Agroforestry Systems **47**: 253–262, 1999.

Soil nitrate dynamics in relation to nitrogen source and landscape position in Malawi

R. H. PHIRI[1,3], S. SNAPP[2,*] and G. Y. KANYAMA-PHIRI[1]
[1]*Bunda College of Agriculture, P.O. Box 219, Lilongwe, Malawi;* [2]*ICRISAT, P.O. Box 1096, Lilongwe, Malawi;* [3]*Current address: SADC-ICRAF Agroforestry Research Project, Makoka Agricultural Research Station, P.O. Box 134, Zomba, Malawi (*Author for correspondence: E-mail: s.snapp@cgiar.org)*

Key words: inorganic nitrogen, N input, N mineralization, relay intercrop, *Sesbania sesban*

Abstract. Nitrogen is normally the nutrient most limiting production of maize (*Zea mays*) – the main staple food crop – in southern Africa. We conducted a field study to determine the effect of N sources on soil nitrate dynamics at three landscape positions in farmers' fields in southern Malawi. The landscape positions were dambo valley or bottomland, dambo margin, and steep slopes. The N sources were calcium ammonium nitrate fertilizer applied at 120 kg N ha^{-1}, biomass from *Sesbania sesban*, and no added N. Sesbania biomass was produced *in situ* in the previous season from sesbania relay cropped with maize. Nitrate in the topsoil (0 to 15 cm depth) increased to 85 days after maize planting (mean = 48 kg N ha^{-1}) and then decreased markedly. Application of N fertilizer and sesbania biomass increased soil nitrate, and nitrate-N in topsoil correlated positively with amount of incorporated sesbania biomass. The strongest correlation between sesbania biomass added before maize planting and topsoil nitrate was observed at 85 days after maize planting. This suggests that the sesbania biomass (mean N content = 2.3%) mineralized slowly. Inorganic N accumulated in the subsoil at the end of the maize cropping season when N fertilizer and sesbania were applied. This study demonstrated the challenges associated with moderate quality organic N sources produced in smallholder farmer's fields. Soil nitrate levels indicated that N was released by sesbania residues in the first year of incorporation, but relay cropping of sesbania with maize may need to be supplemented with appropriately timed application of N fertilizer.

Introduction

Soil erosion and degradation of natural resources resulting from increasing land pressure have become serious problems in Malawi. The consequence has been a rapid decline in soil fertility, crop yields, and firewood for domestic fuel. Acute land pressure over the last 10 to 15 years has resulted in accelerated clearance of much of indigenous forests and the cultivation of maize and other crops on very steep slopes of up to about 50% (JHA Maida, personal communication, 1988). In the course of the rapid decline in soil fertility, N has become the most limiting nutrient to maize (*Zea mays* L.) production in Malawi (Saka et al., 1995).

Practices of incorporating organic materials into the soil are widely used in southern Malawi. The most common sources such as crop residues and weeds, however, are commonly low in N (Kanyama-Phiri et al., 1998). Use of mineral fertilizer is increasingly seen as a solution to the problem of restoring soil fertility and providing food for people. However, from 1992 to 1997 the cost of farm inputs, especially mineral fertilizers, has more than doubled in Malawi (Agricultural Development and Marketing Corporation, personal communication, 1997).

In recent years there has been interest in use of alternatives such as integration of fast-growing, N_2-fixing trees into cropping systems to enhance N and C inputs through biomass production, biological N^2 fixation, and recycling of N. One promising tree species is sesbania [*Sesbania sesban* (L.) Merr.]. Sesbania contributes to the N economy of the soil through N_2 fixation and N recycling from subsoil (Yamoah, 1988; Hartemink et al., 1996). Foliage of sesbania is an excellent source of high-quality green manure and organic N. Ghai et al. (1985) reported that sesbania within a growth period of 100 days produces biomass that supplies 39 to 85 kg N ha^{-1} when incorporated into soil. Sesbania is productive and effective in alley-cropping systems (Yamoah and Burleigh, 1990). The N input and improved cycling achieved by sesbania, however, has not been characterized for a range of on-farm conditions in the southern Africa smallholder sector. This is critical because legumes often produce much lower amounts of biomass under the low-fertility, high-stress environments of farmers' fields than in research stations.

In southern Malawi, agriculture is carried out on three major landscape positions: (i) dambo valleys or bottomland near the drainage lines, (ii) dambo margins with < 12% slopes, and (iii) steep sites with > 12% slopes. Because of variations in soil characteristics across landscape positions, N requirements can vary widely within a locality. Fertilizer recommendations are for a single rate of N across landscape positions, which can result in areas of over and under application.

Past research in Malawi has not clearly quantified N requirements across landscape positions. Hence there is need to quantify soil N dynamics and N requirement in maize-based cropping systems as influenced by landscape position as well as N source. The objectives of this study were to monitor soil nitrate as a measure of N availability at different landscape positions during a maize cropping season and to evaluate soil nitrate dynamics following incorporation of sesbania biomass, as compared to N from N fertilizer.

Materials and methods

A field study was conducted in 22 farmers' fields in Songani (15°18.5′ S, 35°23.5′ E) in Malosa Extension Planning Area in Zomba Rural Development Project, southern Malawi. The area is at about 800 m elevation with a mean annual rainfall of about 1150 mm. Soils are classified as Alfisols and Ultisols (GY Kanyama Phiri et al., Preliminary findings on adoption of agroforestry technologies by smallholder farmers in Zomba RDP. Paper presented at the agroforestry symposium held at Bvumbwe Agricultural Research Station, 24–28 October 1994), and they generally range from loamy sand to clay loam. The cropping system is dominated by maize – the staple food crop in Malawi. For this study, fields representing three different landscape positions were identified along six transects. Properties of soils at the landscape positions are reported by Phiri et al. (1999).

Experimental design and management

This experiment was a factorial combination of three N sources (no added N, 120 kg N ha^{-1} as calcium ammonium nitrate, and biomass from sesbania previously relayed cropped with maize) and three landscape positions (dambo valley or bottomland, dambo margin, and steep slopes). The three N treatments were laid out in seven farmers' fields in the dambo valley and steep slope positions and eight farmers' fields in the dambo margin position. The farmers' fields in each landscape position served as replicates. Each experimental plot was 15 m by 15 m.

Three seeds of maize hybrid (MH18) were planted on ridges spaced 90 cm apart with 90 cm between planting stations on ridges. This gave a plant population of 37,000 plants ha^{-1}. Nitrogen fertilizer was applied as calcium ammonium nitrate at 120 kg N ha^{-1} in two equal split applications at 18 and 40 days after planting maize.

Sesbania was planted as a relay intercrop with maize in the previous season (1995/96) at a density of 7400 plants ha^{-1}. Sesbania was cut in October 1996, and non-woody biomass (leaves, pods, flowers, and twigs) was incorporated into the soil in October 1996 as described by Phiri et al. (1999). The rate of addition of sesbania biomass depended upon the growth of sesbania, which varied for the three landscape positions (Phiri et al., 1999). Maize was planted in December 1996, and maize grain yield was determined at maturity from net plots of 10 m by 10 m.

Soil and statistical analyses

Soil nitrate was determined at 10, 50, 85, and 130 days after maize planting. At each sampling time, soil was collected with a 6-cm diameter auger from 0- to 15-, 15- to 30-, and 30- to 45-cm depths. At the very end of the growing season (160 days after planting maize), soil were sampled from one pit in each plot at 15-cm intervals to 120-cm depth. Soil at this sampling time was analyzed for nitrate and ammonium.

For nitrate determination, 3 g of soil was extracted with 30 mL of 2 M KCl by shaking for 30 minutes. Then 1 mL of extract was diluted with 4 mL of distilled water, and absorbance was read at 210 nm using a deuterium lamp and a 1-cm-wide quartz cuvette (Cawse, 1967). Ammonium in the soil extract was determined by the salicylate-hypochlorite colorimetric method (Anderson and Ingram, 1993). Soil water content was determined on a subsample of soil at the time of extraction in order to calculate the dry weight of extracted soil.

At the end of the season, pits were dug in the 22 farms, and bulk density was determined at 15-cm intervals to 120-cm depth from two 100-cm^3 cores of soil collected horizontally in the side of the pit of each depth interval. The bulk density values were used to convert nitrate-N and ammonium-N values from mg kg^{-1} to kg ha^{-1}.

The statistical analyses were handled as a split plot with the three landscape positions as the main plot and the three N sources as subplots. Linear regressions were conducted for each sampling date to examine the relationship of sesbania biomass produced in the relay intercrop in year 1 with nitrate in different soil depths of the same treatment in year 2.

Results and discussions

Soil nitrate

Soil nitrate in the top 15-cm and 45-cm depths was influenced by N source, particularly late in the growing season at 85 and 130 days after maize planting (Table 1). High soil nitrate in the N fertilizer treatment resulted from application of 120 kg N ha^{-1} as calcium ammonium nitrate – one half at 18 days and the remainder at 40 days after maize planting. Despite the application of all fertilizer N before 50 days, soil nitrate was not significantly higher for the N fertilizer than other treatments until 85 days after planting (Tables 2 and 3).

At 10 days after planting – before the application of N fertilizer – soil nitrate in the 45-cm depth (Table 3), but not in the top 15-cm depth (Table 2), tended to be highest following sesbania. This relatively higher initial soil nitrate might have resulted from a flush of N mineralization during decomposition of incorporated sesbania biomass. By 85 days, soil nitrate was consistently higher in plots receiving sesbania than in the unfertilized control for both soil depths (Tables 2 and 3).

Landscape position had no effect on soil nitrate except for 0- to 15-cm depth at 85 days after planting (Table 1). Despite lower soil organic C at steep

Table 1. Analysis of variance for the effect of landscape position and N source on nitrate in two soil depths for sampling times at which effects were significant.

Source of variation	df	Significance level				
		0 to 15 cm depth		0 to 45 cm depth		
		85 days	130 days	10 days	85 days	130 days
Landscape (L)	2	0.001	0.90	0.55	0.24	0.63
N source (N)	2	0.001	0.01	0.001	0.005	0.02
L × N	4	0.01	0.25	0.50	0.58	0.41

Table 2. The effect of landscape position and N source on soil nitrate at 0- to 15-cm depth for four periods after maize planting in southern Malawi.

Treatment	Nitrate-N (kg N ha^{-1})			
	10 days	50 days	85 days	130 days
Dambo valley				
No added N	25 (9)[a]	14 (12)	24 (15)	7 (4)
N fertilizer	10 (5)	19 (13)	97 (47)	6 (5)
Sesbania	17 (12)	18 (14)	65 (32)	6 (2)
Dambo margin				
No added N	15 (7)	16 (14)	19 (13)	4 (3)
N fertilizer	12 (6)	23 (16)	81 (28)	10 (7)
Sesbania	15 (9)	20 (16)	53 (20)	4 (2)
Steep slope				
No added N	17 (6)	17 (15)	22 (16)	5 (3)
N fertilizer	20 (15)	27 (21)	41 (18)	7 (8)
Sesbania	21 (9)	24 (19)	33 (4)	7 (5)

[a] Numbers in parentheses are standard deviations.

Table 3. The effect of landscape position and N source on soil nitrate at 0- to 45-csource on soil nitrate at 0- to 45-cm depth for four periods after maize planting in southern Malawi.

Treatment	Nitrate-N (kg N ha^{-1})			
	10 days	50 days	85 days	130 days
Dambo valley				
No added N	34 (9)[a]	40 (36)	40 (10)	8 (2)
N fertilizer	19 (4)	62 (40)	130 (47)	10 (4)
Sesbania	36 (12)	64 (62)	104 (44)	11 (5)
Dambo margin				
No added N	23 (9)	46 (38)	37 (16)	7 (3)
N fertilizer	20 (7)	69 (45)	101 (23)	19 (16)
Sesbania	35 (15)	54 (42)	81 (23)	9 (4)
Steep slope				
No added N	19 (2)	46 (47)	25 (10)	10 (3)
N fertilizer	26 (3)	75 (62)	78 (18)	16 (18)
Sesbania	36 (14)	55 (14)	87 (40)	11 (5)

[a] Numbers in parentheses are standard deviations.

slopes than at dambo valleys and dambo margins (Phiri et al., 1999), soil nitrate was comparable for the three landscape positions in the absence of N inputs at all sampling times. With N inputs as either N fertilizer or sesbania biomass, soil nitrate at 85 days was higher in the dambo valley and dambo margin than on steep slopes (Table 2). When deeper soil layers were taken into account, however, all the landscape positions had comparable soil nitrate levels at 85 days (Table 3).

Soil nitrate increased during the middle of the growing season and decreased towards the end of the season. The decline in nitrate at the end of the season can be attributed to N uptake by maize and possibly other N sinks, such as leaching and denitrification. Moutonnet and Fardeau (1997) observed a similar pattern in nitrate changes during a maize-growing season on a Calcic Fluvisol.

The high soil nitrate at 85 days in the sesbania treatments suggests that the bulk of the mineralization of sesbania biomass occurred relatively late in the growing season. Nitrogen mineralization of sesbania biomass was not limited by low soil water content because rainfall following maize planting in December (Phiri et al., 1999) was sufficient for N mineralization early in the growing season. Relatively slow release of N from the incorporated sesbania biomass might be associated with the poor quality of the biomass because it contained twigs and pods as well as leaves. The sesbania in our study, which was grown and managed by farmers, might also be of lower quality than the leafy biomass of sesbania produced in research station trials, where relatively rapid mineralization has been observed (Snapp et al., 1998). The period of high N demand by maize – late vegetative and early reproductive growth – was nonetheless synchronized with the apparent maximum N supply from sesbania biomass in our study.

Because of low maize yields at these on-farm sites (Phiri et al., 1999), excess added N might accumulate in the soil at the end of the growing season. Figure 1 shows that N from the added N fertilizer accumulated as inorganic N at all soil depths to 120 cm. Nitrogen from added sesbania also accumulated as inorganic N in the soil, but it was essentially confined above 60-cm depth. These results suggest that some added N leached into the subsoil, and the leaching of added N to deep soil layers appeared to be more serious with N fertilizer than sesbania. These data agree with findings of Olsen et al. (1970) that considerable quantities of N accumulate as nitrate in the soil profile in the dry regions, when high rates of N were applied. Other researchers in Malawi have suggested that N losses on smallholder farms, whether from organic or inorganic N sources, are primarily due to leaching (Thornton et al., 1995).

High variability in the soil nitrate data is not unexpected (Weber et al., 1995) given the wide range of management employed by farmers in this farmer-managed trial and the diversity of soil environments encountered (Kanyama-Phiri et al., 1998). High variability in the nitrate data might account for the few observed effects of landscape position on soil nitrate. However, despite the challenges associated with high spatial variability, pronounced effects of sesbania and N fertilizer on soil nitrate could be detected.

Sesbania biomass and soil nitrate relationships

Maize grain yield for the sesbania treatment (mean = 1.7 Mg ha^{-1}) was comparable to grain yield for N fertilizer treatment (mean = 2.1 Mg ha^{-1}) and much

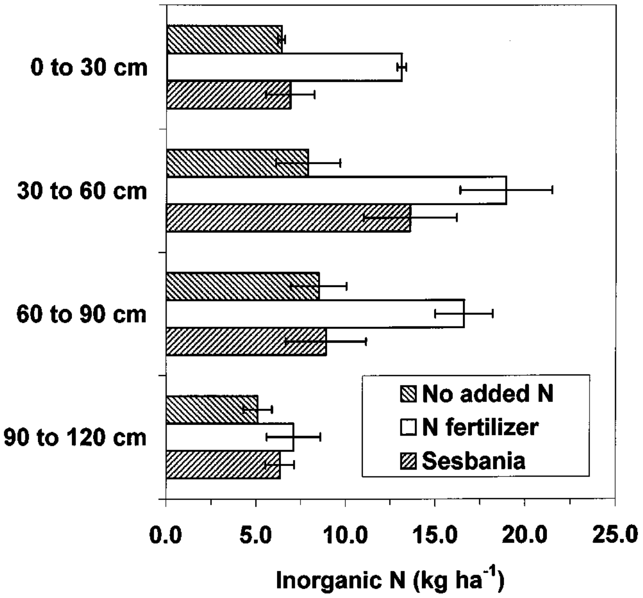

Figure 1. Effect of N source on accumulation of inorganic N in soil layers at the end of the maize growing season in southern Malawi. Data for the top 60 cm are averages for three landscape position, but results for > 60-cm depth are primarily averages for only the dambo valley and dambo margin sites because soils on the steep slopes were shallow. Horizontal bars represent standard deviations.

higher than yield without N inputs (mean = 0.5 Mg ha^{-1}). The ability of sesbania biomass to release N for maize growth is supported by the levels of soil nitrate, which were directly related to the amount of incorporated sesbania biomass.

At 85 days after maize planting, when soil nitrate peaked, soil nitrate in the top 15 cm was directly related to the amount of sesbania biomass incorporated before planting maize (Figure 2). The relationship was better represented by a logarithmic (r^2 = 0.75) than a linear fit (r^2 = 0.53). At 130 days, soil nitrate in the top 15 cm was not longer correlated with added sesbania biomass, but nitrate in the top 45 cm remained directly related to added sesbania biomass (Figure 3). By 130 days, much of the added N in the topsoil had either been taken up by maize or leached to lower soil layers.

Conclusions

New soil-fertility recommendations and technologies based on combinations of organic and inorganic inputs should consider the temporal patterns in N availability from the inputs. The relatively slow build-up of soil nitrate fol-

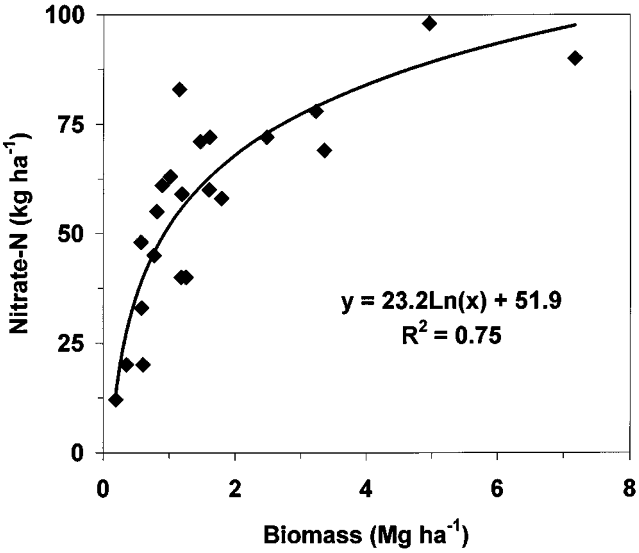

Figure 2. Relationship between biomass of incorporated sesbania and soil nitrate in the top 15 cm at 85 days after planting maize in southern Malawi.

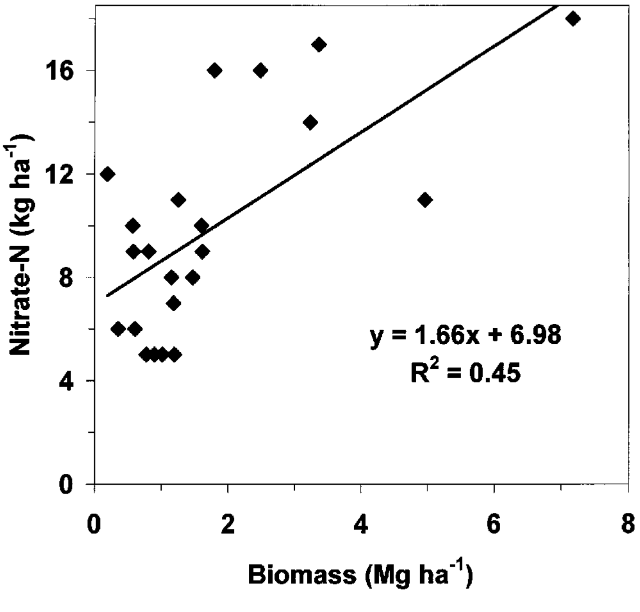

Figure 3. Relationship between biomass of incorporated sesbania and soil nitrate in the top 45 cm at 130 days after planting maize in southern Malawi.

lowing incorporation of sesbania in our study suggests that a basal application of N fertilizer may combine well with sesbania-maize relay cropping system. The basal fertilizer would supply N for early maize growth whereas N released from sesbania could supply N for the later N demand of maize. This is in contrast with suggested combinations of inorganic and organic fertilizer based on the use of high-quality organic sources for a rapid supply of available N (Snapp et al., 1998). For example, mixed cropping systems with gliricidia [*Gliricidia sepium* (Jacq.) Walp.] face the challenge of excess early release of N and insufficient N later in the growing season to meet the N demand of maize (S Ikerra and J Maghembe, personal communication, 1997).

Our results suggest that farmers should consider the appropriate timing of fertilizer applications in combination with organic-based technologies for soil-fertility improvement. Farmers in the Songani watershed of Malawi are experimenting with researchers on different combinations of fertilizer timing with organic inputs (Kanyama-Phiri et al., 1998) in order to match the N supply from organic and inorganic sources with crop's requirement for N.

References

Anderson JM and Ingram JSI (1993) Tropical Soil Biology and Fertility: A Handbook of Methods. CAB International, Wallingford, UK

Cawse PA (1967) The determination of nitrate in soil solutions by ultraviolet spectrophotometry. Analyst 92: 311–315

Ghai SK, Rao DLN and Batra L (1985) Comparative study of the potential of sesbanias for green manuring. Tropical Agriculture (Trinidad) 62: 52–56

Hartemink AE, Buresh RJ, Jama B and Janssen BH (1996) Soil nitrate and water dynamics in sesbania fallows, weed fallows and maize. Soil Science Society of America Journal 60: 568–574

Kanyama-Phiri GY, Snapp SS and Minae S (1998) Partnership with Malawian farmers to develop organic matter technologies. Outlook on Agriculture 27: 167–175

Moutonnet P and Fardeau JC (1997) Inorganic nitrogen in solution collected with tensionic samplers. Soil Science Society of America Journal 61: 822–825

Olsen RJ, Hensler RF, Attoe OJ, Witzel SA and Peterson LA (1970) Fertilizer nitrogen and crop rotation in relation to movement on nitrate nitrogen through soil profiles. Soil Science Society of America Proceedings 34: 448–452

Phiri ADK, Kanyama-Phiri GY and Snapp SS (1999) Maize and sesbania production in relay cropping at three landscape positions in Malawi. Agroforestry Systems (this issue)

Saka AR, Green RI and Ng'ong'ola DH (1995) Soil management in sub-Saharan Africa. Proposed soil management action plan in Malawi. Report to the World Bank. Lilongwe, Malawi, 111 pp

Snapp SS, Mafongoya PL and Waddington S (1998) Organic matter technologies to improve nutrient cycling in smallholder cropping systems of southern Africa. Agriculture Ecosystems and Environment 71: 185–200

Thornton PK, Saka AR, Singh U, Kumwenda JDT, Brink JE and Dent JB (1995) Application of a maize crop simulation model in the central region of Malawi. Experimental Agriculture 31: 213–226

Weber G, Chude V, Pleysier J and Oikeh S (1995) On-farm evaluation of nitrate-nitrogen dynamics under maize in the northern guinea savanna of Nigeria. Experimental Agriculture 31: 333–344

Yamoah C (1988) The potential of alley cropping for hillside farming in Rwanda. Appropriate Intermediate Technology 15(1): 28–30

Yamoah CF and Burleigh JR (1990) Alley cropping *Sesbania sesban* (L.) Merill with food crops in the highland region of Rwanda. Agroforestry Systems 10: 169–181