients supplied when the plant is small and increasing the supply when crop is growing actively. Commonly, the AE is used to describe nutrient use efficiency expressed as the amount of economic yield per unit nutrient applied (Baligar *et al*., 2001). The maximum AE was found to be related to maximum N uptake, by applying the fertilizer in three applications and with a 15-DAE delay in the basal application. There can be a change in the AE, due to increasing N uptake and harvest index (Novoa and Loomis, 1981; Sifola and Postiglione, 2003).

CONCLUSION

Fertilizing strategies involving three to four split applications and delayed basal application (by 7–15 d) in maize production on sandy soil under a high rainfall regime were effective in improving the growth, grain yield and NUE. Improved maize growth by split fertilizer application and delayed basal treatment was best explained by the higher CGR and RGR in the 30-60 DAE period, suggesting that these strategies best synchronized supply with demand. Fertilizing involving three split applications and a delayed basal application until 15 DAE produced the highest AE. Split application and delayed basal fertilizing strategies in the rainy season in a tropical savannah climate could improve maize growth by synchronizing fertilizer supply with the high nutrient demand period and spreading the risk of fertilizer loss by heavy rainfall after application in the early stage of growth.

ACKNOWLEDGEMENT

The research was funded by the Thailand Research Fund through the Royal Golden Jubilee Ph.D. Program.

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