Nutr Cycl Agroecosyst (2012) 94:85–96
DOI 10.1007/s10705-012-9528-7

ORIGINAL ARTICLE

Nitrogen leaching and indirect nitrous oxide emissions from fertilized croplands in Zimbabwe

F. Mapanda · M. Wuta · J. Nyamangara · R. M. Rees

Received: 18 February 2012 / Accepted: 13 August 2012 / Published online: 22 August 2012

Abstract Agricultural efforts to end hunger in Africa are hampered by low fertilizer-use-efficiency exposing applied nutrients to losses. This constitutes economic losses and environmental concerns related to leaching and greenhouse gas emissions. The effects of NH_4NO_3 (0, 60 and 120 kg N ha^{-1}) on N uptake, N-leaching and indirect N_2O emissions were studied during three maize (*Zea mays* L.) cropping seasons on clay (Chromic luvisol) and sandy loam (Haplic lixisol) soils in Zimbabwe. Leaching was measured using lysimeters, while indirect N_2O emissions were calculated from leached N using the emission factor methodology. Results showed accelerated N-leaching (3–26 kg ha^{-1} $season^{-1}$) and N-uptake (10–92 kg ha^{-1}) with N input. Leached N in groundwater had potential to produce emission increments of 0–94 g N_2O-N ha^{-1} $season^{-1}$ on clay soil, and 5–133 g N_2O-N ha^{-1} $season^{-1}$ on sandy loam soil following the application of NH_4NO_3. In view of this short-term response intensive cropping using relatively high N rate may be more appropriate for maize in areas whose soils and climatic conditions are similar to those investigated in this study, compared with using lower N rates or no N over relatively larger areas to attain a targeted food security level.

Keywords Fertilizer · Leaching · Lysimeter · Maize · Nitrogen · Nitrous oxide

Introduction

Research in southern Africa has established that in a manner dependent on seasonal rainfall distribution, the retention of N in topsoil for crop uptake is offset by nutrient leaching (e.g. Mapiki et al. 1993; Nyamangara et al. 2003), soil erosion and runoff (e.g. Nyamadzawo et al. 2006). Rainfall is a major input in cropping systems but, unlike fertilizer, it is difficult to control, and too much or too little rainwater is not avoidable. The relationship between nutrient leaching and greenhouse gas emissions is poorly understood because of limited tracking of leached-N through groundwater and rivers (IPCC 2000). The IPCC guidelines for

F. Mapanda (✉) · M. Wuta · J. Nyamangara
Department of Soil Science and Agricultural Engineering,
University of Zimbabwe, Mt. Pleasant Drive,
P.O. Box MP167, Mt. Pleasant, Harare, Zimbabwe
e-mail: faraimaps@yahoo.com

F. Mapanda
Department of Research and Specialist Services,
Chemistry and Soil Research Institute, Fifth Street
Extension, P.O. Box CY550, Causeway, Harare,
Zimbabwe

J. Nyamangara
International Crops Research Institute for the Semi-Arid
Tropics, Matopos Research Station, P.O. Box 776,
Bulawayo, Zimbabwe

R. M. Rees
Scottish Agricultural College, West Mains Road,
Edinburgh EH9 3JG, UK

national greenhouse gas inventories presented an emission factor of 0.0075 kg N_2O-N kg^{-1} leached-N (de Klein et al. 2006). This N_2O is produced from groundwater that reaches the surface as part of wetlands or rivers and is classified under indirect N_2O emissions from managed soils. An understanding of the contribution of rainfall patterns and N input to N leaching and indirect N_2O emissions may help minimize the contribution of croplands to greenhouse gas emissions and nutrient losses while maintaining reasonable crop productivity.

In justifying the need for the indirect N_2O emissions category, Nevison (1999) indicated that researchers began noticing elevated concentrations of dissolved N_2O in groundwater and rivers (which were not included in the short-term direct N_2O emission measurements), and thus, this category would make it possible to consider both short and long term fates of applied N in agriculture.

The use of lysimeters is a proven method for measuring movement of water and chemicals through the soil profile (Derby et al. 2002; Goss and Ehlers 2009). Hansen et al. (2000) classified lysimeters according to drainage (zero-, low- and equilibrium-tension), packing of test material (block or excavated intact, Ebermayer or in situ and filled-in) and method of measuring water content (weighing and non-weighing). The zero-tension lysimeters have been widely used worldwide, while repacking of soil profiles has been employed in some studies from southern Africa (e.g. Nyamangara et al. 2003; Kamukondiwa and Bergstrom 2007). In this method soil is packed simulating its bulk density under undisturbed conditions and using a number of soil horizons of the same thickness and types as found in the natural state (Hansen et al. 2000). The method is relatively simple although gravity drainage (zero-tension) can only occur when the soil above the drain exceeds field capacity, which may cause an unrealistic soil moisture regime or affect crop growth (Derby et al. 2002). Nevertheless, Webster et al. (1993) showed that the use of field lysimeters in measuring N leaching may give comparable N concentrations to those of ceramic cups, except for the differences in drainage patterns.

The aim of this study was to understand the relationships between fertilizer-N input, N leaching losses (and indirect N_2O emissions) and crop productivity in Zimbabwe. The objectives were to determine the amount N leached below the maize rooting zone using field lysimeters, assess the recovery of applied-N in maize, and relate these to indirect N_2O emissions, thus determining the long term fate of applied N. It was hypothesised that the partitioning of N inputs between crop, N-leaching and N_2O emissions could be optimized for high crop productivity and low losses.

Materials and methods

Study sites

The study was conducted during Seasons I (2006/2007), II (2007/2008) and III (2008/2009) at the University of Zimbabwe Farm (UZ-Farm) located 15 km north of Harare (31°00′48″E; 17°42′24″S, 1,501 m above sea level) and at the Domboshawa Training Centre (DT-Centre) located 30 km north-east of Harare (31°08′31″E; 17°36′17″S, 1,540 m above sea level). The two sites experience cold-dry winters and hot-wet summers (subtropical), with average annual rainfall of about 850–920 mm and average annual temperature of about 18–21 °C. The total weekly rainfall received at the UZ-Farm and DT-Centre during the three seasons is shown in Fig. 1. The red clay soil at the UZ-Farm is classified (FAO) as Chromic luvisol, derived from dolerite, while the brown sandy-loam soil (Haplic lixisol) at the DT-Centre was derived from granite.

Lysimeter installation and soil profiles characterization

A lysimeter station was constructed consisting of 24 repacked and gravity drained lysimeters at the UZ-Farm between August and November of 2006 using the procedure described by Nyamangara et al. (2003). The lysimeters (square-shaped with surface area of 1 m^2, depths of 1.1 m and an outflow pipes at the bottom were constructed from 1.6 mm thick galvanised sheets. The boxes were laid down in the field with their outflow pipes connected to a centralized and roofed drainage-collection pit by polythene pipes (reinforced, Ø 20 mm) laid at a slope of 27 % to facilitate gravity drainage. Prior to repacking of the soil profiles a 1-mm stainless steel mesh was fixed at the bottom of the lysimeter box and covered by a 0.1 m gravel layer, leaving exactly 1 m depth for each soil profile. The soil layers from the UZ-Farm and DT-Centre sites were repacked

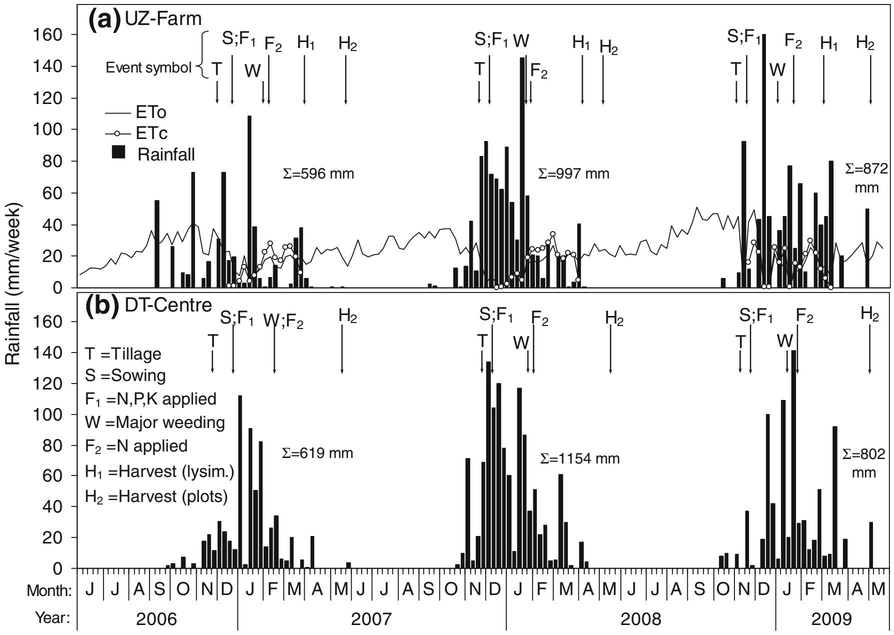


Fig. 1 Weekly rainfall received and some key events timelines at the UZ-Farm (**a**) and DT-Centre (**b**), including pan evaporation (ET_o) and estimated crop water need (ETc.) at the UZ-Farm during the 36 months of study starting June (J) 2006

replicating the number of soil horizons, their thickness and bulk density under undisturbed conditions. The identification of horizons were done from a pit at each site according to Bennett (1985), while soil particle size distribution, bulk density, pH, exchangeable bases, cation exchange capacity, total N and organic C were determined for each horizon using the methods described by Mushiri and Chifamba (1998).

Treatments and management

The leaching experiment was set up at the UZ-Farm. The treatments were: (1) no fertilizer-N applied (control), (2) NH_4NO_3-N, applied at 60 kg ha^{-1}, and (3) NH_4NO_3-N, applied at 120 kg N ha^{-1}. The treatments were replicated four times for the two soil types, making a total of 24 lysimeters randomly laid out in an arc-shaped arrangement with four equal blocks facing a common drainage-collection pit.

Some experimental plots, with identical treatments (but without lysimeters), were laid out at the same time and maintained under similar management at the UZ-Farm (adjacent to the lysimeters), and at the DT-Centre. A randomised complete block design was used to establish the experimental plots (5 m × 6 m). Some key events at the two sites are shown in Fig. 1.

Experimental plots and the field surrounding the lysimeter station were ploughed to about 0.2 m soil depth and disced before sowing each season. Sowing positions were marked at the centre of each lysimeter and in the field plots at 0.9 m × 0.45 m spacing using a hoe. A locally common hybrid maize variety [SC513, with 57 days to silk and 126 days to maturity (Seed-Co 1998)] was sown (to two plants per position).

Mineral-N fertilizer (NH_4NO_3, 34.5 % N) was applied at 0, 60 and 120 kg N ha^{-1}, 50 % at sowing and the remaining 50 % at 6 weeks after sowing (next to crop) each season. In addition, annual basal dressings of P (30 kg ha^{-1}, as single super phosphate) and K (30 kg ha^{-1}, as muriate of potash) were applied at all sowing positions before sowing the seed. In practice farmers are generally recommended to apply 300–400 kg ha^{-1} of an N:P:K (8.0:7.0:6.3) fertilizer for a target yield of 6,000–7,000 kg ha^{-1} in Zimbabwe (ARI 2002). At this rate 19–25 kg K ha^{-1} and 21–28 kg P ha^{-1} are supplied, so the basal dressings of P and K were to ensure that these nutrients are not limiting. The field bordering the lysimeter station and experimental plots was also maize-cropped to protect the experiments and mitigate the border effects. Weed control was done manually using hoes whenever required.

Sampling

Drainage from lysimeters was collected and measured following every rainfall event using 20 L polythene buckets graduated at every 1L. For volumes less than 1 L a measuring cylinder was used. The sampling frequencies ranged from twice a day to three times in 7 days, depending on rainfall amount and distribution. The drainage was also sub-sampled into 0.5 L clear polythene bottles that had been cleaned by soaking in dilute HCl overnight and rinsed thoroughly with distilled water for laboratory analyses. Immediately after sampling, a drop of concentrated HCl was added into each sample before tightly sealing the bottles to preserve the samples during transportation for immediate laboratory analysis of NH_4^+-N and NO_3^--N. Evapotranspiration was estimated using daily maximum and minimum temperatures, wind speed, relative humidity and pan evaporation data from an Automatic Weather Station located 500 m from the lysimeter station, and the FAO (2000) estimation guidelines.

The maize crop was harvested from the lysimeters at late dough stage which was 15–17 weeks after sowing (H_1, Fig. 1a). Generally the rate of N uptake at this stage would have decreased considerably (Ritchie et al. 1992) while a substantial amount of leaf N may have been lost later during leaf senescence, making this stage a reasonable compromise for assessing total N uptake. Cumulative N uptake at dough stage may be proportional to about 70–75 % of total N uptake under water stressed conditions, or 77–86 % of total uptake in irrigated systems (e.g. Lemaire et al. 1996). Aboveground crop material from each lysimeter was removed, chopped into smaller pieces, air-dried for 7 days and oven dried at 70 °C till constant weight before being weighed, ground and passed through a 2-mm mesh sieve. Maize from the plots was harvested air-dry at 22–24 weeks after sowing (H_2 in Fig. 1a, b), by cutting all aboveground material in a net plot area of 3 m × 3 m. The harvests were subdivided into grain, shelled-cob and maize residue, and weighed. Sub-samples from each subdivision were collected for moisture correction and plant N determination.

Analysis of samples

Water samples collected from lysimeters were analysed for NO_3^--N and NH_4^+-N using the method described by Okalebo et al. (1993). The NH_4^+-N was determined after steam distillation of 10 ml sample in approximately 0.2 g of MgO i.e., trapping the NH_3 in boric acid plus indicator (bromocresol-methyl red) solution. The distillate (50 ml) was titrated with 0.005 M H_2SO_4 using a micro-burette (10 ml capacity). The NO_3^--N was determined in the same sample by adding Devarda's alloy to reduce NO_3^--N to NH_4^+-N and distilling again into fresh boric acid, followed by titration with 0.005 M H_2SO_4. Total plant N was determined using the semi-micro Kjeldahl method (Bremner and Mulvaney 1982).

Indirect N_2O emissions, N recovery efficiency and partial N budget

The indirect N_2O emissions from N leaching, which show the contribution of applied N to N_2O emissions in a longer term than direct N_2O emissions (Nevison 1999), were calculated from N leached using the IPCC emission factor, i.e. 0.0075 kg N_2O-N kg^{-1} leached N, with an uncertainty range of 0.05–2.5 % (de Klein et al. 2006). Nitrous oxide emission increments from applied N was estimated as the difference in emissions between the treatment with no N applied and the treatment with NH_4NO_3-N applied.

Nitrogen recovery efficiency, amount of N in crop (above ground biomass) expressed as a fraction of the amount applied (Bruulsema et al. 2004), was also estimated as the difference in N uptake between the treatment with no applied-N and the treatment that received NH_4NO_3-N, divided by that amount of N applied. Addition of N fertilizer to soil has been shown to stimulate the uptake of native soil N through a priming effect recently termed "added N interaction", and this interaction is greater in soils with high soil organic C (Rao et al. 1991). It was assumed that this priming effect would be insignificant since soil organic C of the two studied soils was relatively low. Partial N budgets from the lysimeters were estimated from the summation of N in above-ground maize biomass and in drainage for each treatment. This was meant to give an indication of the relative proportion of applied N in maize and drainage at the time of the first harvest (H_1 in Fig. 1a).

Data analysis

Homogeneity of variance and normality tests were carried out on drainage and plant data using the

Levene's and Kolmogorov–Smirnov's Tests, respectively, at 5 % level. Two-way analysis of variance was carried out to establish any significant treatment and season effects ($P < 0.05$). Kruskal–Wallis test was used instead for the data that did not meet all assumptions of normality and homogeneity of variance, even after transformation, and a pair-wise separation of significantly different treatment means was done using the Mann-Witney test. Genstat 7.2 (Discovery Edition, Lawes Agricultural Trust UK) and SPSS 8.0 (SPSS Inc., USA) statistical packages were used in the statistical analysis of data.

Results

Characteristics of soil profiles

Some properties of the profiles from each site at the start of the experiment are given in Table 1. Both profiles had higher clay content in the subsoil than in top soil, and this was more apparent for the DT-Centre profile that had sandy clay among the subsoil textures. The rate of decrease in soil organic C (0.02 % m^{-1}, $r^2 = 0.97$ for the UZ-Farm profile; 0.002 % m^{-1}, $r^2 = 0.20$ for the DT-Centre profile) generally indicated higher leaching of soil organic C in the DT-Centre profile that had lower CEC, exchangeable bases and pH than the UZ-Farm profile. Despite the apparently insufficient amounts of exchangeable K, most Zimbabwean soils do not show K deficiency mainly because K is contained in mica and feldspar minerals, making it abundant in most soils derived from granite, basalt and dolerite in Zimbabwe (Piha 1995). A review by Nyamangara et al. (2000) showed adequate to high (>0.1 $cmol^{(+)}$ kg^{-1}) K levels in 94 % of Zimbabwe's surveyed smallholder farming areas.

Drainage

Total drainage from the lysimeters under different NH_4NO_3-N rates on clay soil were nil in Season I, 204–247 mm (i.e., 20–25 % of total rainfall) in Season II, and 128–193 mm (15–22 % of total rainfall) in Season III (Fig. 2a). Higher drainage was found from the sandy loam soil: 80–107 mm (13–18 % of total rainfall) in Season I, 247–273 mm (25–27 % of total rainfall) in Season II, and 200–260 mm (23–30 % of total rainfall) in Season III (Fig. 2b). The highest drainage from both soils were in Season II, although there was no significant effect ($P > 0.05$) of N rate on drainage in this season.

In Season II about 70–74 % of total drainage was found in December alone, while drainage in Season III was fairly distributed between December and March under each treatment. The treatment with 120 kg N ha^{-1} had the lowest drainage ($P < 0.05$) compared with other treatments on the clay soil in Season III, and both treatments having NH_4NO_3 also had lower

Table 1 Particle size (PS) distribution, bulk density (BD), pH, exchangeable (Ex.) bases, cation exchange capacity (CEC) and total N and organic C (OC) of soil profiles from the UZ-Farm and DT-Centre that were used in the installation of a lysimeter station at the UZ-Farm

Profile	Depth (cm)	PS distribution[a] (%: sand, silt, clay)	BD (g cm^{-3})	pH	Ex.Ca ($cmol^{(+)}$ kg^{-1})	Ex. Mg ($cmol^{(+)}$ kg^{-1})	Ex. K ($cmol^{(+)}$ kg^{-1})	Ex. Na ($cmol^{(+)}$ kg^{-1})	CEC ($cmol^{(+)}$ kg^{-1})	Total N (%)	OC (%)
UZ-Farm	0–14	26, 18, 56	1.31	6.5	8.6	3.6	0.21	0.14	13.9	0.14	2.41
	14–42	21, 15, 64	1.60	6.4	8.0	2.7	0.08	0.13	11.5	0.11	1.63
	42–89	16, 24, 60	1.45	6.7	5.4	1.9	0.05	0.12	12.9	0.07	0.93
	89–110	32, 21, 47	1.68	6.4	4.7	1.6	0.05	0.12	6.5	0.11	0.34
DT-Centre	0–11	81, 05, 14	1.72	5.5	1.3	0.7	0.19	0.10	4.2	0.19	1.33
	11–33	77, 06, 17	1.69	5.6	1.2	0.4	0.09	0.10	2.9	0.12	0.70
	33–67	57, 06, 37	1.81	5.5	2.0	0.6	0.08	0.09	3.4	0.10	0.88
	67–96	60, 18, 22	1.63	5.9	1.7	0.5	0.06	0.08	4.3	0.12	–
	96–136	58, 06, 36	1.73	5.3	1.9	0.7	0.05	0.09	4.1	0.10	0.85

[a] According to the FAO, International Soil Reference and Information Centre soil classification system (sand, 63–2,000 μm; silt 2–63 μm; clay <2 μm)

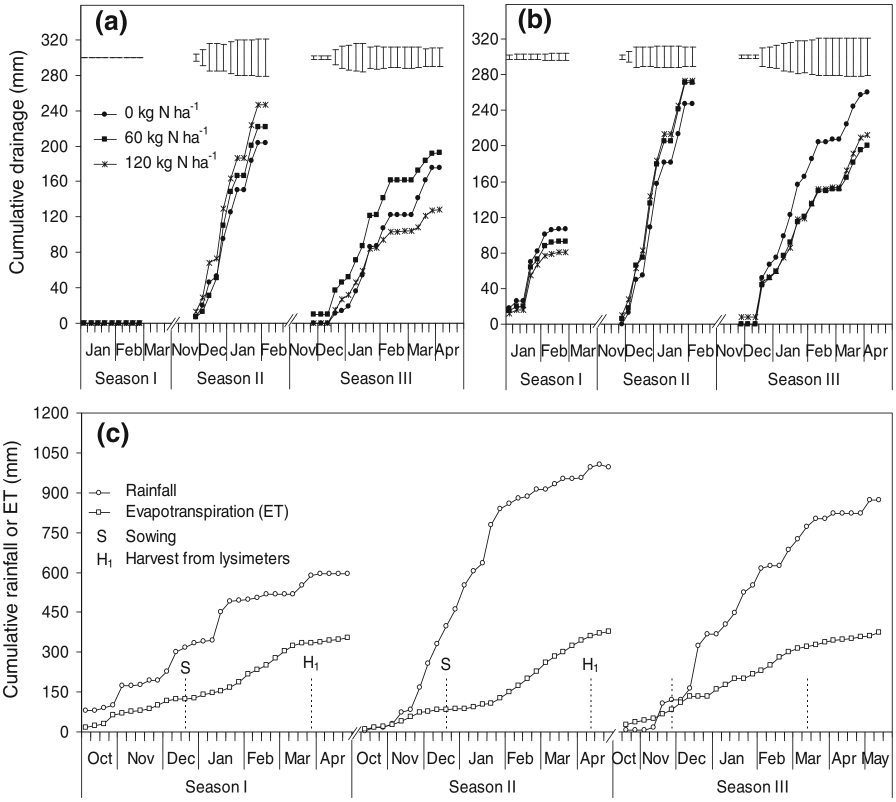


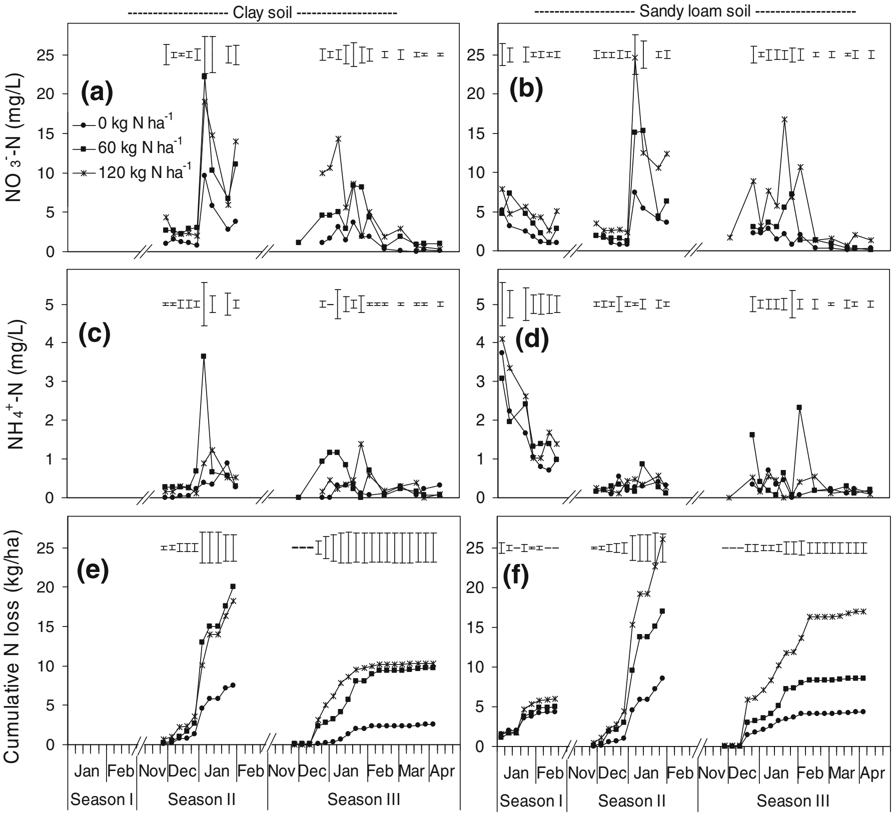
Fig. 2 Cumulative drainage from the UZ-Farm (**a**) and DT-Centre (**b**) profiles under different treatments and the cumulative rainfall and evapotranspiration at the UZ-Farm (**c**). *Error bars* denote standard errors of the difference of treatment means

drainage ($P < 0.05$) than the control treatment on the sandy loam soil. The estimated evapotranspiration was proportional to 59, 38 and 43 % of the total rainfall at the UZ-Farm from Seasons I, II and III, respectively (Fig. 2c). The partial water budget using both drainage and evapotranspiration therefore accounted for up to 77, 65 and 73 % of the total rainfall received at the lysimeter station during Seasons I, II and III, respectively. The unaccounted balance of the water budget was likely to have been a consequence of run-off and water retained in the profiles. The FAO procedures for estimating crop evapotranspiration were revised to use crop coefficients that allow estimates for a wide range of crops and water management practices (Smith 2000). However, the estimates are not flexible to crop performance, e.g. when crop biomass differs under different N rates.

Nitrogen leaching

The concentrations of leached NO_3^--N (0–20.0 mg l^{-1} on clay soil; 4.3–26.2 mg l^{-1} on sandy loam soil, Fig. 3a, b) and NH_4^+-N (0–3.6 mg l^{-1} on clay soil; 0–4.1 mg l^{-1} on sandy loam soil, Fig. 3c, d) responded significantly ($P < 0.05$) to NH_4NO_3 rate, with the highest concentration peaks alternating between the 60 and the 120 kg N ha^{-1}. These peaks were found 2–3 weeks after the first NH_4NO_3 application, while lower peaks were found within or following a week after the second NH_4NO_3 application. Total N leached ranged from 0 to 20.0 kg N ha^{-1} on the clay soil and 4.3–26.2 kg N ha^{-1} on the sandy loam soil, and was highest ($P < 0.05$) in Season II when the highest drainage was recorded and least in Season I when the lowest drainage was recorded (Fig. 3e, f). On the clay soil similar amounts of N loss were found under the 60 and 120 kg N ha^{-1} treatments in both Seasons II and III. These losses were equivalent to up to 0.21 kg N kg^{-1} applied-N under the 60 kg N ha^{-1} rate and to 0.09 kg N kg^{-1} applied-N under the 120 kg N ha^{-1} rate. However, on the sandy loam soil N losses showed a positive linear relationships with NH_4NO_3-N rate during seasons II and III ($P < 0.05$; r^2, 0.72), and the loss was equivalent to up to 0.14 kg N kg^{-1} applied-N at both 60 and 120 kg N ha^{-1} rates.

Fig. 3 The concentrations of NO_3^--N (**a**, **b**), NH_4^+-N (**c**, **d**) and cumulative total-N lost through leaching (**e**, **f**) from the respective soils in field lysimeters under different treatments



Crop responses and N use efficiency

The aboveground biomass and total N-uptake of maize grown on lysimeter profiles and on experimental plots responded positively ($P < 0.05$) to increasing fertilizer applications in all seasons (Table 2). The total amount of N taken up by maize from the clay soil at dough stage was proportional to 35–68 % (mean: 54 %) of the total amount of N taken up at physiological maturity from plots at the same site. These proportions had no correlation with treatment, and excluded Season I (with the least rainfall) in which higher N uptake was noted from maize grown in the lysimeters than in the surrounding plots. It was observed that during Season I the prolonged dry period in February (Fig. 1a) that induced some moisture stress on maize on plots did not cause a similar stress on the maize grown in the lysimeters. Maize biomass accumulation and N uptake from the lysimeters were therefore less affected by dry conditions during Season I. At the DT-Centre rainfall was excessive during Season II (Fig. 1b) hence the least biomass and N uptake were recorded at this site.

Results of N uptake from the experimental plots (Table 2) showed a N recovery efficiency of 0.28–0.46 kg N kg^{-1} N applied, i.e. 28–46 % (mean: 38 %) on the clay soil and 12–49 % (mean: 30 %) on the sandy loam soil. Nitrogen recovery was season dependent on the sandy loam soil (not more than 13 % in Season II with relatively uneven rainfall distribution), while on the clay soil it was rate dependent. The 120 kg N ha^{-1} gave a better N recovery (39–46 %) than the 60 kg N ha^{-1} (28–38 %) on the clay soil.

Calculated indirect N_2O emissions

Indirect N_2O emissions from drainage ranged from nil to 7.8 mg N_2O-N m^{-2} $week^{-1}$ on the clay soil and from nil to 8.1 mg N_2O-N m^{-2} $week^{-1}$ on the sandy loam soil, while less than 2.7 mg N_2O-N m^{-2} $week^{-1}$ for the treatment with no NH_4NO_3 on both soils (Fig. 4). The highest indirect emission peaks from each season coincided with the rainfall peak period and followed NH_4NO_3 application events. The second highest peaks were observed in the last week of January (characteristic of all seasons), which was

Table 2 Aboveground biomass (AGB) and total N uptake by maize harvested from field lysimeters at dough stage (H_1) at the UZ-Farm, and from experimental plots at physiological maturity (H_2) at the UZ-Farm and DT-Centre in three seasons

Treatment	UZ-Farm (clay)				DT-Centre (sandy loam)			
	H_1		H_2		H_1		H_2	
	AGB (kg ha^{-1})	N (kg ha^{-1})	AGB (kg ha^{-1})	N (kg ha^{-1})	AGB (kg ha^{-1})	N (kg ha^{-1})	AGB (kg ha^{-1})	N (kg ha^{-1})
Season I								
0 kg N ha^{-1}	7,762^{c}	53^{d}	6,055^{ab}	39^{a}	3,562^{c}	20^{b}	2,774^{ab}	19^{ab}
60 kg N ha^{-1}	8,525 ^{cd}	61de	7,613^{bc}	58^{bc}	6,670^{e}	42^{d}	4,682^{c}	41^{cd}
120 kg N ha^{-1}	9,043^{de}	63^{e}	10,906^{ef}	92^{d}	7,380^{e}	45^{d}	5,700^{cd}	53^{d}
Season II								
0 kg N ha^{-1}	1,692^{a}	9^{a}	4,213^{a}	26^{a}	579^{a}	2^{a}	1,434^{a}	10^{a}
60 kg N ha^{-1}	4,345^{b}	23^{b}	6,505^{bc}	43^{ab}	2,218^{b}	12^{b}	2,040^{ab}	17^{ab}
120 kg N ha^{-1}	5,014^{bc}	31^{bc}	9,974^{de}	73^{c}	3,156^{c}	17^{b}	2,534^{ab}	25^{b}
Season III								
0 kg N ha^{-1}	4,450^{b}	24^{b}	5,704^{ab}	37^{a}	2,599^{b}	14^{b}	3,950^{bc}	28^{b}
60 kg N ha^{-1}	6,335^{bc}	35^{c}	8,172^{cd}	60^{c}	4,466^{d}	31^{c}	6,843^{d}	53^{d}
120 kg N ha^{-1}	11,063^{e}	53^{d}	12,857^{f}	92^{d}	10,627^{f}	62^{e}	10,145^{e}	87^{e}
Significance	*	*	*	*	*	*	*	*
CV (%)	28.6	33.5	17.3	18.4	27.1	39.6	26.3	23.5
SED	1,308	9	977	7	879	8	827	6

* Significant at the 0.05 probability level; Different letters denote significant differences

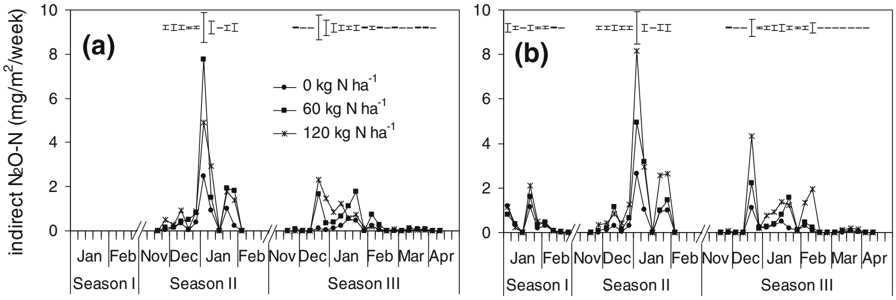


Fig. 4 Calculated indirect N_2O emissions from drainage of the UZ-Farm (**a**) and DT-Centre (**b**) profiles under different treatments during the three seasons at the UZ-Farm

within or following a week after the second N-fertilizer application.

Using the IPCC emission factor leached N in groundwater had potential to emit a cumulative total of 0–150 g N_2O-N ha^{-1} season^{-1} (mean: 57 g N_2O-N ha^{-1}) on the clay soil, and 32–197 g N_2O-N ha^{-1} season^{-1} (mean: 81 g N_2O-N ha^{-1}) on the sandy loam soil. Some indirect N_2O emission increments of 0, 94 and 54 g N_2O-N ha^{-1} could be estimated on the clay soil with 60 kg NH_4NO_3-N ha^{-1} relative to the control treatment in Seasons I, II and III, respectively. In contrast, lower increments (5, 63 and 31 g N_2O-N ha^{-1} for Seasons I, II and III, respectively) could be estimated on the sandy loam soil with the same N rate, and this difference basically reflected higher N-leaching losses from the control treatment on the sandy loam soil than on the clay soil. With a fertilizer rate of 120 kg N ha^{-1} on the clay soil the indirect N_2O emission increments showed no considerable difference from those that may be caused by the 60 kg NH_4NO_3-N ha^{-1} in all seasons. However, on the sandy loam soil the indirect N_2O emission increments were higher with the 120 kg N ha^{-1} (13, 132 and 95 g N_2O-N ha^{-1} for Seasons I, II and III, respectively) than with half this rate.

Table 3 The relative partial N budget (±standard deviation) from leaching losses and crop uptake under different treatments at the UZ-Farm and DT-Centre in Seasons I to III

Soil	UZ-Farm (clay)			DT-Centre (sandy loam)		
NH_4NO_3 applied (kg N ha^{-1})	0 (kg ha^{-1})	60 (kg ha^{-1})	120 (kg ha^{-1})	0 (kg ha^{-1})	60 (kg ha^{-1})	120 (kg ha^{-1})
Season I						
N-lost by leaching	0.0	0.0	0.0	4.3 ± 0.2	5.0 ± 0.6	6.0 ± 0.8
N-uptake by maize crop	53.0 ± 4.1	60.8 ± 9.0	63.2 ± 12.4	19.7 ± 2.9	42.3 ± 7.6	45.3 ± 3.3
N accounted from leaching and uptake	53 ± 4	61 ± 9	63 ± 12	24 ± 3	47 ± 8	51 ± 4
[a]NH_4NO_3-N indirectly accounted	–	8 ± 13	10 ± 16	–	23 ± 12	27 ± 7
Season II						
N-lost by leaching	7.5 ± 1.1	20.0 ± 5.8	18.3 ± 3.9	8.5 ± 0.6	17.0 ± 4.7	26. 2 ± 7.2
N-recovered by maize crop	8.9 ± 1.6	22.5 ± 4.4	30.6 ± 8.7	2.3 ± 1.8	12.1 ± 7.6	17.2 ± 2.3
N accounted from leaching and uptake	16 ± 3	43 ± 10	49 ± 13	11 ± 2	29 ± 12	43 ± 10
[a]NH_4NO_3-N indirectly accounted	–	27 ± 13	33 ± 16	–	18 ± 14	32 ± 12
Season III						
N-lost by leaching	2.5 ± 0.6	9.8 ± 1.0	10.4 ± 4.5	4.3 ± 1.2	8.6 ± 2.3	17.0 ± 0.8
N-recovered by maize crop	23.9 ± 2.0	34.8 ± 8.3	53.3 ± 14.5	13.7 ± 5.6	31.0 ± 7.1	63.7 ± 17.2
N accounted from leaching and uptake	26 ± 3	45 ± 9	64 ± 19	18 ± 7	40 ± 9	81 ± 18
[a]NH_4NO_3-N indirectly accounted	–	19 ± 12	38 ± 22	–	22 ± 16	63 ± 27

[a] The amount of fertilizer N was indirectly accounted from the summation of N partitioned to crop and drainage, less the similar summation of N from the control treatment

Partial N-balance

The relative partial N balance under different treatments in Seasons I, II and III at the UZ-Farm and DT-Centre are given in Table 3 for the lysimeters. The summed totals of crop-recovered (aboveground)-N and leached-N could indirectly account for 8–45 % and 23–52 % of applied N on clay and sandy loam soils, respectively. The amount of fertilizer-N accounted for using this summation depended more on season and site than on the rate of applied N. Season I with the least rainfall had the highest amount of applied N that could not be accounted for (up to 92 %) on the clay soil, while in Season III with a relatively more even rainfall distribution up to 52 % of the applied N could be accounted for as uptake and leaching losses.

Discussion

This study demonstrates the important relationships between fertilizer-N input, N-uptake (and crop yield), N-leaching and indirect N_2O emissions from leached N, and that in some cases these relationships are consistent across different soils. The relationships largely shown were accelerated N-uptake, N-leaching and thus indirect N_2O emissions with increased N input, but more important was the influence of season on these relationships. This observation highlights the importance of incorporating the characteristics of a season, particularly in terms of rainfall distribution, into the emission factors that are normally used to provide annual greenhouse gas inventories at national scale.

The findings from this study are linked to Burneya et al. (2010)'s suggestion that investment in yield improvement compares favourably with other commonly proposed climate change mitigation strategies. High crop productivity was obtained by using N rate of 120 kg ha^{-1}, except in a season where the rainfall distribution was relatively uneven, and increasing the N rate did not result in substantial increase in leached N and calculated indirect N_2O emissions per unit amount of yield. It follows therefore that high N input would make it easier to attain food security, without potentially requiring more land to be cultivated at great cost in terms of soil organic carbon (C) losses (Flynn and Smith 2010) and wider ecosystem services (Power 2010). Some cropping systems have recommended a decrease in total N input as a way to reduce direct emissions of N_2O, e.g. in Netherlands

(Kuikman et al. 2003). In these circumstances where large fertilizer applications (e.g. 400 kg N ha^{-1}) have been applied over long periods, it is likely that N accumulated in organic matter pools can counterbalance a reduction in N input. However, in relatively infertile soils from most parts of Zimbabwe and Africa in general, studies have shown low N_2O-N losses that are often below the IPCC's default emission factor of 1 % of the applied-N (e.g. Chikowo et al. 2004; Mapanda et al. 2011).

Increased N-uptake by maize was associated with high crop productivity and possibly high evapotranspiration that resulted in reduced drainage from both profiles in Season III (Fig. 2a, b). Silva et al. (2009) also reported smaller water flux densities at 0.8 m depths under treatments that received N applications in the period of high water demand in maize (tasseling, flowering and grain filling) in Brazil, which resulted in increased water uptake by the plants (257 mm, against 186 mm for treatments with no N-fertilizer). In this study, high crop productivity may also have maintained low N-leaching on the clay profile at the highest NH_4NO_3-N rate (Fig. 3e). It is therefore possible to optimise the above relationship by adopting the local general fertilizer-N recommendations rate for maize in areas whose soils and climatic conditions are similar to those investigated in this study, given that contribution of applied-N to greenhouse gas emissions was relatively low on both soils.

Drainage from the lysimeters was dependant on rainfall amounts and soil type, and was generally lower (in proportion to the amounts of rainfall received) than those reported by Nyamangara et al. (2003) who found that 45–88 % of total rainwater drained below the 1 m depth. This contrast could be largely attributed to the coarser soil texture (loamy sand) that they worked on, and the observation that their highest drainage was attributed to poor maize growth after a fungal attack. In this study the effect of crop performance on drainage (through evapotranspiration) was only observed in Season III, because in Season II all the drainage had ceased by the last week of January (Fig. 2a, b) missing much of the flowering and grain filling stage (February–March) which are associated with the highest water demand for evapotranspiration.

The results of this study provided evidence that the clay soil could retain more applied fertilizer-N at 120 kg N ha^{-1} than the sandy loam soil, although overall the gap between N recovered and N applied was relatively wide on both soils. Mineral-N movement down the soil profile has been fairly well studied in east and southern Africa and many studies have shown that when rainfall is adequate mineral-N concentrations gradually accrue in lower soil depths as the season progresses, particularly when N-fertilizer is applied (e.g. Mapiki et al. 1993; Kimetu et al. 2006; Nyamangara 2007; Bahmani et al. 2009). Kimetu et al. (2006) found increasing soil mineral-N with depth from about 8 mg kg^{-1} in the topsoil to almost double that at depths beyond 0.8 m from the surface at the end of the cropping season for N-fertilized soils. The amount of N in drainage received in one season therefore also depended on the N movement in the previous season, and the wide gap between N recovered and N applied could also be explained by possible retention of applied N in the soil profile.

The partial N budget supported indications by Raun and Johnson (1999) that grain cereal N-use-efficiency in the region has remained low being on average 29 %, and in this study 12–49 %. Fertilizer not recovered by crop is liable to losses by atmospheric emissions, surface runoff, erosion and leaching, particularly under uneven rainfall distribution. Studies by Reay et al. (2009) showed that indirect N_2O emissions may constitute about 25 % of the combined direct and indirect N_2O emissions at field scale. Results of this study and the direct emissions reported by Mapanda et al. (2011) at the same sites (and same period) showed that in Season II, with relatively uneven rainfall distribution, this would be about 22–38 % (mean: 28 %) of the combined direct emissions and indirect emissions from N leaching. These ratios were less responsive to soil type and N rate, but depended more on season. For Season III, with relatively more even rainfall distribution, the indirect emissions contributed 25–78 % (mean: 60 %) of the total emissions. Thus, rainfall distribution could also affect the proportion of direct and indirect N_2O emissions, with more N_2O emissions through leaching losses than direct emissions under uneven rainfall distribution. This highlights the urgent need for agricultural research programmes that aim to increase N use efficiency and reduce environmental degradation in sub-Saharan Africa.

Conclusion

The overall contribution of applied N to N leaching and thus indirect N_2O emissions, relative to N uptake and maize productivity, was strongly influenced by rainfall amount and distribution (season characteristics). The ratio of maize yield per unit of N leached did not decrease considerably with increasing rate of NH_4NO_3 and was largely unchanged on the sandy loam soils. In a season where rainfall was evenly distributed between December and March, high productivity in the high fertilizer treatment was able to reduce the amount of drainage from the clay soil which reduced N-leaching losses. In another season where rainfall was highly intense in December and January the highest N leaching and yield losses were observed. In addition, the potential contribution of evapotranspiration to reduced drainage was not evident because the rainfall distribution did not synchronise with the crop water demand peak towards grain filling. In view of these short-term responses intensive cropping using relatively high N rate may be more appropriate for maize in areas whose soils and climatic conditions that are similar to those investigated in this study, compared with using lower N rates or no N over relatively larger areas to attain a targeted food security level.

Acknowledgments This study was sponsored through grants from the European Union (NitroEurope Project No. 017841) for which the authors are extremely grateful. We are also grateful for the technical assistance from the Department of Physics (University of Zimbabwe).

References

ARI (2002) Simplified production factsheets on selected crops grown in Zimbabwe. Agronomy Research Institute, Dept Agric Res Ext Publication, Harare

Bahmani O, Nasab SB, Belizad M, Naseri AA (2009) Assessment of nitrogen accumulation and movement in soil profile under different irrigation and fertilization regime. Asian J Agric Res 3:38–46

Bennett JG (1985) A guide to soil and site description in Zimbabwe. Technical Handbook 6. Chemistry and Soil Research Institute. Dept Agric Res Spec Ser Publication, Harare

Bremner JM, Mulvaney CS (1982) Nitrogen–total. In: Page AL et al. (eds) Methods of soil analysis, 2nd edn. Agron Monogr 9. ASA and SSSA, Madison, WI, pp 595–624

Bruulsema TW, Fixen PE, Snyder CS (2004) Fertilizer nutrient recovery in sustainable cropping systems. In: Armstrong DL (ed) Better crops with plant food. USA, Potash and Phosphate Institute, Norcross, Georgia, pp 15–17

Burneya JA, Davis SJ, Lobella DB (2010) Greenhouse gas mitigation by agricultural intensification. In: Robertson GP, Kellogg WK (eds) Proceedings of the national academy of science of the United States of America, MI, pp 12052–12057

Chikowo R, Mapfumo P, Nyamugafata P, Giller KE (2004) Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe. Plant Soil 259:315–330

de Klein C, Novoa RSA, Ogle S, Smith KA, Rochette P, Wirth TC et al (2006) N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In: Eggleston H, Buendia L, Miwa K, Ngara T, Tanabe K (eds) 2006 IPCC guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies, Japan

Derby EN, Knighton ER, Montgomery RB (2002) Construction and performance of large soil core lysimeters. Soil Sci Soc Am J 66:1446–1453

FAO (2000) Crop evapotranspiration (guidelines for computing crop water requirements). FAO irrigation and drainage paper no. 56. Food and Agriculture Organization of the United Nations, Rome

Flynn HC, Smith P (2010) Greenhouse gas budgets of crop production–current and likely future trends. International Fertilizer Industry Association, Paris. http://www.fertilizer.org/ifacontent/download/35735/516582/version/1/file/2010_ifa_greenhouse_gas.pdf, Accessed 23 Aug 2010

Goss MJ, Ehlers W (2009) The role of lysimeters in the development of our understanding of soil water and nutrient dynamics in ecosystems. Soil Use Man 25:213–223

Hansen JB, Holm PE, Hansen EA, Hjelmar O (2000) Use of lysimeters for characterisation of leaching from soil and mainly inorganic waste materials. Nordtest Technical Report 473. http://www.nordicinnovation.net/nordtestfiler/tec473.pdf. Accessed 21 Sept 2009

IPCC (2000) Good practice guidance and uncertainty management in national greenhouse gas inventories. National Greenhouse Gas Inventories Publication, Japan. http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_6_Indirect_N2O_Agriculture.pdf. Accessed 21 Aug 2010

Kamukondiwa W, Bergstrom L (2007) Nitrate leaching in field lysimeters at an agricultural site in Zimbabwe. Soil Use Man 10:118–124

Kimetu JM, Mugendi DN, Bationo A, Palm CA, Mutuo PK, Kihara J, Nandwa S, Giller K (2006) Partial balance of nitrogen in a maize cropping system in humic nitisol of Central Kenya. Nutr Cycl Agroecosyst 76:261–270

Kuikman PJ, Velthof GL, Oenema O (2003) Controlling nitrous oxide emissions from agriculture: experiences in the Netherlands. In: Proceedings of the 3rd international methane and nitrous oxide mitigation conference. Beijing, China, pp 415–422

Lemaire G, Charrier X, Hebert Y (1996) Nitrogen uptake capacities of maize and sorghum crops in different nitrogen and water supply conditions. Agronomie 16:231–246

Mapanda F, Wuta M, Nyamangara J, Rees RM (2011) Effects of organic and mineral fertilizer nitrogen on greenhouse gas emissions and plant-captured carbon under maize cropping in Zimbabwe. Plant Soil 343:67–81

Mapiki A, Reddy GB, Singh BR (1993) Fate of fertilizer-15 N to a maize crop grown in Northern Zambia. Acta Agric Scand Sect B 43:231–237

Mushiri SM, Chifamba W (1998) Soil survey laboratory methods manual. Chemistry and Soil Research Institute, Dept Agric Res Spec Ser Publication, Harare

Nevison C (1999) Indirect N_2O emissions from agriculture. In: Background paper for IPCC expert group meeting on good practice in inventory preparation–agricultural sources of methane and nitrous oxide. IPCC, Wageningen, Netherlands, pp 381–397

Nyamadzawo G, Nyamugafata P, Chikowo R, Chirwa T, Mafongoya PL (2006) Soil and carbon losses under rainfall simulation from two contrasting soils under maize-improved fallows rotation in Eastern Zambia. In: Roose EJ, LAl R, Feller C, Barthes B, Stewart BA, Francis (eds) Soil erosion and carbon dynamics. CRC Press LLC, Boca Raton, pp 197–206

Nyamangara J (2007) Mineral N distribution in the soil profile of a maize field amended with cattle manure and mineral N under humid sub-tropical conditions. In: Bationo A, Waswa B, Kihara J, Kimetu J (eds) Advances in integrated soil fertility management in Sub-Saharan Africa: challenges and opportunities. Springer, The Netherlands, pp 737–748

Nyamangara J, Mugwira LM, Mpofu SE (2000) Soil fertility status in the communal areas of Zimbabwe in relation to sustainable crop production. J Sustain Agric 16:15–29

Nyamangara J, Bergstrom LF, Piha MI, Giller KE (2003) Fertilizer use efficiency and nitrate leaching in a tropical sandy soil. J Environ Qual 32:599–606

Okalebo JR, Gathua KW, Woomer PL (1993) Laboratory methods of soil and plant analysis: a working manual. Tropical soil biology and fertility programme. soil society of east africa technical publication no. 1. Marvel EPZ (Kenya), Nairobi

Piha M (1995) Soil fertility handbook. Department of Soil Science and Agricultural Engineering, Faculty of Agriculture, University of Zimbabwe, Harare 93 pp

Power AG (2010) Ecosystem services and agriculture: tradeoffs and synergies. Phil Trans R Soc B 365:2959–2971

Rao ACS, Smith JL, Papendick RI, Parr JF (1991) Influence of added nitrogen interactions in estimating recovery efficiency of labelled nitrogen. Soil Sci Soc Am 55:1616–1621

Raun WR, Johnson GV (1999) Improving nutrient-use-efficiency for cereal production. Agron J 91:357–363

Reay DS, Edwards AC, Smith KA (2009) Importance of indirect nitrous oxide emissions at the field, farm and catchment scale. Agric Ecosyst Environ 133:163–169

Ritchie SW, Hanway JJ, Benson GO (1992) How a corn plant develops. Special report 48. Iowa State University of Science and Technology. Cooperative Ext Service Ames, Iowa

Seed-Co (1998) Productive farming seed manual 1998/99. Seed-Co Company, Harare

Silva MM, Libardi PL, Fernandes FCS (2009) Nitrogen doses and water balance components at phenological stages of corn. Sci Agric 66:515–521

Smith M (2000) The application of climatic data for planning and management of sustainable rainfed and irrigated crop production. Agric Forest Met 103:99–108

Webster CP, Shepherd MA, Goulding KWT, Lord E (1993) Comparisons of methods for measuring the leaching of mineral nitrogen from arable land. J Soil Sci 44:49–62