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The effect of fertilizer placement on nitrogen uptake and yield of wheat and maize in Chinese loess soils

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Abstract

Field trials were carried out to study the fate of ^{15}N-labelled urea applied to summer maize and winter wheat in loess soils in Shaanxi Province, north-west China. In the maize experiment, nitrogen was applied at rates of 0 or 210 kg N ha^{-1}, either as a surface application, mixed uniformly with the top 0.15 m of soil, or placed in holes 0.1 m deep adjacent to each plant and then covered with soil. In the wheat experiment, nitrogen was applied at rates of 0, 75 or 150 kg N ha^{-1}, either to the surface, or incorporated by mixing with the top 0.15 m, or placed in a band at 0.15 m depth. Measurements were made of crop N uptake, residual fertilizer N and soil mineral N. The total above-ground dry matter yield of maize varied between 7.6 and 11.9 t ha^{-1}. The crop recovery of fertilizer N following point placement was 25% of that applied, which was higher than that from the surface application (18%) or incorporation by mixing (18%). The total grain yield of wheat varied between 4.3 and 4.7 t ha^{-1}. In the surface applications, the recovery of fertilizer-derived nitrogen (25%) was considerably lower than that from the mixing treatments and banded placements (33 and 36%). The fertilizer N application rate had a significant effect on grain and total dry matter yield, as well as on total N uptake and grain N contents. The main mechanism for loss of N appeared to be by ammonia volatilization, rather than leaching. High mineral N concentrations remained in the soil at harvest, following both crops, demonstrating a potential for significant reductions in N application rates without associated loss in yield.

Introduction

The efficient recovery of fertilizer nitrogen by crops is desirable both for economic reasons and to minimise environmental problems. However, various studies in China have shown that N losses following the use of urea can be high (Roelcke, 1994; Zhang et al., 1992). Much of this nitrogen may be lost by volatilization as NH_3 (Roelcke et al., 1996a), although leaching losses, and gaseous losses as N_2 and N_2O are likely to be important in some circumstances (Xu et al., 1987, Cai et al., 1991).

The Guanzhong Plain in the southern part of the loess plateau in the Chinese province of Shaanxi typically supports two crops per year: winter wheat and summer maize. Maize is sown by hand into a standing wheat crop at the end of May or early June and harvested in late September to early October. Wheat is sown immediately after the maize, again by hand, and harvested between June 5 and 15. Mineral nitrogen is applied as NH_4HCO_3 or urea, at rates of about 150 kg N ha^{-1} per crop, usually in a single application. The fertilizer for wheat is usually incorporated uniformly into the top 0.15 m of soil, but for maize it is placed in holes approximately 0.1 m deep between individual maize plants. Phosphorus is applied as superphosphate at rates of 75-80 kg P_2O_5 ha^{-1} as a basal dressing to wheat. Straw is normally burnt as fuel and the ashes returned to the field. Winter wheat often receives a basal dressing of "soil manure", a traditional farmyard manure consisting of 80-90% soil used as bedding material and 10-20% animal excreta. Analyses have shown that samples of this manure have an average water content of 39%, a total N content of 2.2 g kg^{-1}, and an organic C content of 26 g kg^{-1} (Roelcke et al., 1996b). Soil manure is usually applied at rates of between 75 and 120 t ha^{-1} a^{-1} (fresh matter). A flood irrigation is carried out up to three times for maize with 60-90 mm at each application, while wheat is usually irrigated with 90-150 mm in December and 60-120 mm in early spring. Average wheat yields are around 5.0-5.25 t ha^{-1}, and average maize yields are around 6.0-7.5 t ha^{-1}. Average total N-uptake rates are 135-145 kg ha^{-1} for wheat and 140-170 kg N ha^{-1} for maize. The average annual N-supply is approximately 300 kg N ha^{-1} from mineral fertilizers, and (in the case of regular applications of soil manure) 100-120 kg N ha^{-1} from organic sources. This results in a surplus N supply of about 110 kg N ha^{-1} a^{-1}, indicating the possible magnitude of N loss from the cropping system in the area.

Ammonia volatilization is an important pathway of nitrogen loss from these soils when ammonium-based fertilizers are used. For example, Zhang et al. (1992) found that 30-32% of the N applied as urea could be lost in this way from calcareous soils in N. China. Such losses may be reduced by soil incorporation, such as a banded fertilizer placement, for small grains (Campbell et al., 1993; Strong et al., 1992), and, for maize, point placement, i.e. burying the fertilizer N adjacent to an individual plant. Zhang et al. (1992) found that where urea-N was applied as a surface application, 71% of the fertilizer N lost resulted from ammonia volatilization, but the corresponding loss from point-placed urea was 40%. Point placement of urea has also been shown to result in an increased recovery of fertilizer N, as a consequence of the lower losses (Humphreys et al., 1992; Sawyer et al., 1991; Xu et al., 1987).

The specific purpose of this study was to quantify fertilizer N utilisation by wheat/maize rotations using fertilizer practices which are typical of the region. The use of ^{15}N-labelled fertilizers helped to determine the fate of applied N in the plant/soil system, as well as providing information on the proportions of N supplied by fertilizer and by other sources.

Sites, materials and methods

The study area was situated at the southern edge of the loess plateau on the third (northern) terrace of the Wei River near the NW Agricultural University at Yangling, where the loess is about 100 m deep (Zhu, 1986). In 1990, the field sites were 5 km west of the University, in the village of Shangzhuang (34°17' N, 108°00' E; altitude 570 m) on two farmers' fields. In 1991 the site was on the University's "No. 1 experimental farm" (altitude 521 m). The soil at the experimental sites is classified as a *lou* soil (*old manured loessial soil*) in the Chinese classification system (Institute of Soil Science, Academia Sinica, 1988) and as a Udic Haplustalf in the USDA (1994) system. It is a highly calcareous (10% $CaCO_3$) silt loam with an average texture of 23% clay (<2 μm), 74% silt (2-63 μm) and 3% sand (63-2000 μm). The topsoil (0-0.2 m) has an organic C content of 6.5-7.5 g kg^{-1} and a total N content of 800-900 mg kg^{-1}. The pH ($CaCl_2$) is 7.6-7.8, and cation exchange capacity is about 15 cmol kg^{-1}. The climate is subhumid continental with a mean annual temperature of 12.9 °C, a mean precipitation of 632 mm a^{-1} (Water Economy Bureau, Xianyang, 1989) and a reference evapotranspiration (ET_0) of 772 mm a^{-1} (Kang et al., 1992).

Field Studies

A) Maize. Two adjacent fields were used; Field I had received no organic manure during the last four years, whereas Field II had received regular additions of soil manure during the same period, at a rate of about 100 t ha^{-1} a^{-1} (fresh weight). Maize (*Zea mays* L.) was sown by hand into a standing wheat crop on May 31, 1990, with inter-row spacings of 0.6 m and intrarow spacings of 0.4 m (4.17 plants m^{-2}). Where seeds failed to germinate, plants from elsewhere in the field were transplanted to fill the gaps.

On July 3, 12 replicate 18 mm soil cores were taken from each of the two experimental fields, to a depth of 1.2 m and divided into 0-0.2, 0.2-0.6, 0.6-0.9 and 0.9-1.2 m sections. For each field, the replicates from each depth interval were bulked and analysed for mineral N. In each field, four microplots were marked out, each measuring 2 m × 2 m. One received no fertilizer N; the other three received 210 kg urea-N ha^{-1} on July 17, 1990, applied as a fine powder with a ^{15}N content of 0.8 atom% . A guard area 1 m wide around each plot received unlabelled urea at the same rate as the microplots. Three methods of application were investigated: surface application, mixing with the uppermost 0.15 m with a hand-held hoe, and point-placement of equal amounts of urea in holes dug to a depth of 0.1 m, midway between the plants in each row.

A total of 162 mm of rain fell during the experiment (July 17 to Sept 27). A single flood irrigation of 60-75 mm was carried out on August 10 on both fields according to local practice. Average reference evapotranspiration for the area (ET_0, calculated on the basis of long-term average local values from Kang et al., 1992) was 226 mm; the average maximum crop evapotranspiration (ET_{crop}) for the same period was 306 mm.

The maize crop was harvested on September 27. A central area of 1.5 m × 1.5 m was removed from each microplot, and plant material was separated into cobs and leaves plus stems before drying. Fresh and dry weights of each subsample were recorded and dry matter yields calculated. After harvest, three 18-mm soil cores were taken at random locations within each plot to a depth of 1.2 m, and divided into 0.1 m sections. Replicate sections were bulked as before, and analysed for mineral N, total N and the ^{15}N enrichment of the total N.

B) Winter wheat. In October 1991, winter wheat (*Triticum aestivum* L., var. "8 - 8") was planted, following a crop of soybean. Immediately prior to the experiment, 10 replicate 18-mm soil cores were taken to a depth of 1.2 m randomly within the experimental area, divided into 0.2 m sections, and bulked and analysed for mineral N as before. Sixteen plots measuring 4 m × 4 m were marked out, and microplots measuring 2 m × 2 m were established in the centre of each plot. Superphosphate was applied to all plots at a rate of 84 kg P_2O_5 ha^{-1}. On October 6-7, winter wheat was sown at a seed rate of 105 kg ha^{-1}, with inter-row spacings of 0.2 m and a sowing depth of 0.06 m. ^{15}N-labelled urea (0.8 atom%) was applied to the microplots, and unlabelled urea applied to the surrounding areas of each main plot (12 m^2). These plots were arranged as two randomised blocks of eight. Each block contained two zero N (control) plots and one replicate of each of the six treatments: two N rates, 75 and 150 kg ha^{-1} × three application methods: surface broadcasting, uniform mixing into the 0-0.15 m layer, and a banded placement at 0.15 m depth under each row of seeds.

In early December, according to local practice, the wheat crop was flood-irrigated once with 200 mm of water. A total of 146 mm of rain fell during the period of the field experiment (Oct. 7, 1991 to June 9, 1992). Average reference evapotranspiration for the area was 368 mm during the experiment; the average maximum crop evapotranspiration (ET_{crop}) for the same period was 408 mm.

On April 10 and 11, 1992, random soil samples in the outer area of each plot were taken to a depth of 1 m in 0.1 m increments, and 3 replicate 18-mm soil cores per microplot were taken to a depth of 1.2 m, divided into 0.1 m sections and bulked; the mineral N was determined in all samples. The trial was harvested on June 9. A central area of 1 m^2 was cut from each microplot and samples were used to make determinations of total N content and isotopic enrichment. Around every 1 m^2 area, four replicate areas of 2 m^2 each were cut, plant material was separated into heads and straw, and head:straw ratios were determined.

Laboratory analyses

Dried plant samples were milled in two stages to a fine "floury" consistency and analysed for total-N and ^{15}N enrichment in a single determination, using a Carlo-Erba 1400 automatic N analyser linked to a VG Isogas 622 mass spectrometer (Robinson and Smith, 1991). The isotopic enrichment of soil samples was determined in the same way, using soils that had been air-dried and ground to 0.25 mm.

Mineral N concentrations were determined on fresh soil samples, in duplicate. Soils were refrigerated at 5 °C when they could not be analysed on the day of sampling. Soils were extracted for 1 h with 1 m KCl (Analar) in a ratio of 1:5 (w/w) fresh soil:KCl solution, and filtered through Whatman No 42 filter paper; the resulting solutions were analysed for NH_4^+-N (Crooke and Simpson, 1971) and NO_3^--N (Best, 1976) using a Chemlab autoanalyser. For all sites and experiments, a soil bulk density of 1400 kg m^{-3} was used for converting the nitrogen contents to an area basis.

Field experiment results were compared by means of multifactorial analyses of variance using the program STATGRAPHICS (Statistical Graphics Corporation, 1991).

Table 1. Crop yield, N uptake and fertilizer recovery in the maize experiment.

Site/treatment	Crop yield (t dm ha^{-1})			N uptake (kg ha^{-1})			Recovery of fertilizer-N	NDFF
	Cob	Stover	Total above ground	Cob	Stover	Total above ground	(%)	(%)
I. *Unmanured*								
Control	3.20	4.44	7.64	48	34	82	-	-
Surface application	5.20	5.78	10.98	81	53	134	23	36
Point placement	5.24	4.22	9.46	85	38	123	27	46
Mixed incorporation	3.64	6.44	10.08	58	58	116	25	45
II. *Manured*								
Control	6.13	5.78	11.91	96	48	144	-	-
Surface application	4.80	4.98	9.78	73	44	117	14	24
Point placement	7.73	3.33	11.06	118	30	148	22	32
Mixed incorporation	4.89	6.44	11.33	72	51	123	11	19
Mean values								
Control	4.67	5.11	9.78	72	41	113	-	-
Surface application	5.00	5.38	10.38	77	49	126	18	30
Point placement	6.49	3.78	10.26	102	34	136	25	39
Mixed incorporation	4.27	6.44	10.71	65	54	119	18	32
Unmanured	4.32	5.22	9.54	68	46	114	25	43
Manured	5.89	5.13	11.02	90	43	133	16	25

NDFF = Nitrogen derived from fertilizer

Results

A) The 1990 maize experiment

Average mineral-N concentrations in July 1990 in the 0-1.2 m layers were 114 kg N ha^{-1} on the unmanured sites and 176 kg N ha^{-1} on the manured sites. The total above-ground dry matter yield of maize in the 1990 experiment varied between 7.6 and 11.9 t ha^{-1} (Table 1). The dry matter yields of cobs varied between 3.2 and 7.7 t ha^{-1}; however, differences between sites and treatments were not significant. The total N uptake by the crop varied between 82 and 148 kg ha^{-1} and that of the cobs between 48 and 118 kg ha^{-1}, but again differences were not significant (Table 1). At sites I and II, the contribution of the fertilizer to this N uptake was 53 and 33 kg N ha^{-1}, or 25 and 16% of the fertilizer N, respectively, while fertilizer-N uptake by cobs was 33 and 22 kg N ha^{-1} (16 and 10% of the fertilizer N) at the two sites. Cob dry matter yields were about average for the area under investigation, while values for total N uptake were slightly lower than average.

Different methods of fertilizer application had a limited effect on total N uptake and fertilizer-N uptake by the maize crop. Differences were significant only in the amount of fertilizer N recovered by the cobs ($p<0.05$), with the cobs from the point placement treatments taking up more fertilizer N (40 kg ha^{-1}) than those from the mixed treatments (18 kg ha^{-1}). Statistical details are given in Table 2. The proportions of N in plants derived from fertilizer were 30% (surface broadcast), 32% (mixed incorporation) and 39% (point placement); these values were not significantly different (Table 1).

Much mineral N remained in the soil at harvest: 72-342 kg ha^{-1} to a depth of 1.2 m (Table 3). The contents (mainly as nitrate) were generally higher on the manured site II than on the unmanured site I, and were also about twice as high in the mixed incorporation treatments as in the surface treatments. Mineral N contents were lowest, but still quite substantial, in both of the zero N treatments. The three fertilizer treatments differed in the amount of residual ^{15}N from fertilizer recovered from the soil (0-0.6 m) after harvest (Figure 1a and b). Below 0.6 m the ^{15}N enrichments were not significantly different from background levels. A selection of results from unmanured plots is given in Table 4. The residual fertilizer N in the soil was about twice as high in the mixed incorporation treatments as

Table 2. Statistically significant treatment effects

Parameter analyzed	Mean square	d.f.	Signif. level
Maize: Effect of placement on cob ^{15}N uptake	249.7	2	$p<0.05$
Wheat: Effect of fertilizer rate on grain dry matter yield	5107642.7	2	$p<0.001$
Wheat: Effect of fertilizer rate on total dry matter yield	16001443	2	$p<0.001$
Wheat: Effect of fertilizer rate on grain N contents	2125.2	2	$p<0.001$
Wheat: Effect of fertilizer rate on total N uptake	3195.1	2	$p<0.001$
Wheat: Effect of fertilizer rate on grain ^{15}N uptake	1135.8	1	$p<0.01$
Wheat: Effect of fertilizer rate on whole plant ^{15}N uptake	1460.8	1	$p<0.01$
Wheat: Effect of fertilizer rate on% NDFF	971.4	1	$p<0.01$

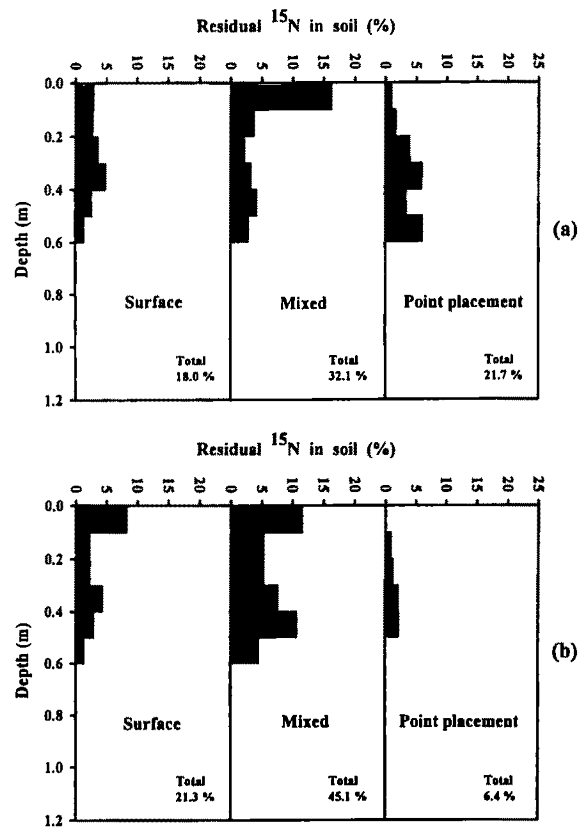

Figure 1. Residual ^{15}N from labelled fertilizer in soil (% of original application); maize experiment at (a) unmanured site I, (b) manured site II, for surface, mixed and point placement fertilizer applications.

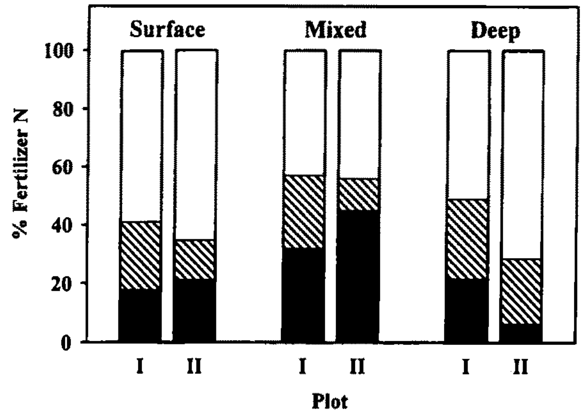

Figure 2. Distribution of fertilizer N between soil and plant in the maize experiment at harvest on plots receiving no manure (I) and manured plots (II). Solid areas represent soil N, hatched areas represent plant N and unshaded areas unaccounted-for N.

in the corresponding surface broadcast treatments. In the point placement treatments, there was a great variation between the two field sites in the amounts of ^{15}N and mineral N remaining in soil, with the amounts of ^{15}N at site II being particularly low (less than 7% of the original fertilizer application; Figure 1b).

Nitrogen fertilizer recovery by the maize at harvest was between 11 and 27% (Figure 2), and did not differ significantly between placement techniques. The amounts of fertilizer unaccounted for in the different treatments were: mixed incorporation (43%) $<$ point placement (61%) $\approx$ surface broadcast (62%).

B) The 1991-92 winter wheat experiment

Before fertilizer was applied in October 1991, the field site contained an average of 166 kg N ha^{-1} of mineral

Table 3. Mineral nitrogen (NO_3^--N + NH_4^+-N) contents of soil profiles in different treatments (S = surface N application, M = mixed N application, D = deep N application, all at 210 kg N ha^{-1}) at two sites, in September 1990, immediately after maize harvest.

Soil depth [m]	Mineral N (kg ha^{-1}) Zero N	S	M	D
Field Site I				
0-0.1	10.8	7.3	10.6	13.5
0.1-0.2	7.4	6.9	15.4	11.1
0.2-0.3	7.6	9.6	22.1	23.7
0.3-0.4	6.6	8.6	22.2	28.1
0.4-0.5	7.0	8.3	16.2	27.2
0.5-0.6	6.3	9.4	14.1	19.7
0.6-0.7	4.9	9.5	12.2	24.5
0.7-0.8	4.5	8.4	17.5	18.7
0.8-0.9	4.8	9.5	16.6	22.9
0.9-1.0	4.0	9.1	14.3	17.7
1.0-1.1	3.9	7.3	6.3	6.4
1.1-1.2	4.4	5.8	5.2	4.6
Total	*72.2*	*99.7*	*172.7*	*218.1*
Field site II				
0-0.1	11.9	17.5	29.6	12.9
0.1-0.2	12.5	11.6	30.1	16.5
0.2-0.3	9.4	14.9	34.2	16.2
0.3-0.4	7.6	15.4	32.9	18.2
0.4-0.5	9.7	15.7	33.8	14.3
0.5-0.6	6.7	12.5	29.8	14.1
0.6-0.7	6.2	10.0	28.7	12.9
0.7-0.8	6.3	10.8	31.2	16.1
0.8-0.9	6.8	10.0	34.7	14.6
0.9-1.0	4.9	8.0	26.7	11.5
1.0-1.1	4.7	7.4	17.1	9.1
1.1-1.2	7.2	16.3	13.3	7.8
Total	*93.9*	*150.1*	*342.1*	*164.2*

nitrogen in the uppermost 1.2 m of soil. Fertilizer N had a significant effect ($p<0.05$) on grain and total dry matter yield: without fertilizer application the grain yield was 2.7 t ha^{-1}, which increased to 4.3 t ha^{-1} at 75 kg N ha^{-1} and 4.7 t ha^{-1} at 150 kg N ha^{-1} (Table 5). The fertilizer rate had a significant effect ($p<0.05$) on grain N contents. At 75 and 150 kg N ha^{-1}, these were 1.65 and 1.81% respectively, and the fertilizer nitrogen in the grain amounted to 20 and 39 kg N ha^{-1}. The corresponding amounts of fertilizer N contained in the whole plant (above ground) were 24 and 46 kg N ha^{-1}. Total N uptake by wheat plants was 48 kg N ha^{-1} on the zero N plots, and significantly ($p<0.05$) increased to 84 and 99 kg N ha^{-1} at fertilizer rates of 75 and

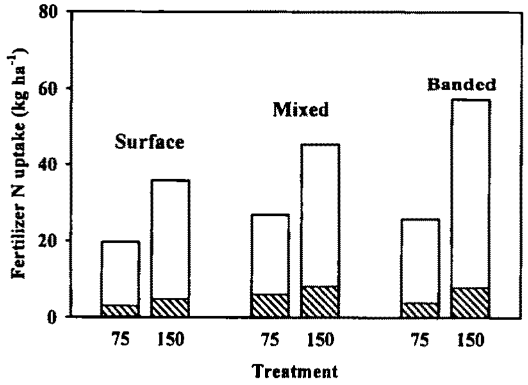

Figure 3. Uptake of fertilizer N by wheat crop, at 75 and 150 kg N ha^{-1} application rates. N uptake by straw is represented by hatched areas, and that by grain by unshaded areas.

150 kg N ha^{-1}, respectively. Also, the proportion of fertilizer-derived nitrogen in plants was significantly higher ($p<0.05$) at the higher fertilizer application rate (47%) than at the lower rate (29%) (Table 5).

Fertilizer placement did not significantly affect dry matter yields, but did influence the amount of fertilizer N recovered. An average of 24 kg N ha^{-1} was recovered by the grain following surface application, compared with 29 and 36 kg ha^{-1} from mixed and placed treatment plots, respectively (Figure 3). Corresponding values for the total plant (above ground) were 28 (surface), 36 (mixed) and 42 kg ha^{-1} (placement). Total N recovery rates in the year of fertilizer application ranged from 24% to 38%. The efficiency of recovery did not vary significantly with the amount of fertilizer applied: 32 and 31% at the low and high fertilizer rates, respectively (Table 5).

The highest concentrations of ^{15}N in the 0-0.1 m layer occurred in the surface treatment (Figure 4). The overall amount of residual labelled (fertilizer) N in the banded placement treatment was only about half the amount in the other two treatments. Due to the small quantities of residual fertilizer-N in the soil and its low enrichment, only the treatments with 150 kg N ha^{-1} were evaluated. However, even in these treatments, at depths greater than 0.6 m soil ^{15}N enrichment values did not differ significantly from background.

As in the maize experiment, mineral N was present mainly as nitrate. In April, the 150 kg N ha^{-1} treatments still contained more than 170 kg mineral N ha^{-1} in the uppermost 1.0 m, in the order surface broadcast < mixed incorporated < banded placement (Table 6). For the surface broadcast and mixed incorporation

Table 4. Distribution of ^{15}N in the soil after maize harvest in the unmanured plots from the mixed fertilizer application.

Depth (m)	% N			Atom % ^{15}N			Soil N	^{15}N DFF (kg/ha)	% Fertilizer (g/ha)*	remaining**
	rep 1	rep 2	mean	rep 1	rep 2	mean	Standard error			
0-0.1	0.09	0.09	0.09	0.3919	0.3910	0.3915	0.00045	1260	272.8	16.2
0.1-0.2	0.07	0.07	0.07	0.3761	0.3761	0.3761	0.00000	980	61.7	3.7
0.2-0.3	0.06	0.06	0.06	0.3737	0.3745	0.3741	0.00040	840	36.1	2.2
0.3-0.4	0.07	0.07	0.07	0.3746	0.3760	0.3753	0.00070	980	53.9	3.2
0.4-0.5	0.07	0.07	0.07	0.3766	0.3772	0.3769	0.00030	980	69.6	4.1
0.5-0.6	0.07	0.07	0.07	0.3736	0.3753	0.3745	0.00085	980	45.6	2.7

* Calculated as (soil at% × mass of N in layer) - (background at% × mass of N in layer)
** Calculated as $^{15}NDFF/^{15}N$ applied in fertilizer x 100
Background value of atom% $^{15}N = 0.3698$

Table 5. Crop yield, N uptake and fertilizer N recovery, in the wheat experiment.

Site/treatment	Crop yield (t dm ha^{-1})			N uptake (kg ha^{-1})			Recovery of fertilizer N	NDFF
	Straw	Grain	Total	Straw	Grain	Total	(%)	(%)
Control	1.80	2.68	4.48	5	42	48	-	-
Surface application								
N_{75}	2.98	3.97	6.94	11	67	78	26	25
N_{150}	3.07	4.66	7.73	12	77	89	24	41
Mixed incorporation								
N_{75}	3.70	4.23	7.92	19	73	92	36	29
N_{150}				18	87	105	30	43
Banded placement								
N_{75}	3.48	4.73	8.20	10	71	81	34	31
N_{150}	2.84	4.38	7.21	14	89	103	38	56
Mean values								
Control	1.80	2.68	4.48	5	42	48	-	-
Surface	3.02	4.31	7.34	12	72	84	25	33
Mixed	3.59	4.60	8.19	18	80	98	33	36
Banded	3.16	4.55	7.71	12	80	92	36	43
N_{75}	3.38	4.31	7.69	13	71	84	32	29
N_{150}	3.13	4.67	7.80	15	84	99	31	47

NDFF = Nitrogen derived from fertilizer

6). For the surface broadcast and mixed incorporation treatments, mineral N was mainly concentrated in the 0-0.5 m region, while following the fertilizer placement treatment mineral N concentrations were considerably enhanced to a depth of 0.9 m. By contrast, the profiles were depleted in mineral N after harvest in June and no major differences could be detected between treatments.

At the 150 kg ha^{-1} application rate, the amount of fertilizer N unaccounted for in the mixed incorporation was 36%, considerably less than the percentage from the surface application (43%) or that from the placement treatment (46%) (Figure 5).

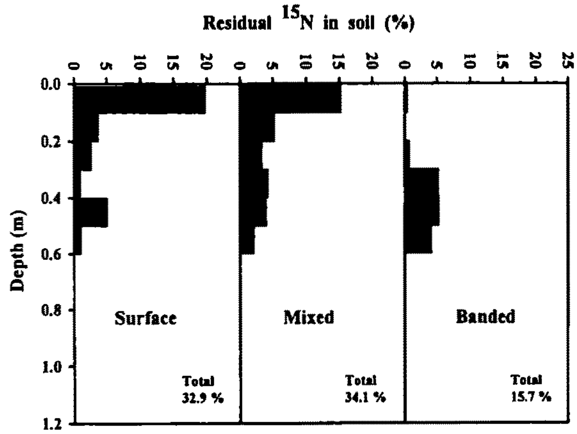

Figure 4. Residual ^{15}N from labelled fertilizer in soil (% of original application); wheat experiment, for surface, mixed and banded fertilizer applications at a rate of 150 kg N ha^{-1}.

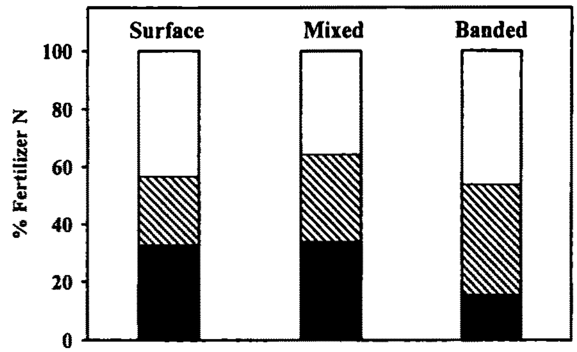

Figure 5. Distribution of fertilizer N between soil and plant in the wheat experiment at harvest (150 kg N ha^{-1} application rate). Solid areas represent soil N, hatched areas represent plant N and unshaded areas unaccounted-for N.

Discussion

Grain yields at 150 kg N ha^{-1} were slightly lower and total N uptake considerably lower than average figures reported for the area. The reason may be that, during the first month of the experiment, very low soil water contents due to dry autumn weather led to a delay in germination and a reduction in plant density on some of the microplots.

On the whole, the nitrogen fertilizer recovery rates were lower and N losses higher in our experiments than in similar experiments in other areas of China. For example, a microplot experiment by Wang et al. (1991) with ^{15}N-labelled urea carried out in the province of Henan on a soil of pH 8.8 resulted in uptake efficiencies of 32 to 55% for winter wheat and 23 to 48% for summer maize.

Mixing N fertilizer into the topsoil or placing it in bands (for winter wheat) and employing point placement (for summer maize) help to increase fertilizer efficiency and reduce losses. However, for winter wheat an incorporation of fertilizer at sufficient depth is only feasible before sowing. Split applications of fertilizer would be expected to reduce the percentage loss of the applied N as NH_3.

In both the maize and the wheat experiments, the fertilizer treatments involving mixing with the soil resulted in less N being unaccounted for than following surface application or placement below the surface, although in the case of maize, uniform incorporation did not improve fertilizer recovery. There is little reason to doubt that the greater losses resulting from surface application were due to NH_3 volatilization. In laboratory measurements using the same soil and a forced draught system with acid traps at an air exchange rate of 16.3 exchange volumes min^{-1} (Roelcke, 1994), total NH_3 losses after 17-21 days were 66% and 51% of the N applied to the surface as NH_4HCO_3 and urea, respectively. Following uniform incorporation to 0.15 m, these values decreased to only 0.5 and 2.5%, and when uniformly spread fertilizer was covered with soil to a depth of 0.15 m, no losses above the control level could be detected. A possible explanation for the lack of improvement in fertilizer recovery, following mixing of the maize fertilizer with the soil, is that the higher evaporation rates in summer may have increased the transport of unhydrolyzed urea and ammoniacal N in capillary water moving towards the soil surface. Such an effect would make uniform incorporation of fertilizer less effective in reducing NH_3 volatilisation than it was for the winter wheat fertilization.

However, the use of low ^{15}N-enrichment is likely to have resulted in an under-estimate of the amounts of residual ^{15}N remaining in the soil, and therefore to an overestimation of the percentage of fertilizer N unaccounted for, in the placement treatment. Thus the apparent difference in this regard between placement and mixing is much less certain than the difference between surface application and mixing.

The estimated maximum possible water deficit during the maize growing period was around 80 mm. It is therefore unlikely that large amounts of fertilizer ^{15}N were leached out of the profile as NO_3^--N. Residual ^{15}N was mainly concentrated in the 0-0.5 m layer (Figures 1a and b), whereas significant nitrate concentrations occurred throughout the top 1.0 m. During the

Table 6. Mineral nitrogen (NO_3^--N + NH_4^+-N) contents of soil profile in different treatments (S = surface N application, M = mixed N application, D = deep N application) at two stages of wheat experiment: (a) April 1992 (early booting stage) and (b) June 1992 (immediately following harvest). Mean values of two replicates per treatment.

Soil depth	Mineral N (kg ha^{-1})						
[m]	Zero N	75 S	75 M	75 D	150 S	150 M	150 D
April							
0-0.1	7.7	20.2	13.2	12.0	31.8	41.8	42.4
0.1-0.2	9.2	13.7	10.9	12.4	20.7	35.5	43.5
0.2-0.3	9.9	13.0	8.8	10.6	23.8	28.5	44.3
0.3-0.4	7.7	12.5	10.5	9.2	23.6	19.7	28.5
0.4-0.5	8.0	9.6	8.5	8.4	16.8	16.9	21.7
0.5-0.6	8.8	9.2	8.0	6.8	10.0	22.0	21.4
0.6-0.7	9.1	9.6	6.8	9.1	11.2	14.9	40.4
0.7-0.8	9.2	8.1	7.6	9.2	11.1	18.1	37.3
0.8-0.9	9.3	10.9	7.1	8.9	12.0	18.2	30.8
0.9-1.0	8.5	8.6	7.0	7.1	9.8	10.3	14.3
Total	*87.4*	*115.4*	*88.4*	*93.7*	*170.8*	*225.9*	*324.6*
June							
0-0.1	7.9	9.4	6.9	6.8	9.1	10.7	8.0
0.1-0.2	8.4	10.9	7.4	8.2	10.8	9.2	10.0
0.2-0.3	8.0	8.9	6.9	6.6	9.7	7.3	11.9
0.3-0.4	6.8	8.5	6.4	4.9	7.4	7.9	10.6
0.4-0.5	6.9	8.1	5.6	5.1	6.5	6.8	10.8
0.5-0.6	6.5	7.6	5.7	4.4	7.6	5.7	8.6
0.6-0.7	6.2	8.1	4.7	4.1	7.7	4.1	7.9
0.7-0.8	6.1	6.9	4.3	4.2	7.0	4.5	6.8
0.8-0.9	5.8	6.8	4.3	3.9	5.4	5.1	10.4
0.9-1.0	5.8	6.0	4.4	4.8	5.3	6.3	11.8
1.0-1.1	5.9	5.6	3.2	2.9	4.5	4.5	5.3
1.1-1.2	6.9	5.0	4.3	3.7	4.4	5.9	6.3
Total	*81.2*	*91.8*	*64.1*	*59.6*	*85.4*	*78.0*	*108.4*

growth period of winter wheat in 1991-92, average maximum crop evapotranspiration (ET_{crop}) exceeded the water supply (precipitation and irrigation) by 62 mm. In April 1992, elevated mineral-N contents were only detected above a depth of 0.9 m, suggesting that large amounts of NO_3^--N were not leached from the profile during the period of the experiment.

There are several possible reasons for the difference between ^{15}N and soil nitrate distributions down the profile. The buffer distance (0.25 m) maintained between adjacent plots amended with labelled fertilizer may have been inadequate, or the 3 cores taken from each plot may not have given representative values for the ^{15}N and/or the nitrate content. Furthermore, the plant crowns were partly above ground, and the stems were cut 2-5 cm above them. This residual aboveground material was not collected and analyzed and thus not included in the ^{15}N balance.

Alternatively, the low ^{15}N enrichment of the fertilizer may have led to failure to detect labelled N at depth. In this work and elsewhere (e.g. Smith et al., 1984), fertilizer N containing 0.7-0.8 atom% has been perfectly adequate for estimating the proportion of plant N derived from fertilizer (the primary objective of its use here). Rennie and Fried (1971) showed that such enrichments (ca. 0.3-0.4 atom% above natural abundance) would have given results with no greater error than those obtained with enrichments of $\geq$ 1 atom%. However, it is undeniable that the procedure reduces the sensitivity with which residual fertilizer-derived N can be detected, because of the large isotopic dilution it has undergone, and in the case of the banded placement the percentage of fertilizer unaccounted for may have been overestimated. Nonetheless, even with these limitations, the work has shown that the distribution of the residual labelled N in the profile (averages of the two replicate treatments) clearly reflects the differences in the methods of fertilizer application (Figure 4).

Between 1989 and 1991, mineral N was measured at regular intervals on several field sites in the same location. During the wheat growing period, a downward movement of about 30 kg NO_3^--N from the 0-0.6 m to the 0.6-0.9 m layer between January and April was observed only on one plot, which had been irrigated with 90 mm of water (unpublished data). Evidence of nitrate leaching was observed down to a depth of 0.9 m on several plots during the growth period of maize. However, on site II of the maize experiment, up to 400 kg NO_3^--N ha^{-1} were found in the 0-2.5 m profile, with >200 kg accumulated at a depth of 1.4-2.0 m. These amounts of nitrate were more or less stationary over the three-year period investigated and are probably due to the fact that, on a yearly average, the equilibrium zone between downward and upward water movement in the profile seems to lie at about this depth.

In the maize experiment, differences in the recovery of N at the two sites were attributed to a difference in the amounts of soil-derived N recovered by the crops, due partly to the different mineral N contents of the soils at the start of the experiment. Where previous additions of manure had been made, N released from that source by mineralization may have substituted for fertilizer N. Similar observations have been made in previous studies (Powlson et al., 1986). As can be observed from Table 3, considerable amounts of mineral N remained in the 0-1.2 m zone at the end of the maize experiment in 1990. The decrease in mineral N contents on the zero N plots of the maize experiment was smaller than the total uptake of N by the crops. Similarly, over three separate 6-month periods between April 1989 and October 1990 (Roelcke, 1994), no strong depletion in mineral N was found in the 0-0.9 m layer on several field sites. Nitrogen mineralization was estimated with aerobic incubation experiments (method of Stanford and Smith, 1972, modified by Nordmeyer and Richter, 1985), using topsoils with additions of different amounts of soil manure. The results indicated an average contribution from mineralized nitrogen of 75-80 kg N ha^{-1} 0.2 m^{-1} from the easily decomposable organic matter fraction and of 27-40 kg N ha^{-1} 0.2 m^{-1} from the resistant fraction (for an assumed period of 120 days and an average soil temperature in the 0-0.2 m layer in summer of 20 °C (Roelcke et al., 1996b).

Average precipitation exceeds the average crop evapotranspiration (ET_{crop}) only slightly (42 mm total) during the months of September and October in the Yangling area (data from Water Economy Bureau, Xianyang, 1989, and Kang et al., 1992). Nitrate leaching may possibly occur if excessive irrigation water is applied (especially in the winter), or where uneven infiltration occurs. It may also be caused by extreme rainfall events (e.g. >110 mm within one 24-hour period) which are occasionally encountered in the area in the summer months. Split applications would help to minimise leaching but since the root zone reaches down to 2.5 m in these loess-derived soils, residual fertilizer nitrate N remaining above this depth may, in any case, still be recoverable by the following crop.

On the basis of our observations, the main focus for improving fertilizer use efficiency in the cereal growing areas of the Loess Plateau region should lie in a reduction in the prevalent high application rates of mineral N fertilizer, to take account of the amount remaining in the profile. In many of our field measurements (although not the case in our winter wheat experiment), 100 to 300 kg ha^{-1} of mineral nitrogen were frequently still present in the 0-1.2 m zone at harvest. Work by Wehrmann and Scharpf (1986) and Wehrmann et al. (1988) (also on loess soils) has shown that considerable increases in fertilizer use efficiency can be achieved where the quantity of soil mineral nitrogen present at the start of crop growth is taken account of in fertilizer recommendations. This "N_{min}" method merits investigation as a way of quantifying the appropriate reductions in application rates in the Loess Plateau soils. The work of Wehrmann's group also suggests that an additional adjustment should be made to allow for the nitrogen supplying capacity of the organic manure commonly applied.

Conclusions

When comparing the two ^{15}N experiments, nitrogen uptake efficiencies by the first crop following fertilizer application were higher in the winter wheat experiment (25-36%) than with summer maize (18-25%). The corresponding amounts of fertilizer unaccounted for were smaller under wheat (36-46%) than under maize (43-62%).

Mixing N fertilizer into the topsoil or placing it in bands (for winter wheat) and employing point placement (for summer maize) helped to increase fertilizer efficiency and reduce losses.

Split applications of N fertilizer would be likely to reduce losses as NH_3, compared with single applications, and also possibly reduce losses due to nitrate leaching following excessive winter irrigation.

In these calcareous soils with high pH, in which little leaching seems to occur in most seasons, ammonia volatilization is likely to be the main pathway of nitrogen loss.

The high soil mineral nitrogen concentrations observed in this study indicate that there is scope for reducing N fertilizer inputs and improving N use efficiency in this wheat-maize rotation system.

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