EFFECTS OF FERTILIZER N AND SOIL MOISTURE ON MINERALIZATION, N RECOVERY AND A-VALUES, UNDER SPRING WHEAT GROWN IN SMALL LYSIMETERS

C. A. CAMPBELL[1] and E. A. PAUL[2]

[1]*Research Station, Research Branch, Agriculture Canada, Swift Current, Saskatchewan S9H 3X2.*
[2]*Saskatchewan Institute of Pedology, University of Saskatchewan, Saskatoon, Sask. S7N 0W0.*
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The influence of rate of fertilizer N and soil moisture on N uptake by spring wheat, N mineralization, A-values and N recovery was determined in small lysimeters on stubble land by means of ^{15}N-labelled KNO_3. Net mineralization was enhanced by frequent irrigations but depressed by cropping. In contrast to most growth chamber results, N uptake was not linearly but logarithmically related to rate of application; uptake from fertilizer was positively related to rate, but only up to a point beyond which it levelled off; uptake from native soil N was generally negatively related to rate; A-values were not constant but negatively related to rate except at the highest rates (123–164 kg N/ha) when they were positively related especially under dry conditions. These differences in results were credited to the fact that the pot system does not adequately simulate the field situation. On dryland an average of 68, 20 and 12% of the plant N was located in the grain, straw and roots, respectively; under irrigation the corresponding values were 75, 16 and 9%. Average recovery of fertilizer N on dryland was: soil 34.6%, grain 37.3%, straw 12.2%, roots 2.6%, error 6.0%, and unaccounted 7%; under irrigation it was 15.4, 58.3, 13.0, 3.5, 6.0 and 4.0%, respectively. On dryland about 28% of the fertilizer N was left in the soil at rates up to 82 kg N/ha, while 57% was left at 164 kg N/ha; under irrigation the corresponding values were 15 and 21%, respectively. On dryland > 70% of the residual N was located in the 0- to 30-cm soil segment at fertilizer rates < 82 kg N/ha; at higher rates > 50% was in the 30- to 60-cm segment. Only at 164 kg N/ha was there appreciable residual N in the 30- to 60-cm segment under irrigation. There was negligible fertilizer N below 60 cm in all treatments.

Dans de petits lysimètres installés sur chaume, on a déterminé, au moyen de KNO_3 marqué (^{15}N), l'incidence du taux de fumure azotée et de la teneur en eau du sol sur l'absorption de N par le blé de printemps, les valeurs A, la minéralisation et la récupération de N. Les irrigations fréquentes ont accru la minéralisation nette, mais les cultures l'ont réduite. Contrairement à la plupart des résultats obtenus en chambre de croissance, l'absorption de N affichait une corrélation logarithmique positive (non linéaire) à la dose d'épandage, mais seulement jusqu'à un seuil au-delà duquel elle se stabilisait; par contre, celle de N natif du sol montrait généralement une corrélation négative à la doze d'épandage; les valeurs A étaient irrégulières et affichaient une corrélation négative, sauf au plus fortes doses (123–164 kg de N/ha) et particulièrement sans irrigation. Ces différences dans les résultats ont été attribuées au fait que les lysimètres ne simulent pas correctement la situation au champ. Sans irrigation, le grain, la paille et les racines contenaient en moyenne 68, 20 et 12% respectivement du N total des plants par rapport à 75, 16 et 9% en irrigation. La récupération moyenne de N sans irrigation était, dans l'ordre, de 34.6% par le sol, 37.3% par le grain, 12.2% par la paille, 2.6% par les racines, 6.0% d'erreur et 7.0% de cause indéterminée, comparativement à 15.4, 58.3, 13.0, 6.0 et 4.0 respectivement en irrigation. Sans irrigation, environ 28% de la fumure azotée est restée dans le sol jusqu'à concurrence de 82 kg de N/ha, alors que celui-ci en retenait 57% à la dose de 164 kg de N/ha; en irrigation, les valeurs correspondantes étaient de 15 et 21% respectivement. Sans irrigation, plus de 70% du N résiduel se situait dans les 30 premiers centimètres du sol aux doses de fumure inférieures à 82 kg de N/ha; aux plus fortes doses, plus de 50% se retrouvait dans la couche de 30–60 cm. Ce n'est qu'à 164 kg de N/ha, en irrigation, qu'on a observé une quantité appréciable de N résiduel dans cette couche. Pour tous les traitements, on n'a retrouvé que des quantités négligeables de N en dessous de 60 cm.

At the present rate of world population expansion, agricultural production will be taxed to keep pace with the consumption of food and fibre. Although increased application of N is required to maximize the production of high-quality crops, there is the danger of possible pollution of ground waters, and the atmosphere and eutrophication of lakes. Research must find ways to increase the efficiency of plant use of fertilizer N, since this will increase yields and reduce the pollution potential.

Numerous fertilizer studies have been carried out in which ^{15}N-labelled materials have been used. However, as stressed by Hauck (1973), "few studies provide quantitative information . . . or information which is useful for calculating N balance in the total biosphere." Furthermore, most N balance studies have been conducted in the laboratory or greenhouse. The results obtained in such studies may be quite different from those found under field conditions.

Kundler (1970) summarized ^{15}N results obtained under various experimental conditions. He reported 1st yr plant recoveries of fertilizer N ranging from 30 to 70%, with 10–40% left in the soil, 5–10% lost by leaching, and 10–30% unaccounted for. In a comprehensive review of the fate of fertilizer N under controlled conditions, Allison (1966) concluded that the efficiency of any N carrier will be a function of (a) losses due to leaching, denitrification and other processes leading to gaseous losses; (b) the rate of immobilization of N; (c) the ratio of soil N/fertilizer N in the available N pool; and (d) NH_4 fixation by soil colloids. Environmental factors such as moisture and temperature will also affect N transformation indirectly by influencing plant growth and N uptake.

Field studies using ^{15}N have been carried out with wheat as the test crop (Myers and Paul 1971; Paul et al. 1972), forages (Westerman et al. 1972; Carter et al. 1967), maize and rice (Rennie and Fried 1971), and forests (Overrein 1972). In a recent field study carried out in semiarid southwestern Saskatchewan, Campbell and coworkers examined the influence of rate of fertilizer N application and soil moisture on the growth and moisture use (Campbell et al. 1977a), N accumulation, yield and yield components of spring wheat (Campbell et al. 1977b). This study presented an opportunity to use ^{15}N-labelled fertilizer to determine the influence of moisture and rate of fertilizer N on the efficiency of use of fertilizer and soil N, and to construct a balance sheet for fertilizer N under field conditions.

MATERIALS AND METHODS

General field and weather characteristics and experimental techniques for this study have been described previously (Dyck et al. 1977; Campbell et al. 1977a,b). Thus, only a brief outline and information pertinent to this experiment, but which was not previously presented, will be described here.

During the 1975 growing season, spring wheat (*Triticum aestivum* L. cv. Manitou) was grown in metal lysimeters on a Wood Mountain loam (Mitchell et al. 1944) in a stubble wheat field which contained 18 kg NO_3-N/ha in the top 60 cm at seeding. Two soil moisture regimes [natural rainfall (dry) and irrigated (wet)], seven rates of N (0, 37.5, 75, 112.5, 150, 225, and 300 mg NO_3-N/lysimeter), and five times of sampling (3-leaf, tillering, shot blade, anthesis and maturity) were combined factorially. The seven rates of fertilizer are equivalent to 0, 20.5, 41, 61.5, 82, 123, and 164 kg N/ha. The fertilizer was applied as KNO_3 powder. Only the lysimeters that were sampled at maturity received ^{15}N-labelled KNO_3 (5.525 atom % ^{15}N). A total of 17.8 cm of distilled water was applied to the irrigated treatments. The various non-tracer soil and plant analyses carried out (e.g., exchangeable NH_4-N, NO_3-N, plant weight, plant N, soil density, temperatures, moisture, etc.) are presented elsewhere (Dyck et al. 1977; Campbell et al. 1977a,b).

Mass Spectrometric Analysis

Separate subsamples of soil, grain, straw and roots taken at maturity were used for mass spectrometric analysis. Soil from the various segments was combined to provide samples for depths of 0–15, 15–30, 30–60, 60–90 and 90–105 cm. Roots were combined to represent depths of 0–15 and >15 cm. Total N, including NO_3- and NO_2-N, was determined using a modified semi-micro version of the method of Bremner (1965) as outlined by Rennie and Paul (1971). Soil samples were pretreated with acidified permanganate to oxidize NO_2- to NO_3-N, and with reduced iron and sulfuric acid to reduce the NO_3- to NH_4-N. None of the plant material required this pretreatment because earlier determinations showed that NO_3-N constituted <1% of their total N. A Kjeldahl digestion was used to convert organic N to NH_4-N. Isotope-ratio analysis was performed on an Atlas GD 150 mass spectrometer.

Calculations

The atom % excess, % N derived from fertilizer (% NDFF), % recovery of fertilizer N in plant parts, A-value for N and the amount of plant and soil N derived from the fertilizer and soil sources were calculated by methods outlined by Rennie and Paul (1971). The results were analyzed using a randomized block design. Tukey's ω value (Steel and Torrie 1960) was used to test appropriate differences between means.

Growing Season Conditions

During the 1975 growing season (Campbell et al. 1977a), there was good soil moisture from seeding to midway between tillering and shot blade stages of growth. This was followed by about 4 wk of drought (<1 cm of rain) which lasted until anthesis. Thereafter there was consistent rainfall (6–12 cm) to maturity.

RESULTS AND DISCUSSION

Mineralization During the Growing Season

Net mineralization in a well-aerated soil will be reflected by changes in its NO_3- and exchangeable NH_4-N and the plant N content. In this study the amount of exchangeable NH_4-N was low (4–6 ppm); it was not affected by rate of N, soil moisture treatment, growth stage or cropping. Consequently, all changes in mineral N were examined in terms of NO_3-N (Campbell et al. 1977a).

The NO_3-N was used up rapidly by the crop under wet conditions. Only at rates equal to or greater than 82 kg N/ha under dryland, and at 164 kg N/ha under irrigation, was there appreciable NO_3-N found in the soil at maturity. Based on the NO_3-N changes observed in the summer-fallow treatment it appeared that considerable mineralization occurred between seeding and tillering and between anthesis and maturity under dry conditions (Campbell et al. 1977a). Due to continual plant uptake, comparing changes in NO_3-N levels provides only a rough approximation of mineralization. A better estimate of the amount of the net mineralization taking place throughout the growing season was obtained from Table 1 as follows: Net mineralization during a period = [(NO_3-N in soil + plant-N) at any time less (NO_3-N in soil + plant-N) at an earlier time]. This does not account for re-immobilization of mineralized N. It can be seen that mineralization did occur under wet conditions even though this was not reflected in the NO_3-N results (Campbell et al. 1977a).

Net mineralization up to anthesis or maturity was generally greater under wet than dry conditions (Table 1). Cropping also tended to depress net mineralization. For example, during the period from 3-leaf to anthesis there was little net mineralization. This effect has been noted by others (Allison 1973; Ford et al. 1974). It has been credited to the "rhizosphere effect," largely associated with the production of exudates and sloughed-off cell debris from the roots (Rovira and McDougall 1967).

Uptake and Distribution of N in the Plant

Total N uptake by wheat grown on stubble land under dry conditions in 1975 was 58 kg N/ha (Table 2). The addition of N and water increased N uptake. When 164 kg N/ha was applied, N uptake on dryland increased by 76% to 102 kg N/ha; when 17.8 cm of water was applied, N uptake increased by 60% to 93 kg N/ha; and when both 164 kg N/ha and 17.8 cm of water were applied, N uptake increased by 210% to 180 kg N/ha.

Crop dry matter response to increasing rates of fertilizer N is usually curvilinear (Viets, Jr. 1965; Campbell et al. 1977a) and may be fitted with various second-degree or logarithmic equations. Yield-of-nutrient curves tend to be linear, especially where studies are conducted in pot culture (Terman and Brown 1968; Allison 1973). Often when the regression method is used to calculate recovery of fertilizer N by the crop (Terman and Brown 1968; Westerman and Kurtz 1974), this linear relationship is assumed to provide the best response relationship. In our field study, although a linear plot of the data gave a significant correlation ($r = 0.83$), the response surface was better fitted by a Mitscherlich type of equation under dry conditions (Fig. 1a) or a simple power function type relationship under wet conditions (Fig. 1b). Based on data from field trials, Soper et al. (1971) found that the uptake of N by barley could be predicted from the soil N present at seeding time by means of a parabolic function. Such quantitative relationships can serve as a useful tool for predicting yields (Soper et al. 1971) and for constructing quantitative models of the effects of soil and weather conditions on the response of crops to N fertilizer (Greenwood et al. 1974).

The N taken up was translocated efficiently and was independent of levels of fertilizer N under irrigation (Table 2). Under dryland conditions, an average of 68, 20, and 12% of the plant's N at maturity was located in the grain, straw and roots, respectively; under irrigation, the corresponding values were 75, 16 and 9%. Thus there was an average of 7% more N left in the vegetative parts (roots 3%, straw 4%)

Table 1. N recovered in plant and soil at various growth stages

Sampling time and moisture treatment		N applied (mg/lysimeter)†							
		0‡	0	37.5	75	112.5	150	225	300
	(DAE)§	Plant N plus NO_3-N in soil (mg/lysimeter)†							
Dry									
Initially	–	37	37	75	112	150	187	262	337
3-leaf	(14)	65	74	107	147	185	255	310	385
Tillering	(25)	114	87	125	130	190	220	275	410
Shot blade	(39)	105	120	135	155	167	240	275	340
Anthesis	(51)	117	105	130	142	173	212	280	362
Avg maturity	(85)	225	132	160	207	260	237	305	432
Wet									
Initially	–	–	37	75	112	150	187	262	337
3-leaf	(14)	–	77	112	135	167	207	275	345
Tillering	(25)	–	82	120	162	215	202	295	360
Shot blade	(39)	–	100	126	159	182	224	262	360
Anthesis	(51)	–	116	132	160	227	232	255	345
Avg maturity	(85)	–	185	247	300	297	305	320	397

†mg N/lysimeter × 0.548 = kg N/ha.
‡This was a summer fallow treatment; all others were cropped.
§DAE, days after emergence.

under dryland than under irrigation. As suggested previously (Campbell et al. 1977b), some N present in the straw under dryland conditions was probably "denatured" during the prolonged drought which occurred between tillering and anthesis. Consequently, translocation of N from straw to grain was impeded under dryland conditions at the higher fertilizer N rates (Table 2) where the soils dried out much more rapidly.

Recovery of Fertilizer and Soil N by the Plant

The proportion of the plant N (grain, straw, roots) that was derived from fertilizer N (% NDFF) increased with the rate of N application to a maximum at about 82 kg/ha under dry conditions and 123 kg/ha under irrigation and then levelled off (Table 2). Similar to the findings of Paul et al. (1972), % NDFF was the same for straw and grain. Thus, one should be able to estimate the ^{15}N abundance for grain by measuring ^{15}N abundance in straw and vice versa. The % NDFF was considerably lower in the roots than in the aboveground parts. Thus, root ^{15}N abundance must be determined, especially if the sample is taken at maturity. The lower % NDFF in roots might be an indication that some of the N previously present in the roots was translocated to the tops and that most of the N present in the roots at maturity was taken up from a pool

Table 2. Effects of fertilizer N and moisture on N uptake by the plant, N distribution among plant parts and the source of N found in the plant parts at maturity

Plant part and moisture treatment	N applied (kg/ha)							‡$\omega(P<0.05)$	
	0	20.5	41	61.5	82	123	164	Moisture	N
				Plant N uptake (kg/ha)					
Dry	58.1	63.4	75.9	84.6	91.4	92.4	101.7	9.0	20.1
Wet	93.2	129.2	144.1	149.2	157.9	185.0	180.3		
				% of plant N found in plant parts					
Grain									
Dry	75.9	68.6	67.5	61.1	67.6	69.2	69.3	2.2	6.2
Wet	74.0	75.1	76.1	76.3	73.8	77.9	74.5		
Straw									
Dry	14.6	16.5	20.3	26.2	21.3	20.7	20.0	1.6	4.8
Wet	15.8	15.5	16.3	15.3	17.4	12.2	15.3		
Roots									
Dry	9.5	14.9	12.2	12.7	11.1	10.1	10.8	1.6	4.7
Wet	10.3	9.3	7.6	8.4	8.8	9.9	10.2		
				% of plant part N derived from fertilizer (% NDFF)†					
Grain									
Dry	–	19	33	52	61	57	53	ND	ND
Wet	–	12	18	32	45	60	61		
Straw									
Dry	–	24	36	53	60	57	51	ND	ND
Wet	–	15	23	37	47	59	60		
Roots									
Dry	–	8	7	17	26	31	28	ND	ND
Wet	–	5	16	17	24	26	25		

† $\left(\frac{^{15}\text{N excess in sample}}{^{15}\text{N excess in fertilizer}}\right) \times 100 = \%\ \text{NDFF}$.

‡$\omega(P<0.05)$ is the difference required for significance at the 5% level of probability according to Tukey's method; ND, not determined.

of N now much lower in fertilizer N than was originally the case.

The % NDFF was used to calculate the amount of aboveground plant N derived from the fertilizer and that which came from the soil (Table 3). Rennie and Fried (1971) have shown that where the dilution of applied ^{15}N label is primarily a function of a single variable (e.g. rate of fertilizer application), % NDFF will provide conclusions identical to those provided by N uptake per unit area. Our results confirmed this (compare response of % NDFF and NDFF to N applied). However, when a second interacting variable such as moisture is introduced, % NDFF can no longer be used to assess comparative fertilizer N utilization; instead, a yield-dependent criterion based on the ^{15}N data is required (Rennie and Fried 1971). This point is borne out by the fact that the amount of NDFF is greater under wet conditions than on dryland (Table 3) although the % NDFF is greater (at rates of N $\leq$ 82 kg/ha) on dryland than under irrigation (Table 2).

Most N isotope studies that have been carried out in controlled environments indicate that there is a positive relationship between rate of uptake of soil N and rate of fertilizer N application (Allison 1973; Aleksic et al. 1968). Myers and Paul (1971), in a field tracer study with wheat, did not find an increase in the uptake of soil N by the plant due to increased fertilizer N. We found that increased fertilizer N generally depressed the uptake of soil N (Table 3). Only at the lowest rates of fertilizer under irrigation was there an indication of a positive relationship. Those workers who have found a positive relationship between soil N uptake and fertilizer N applied have credited this to various mechanisms. Some of these are: priming effect, turnover of N, rhizosphere effect, increased root growth, salt or osmotic effects (Allison 1973), and the protolytic effect (Laura 1976).

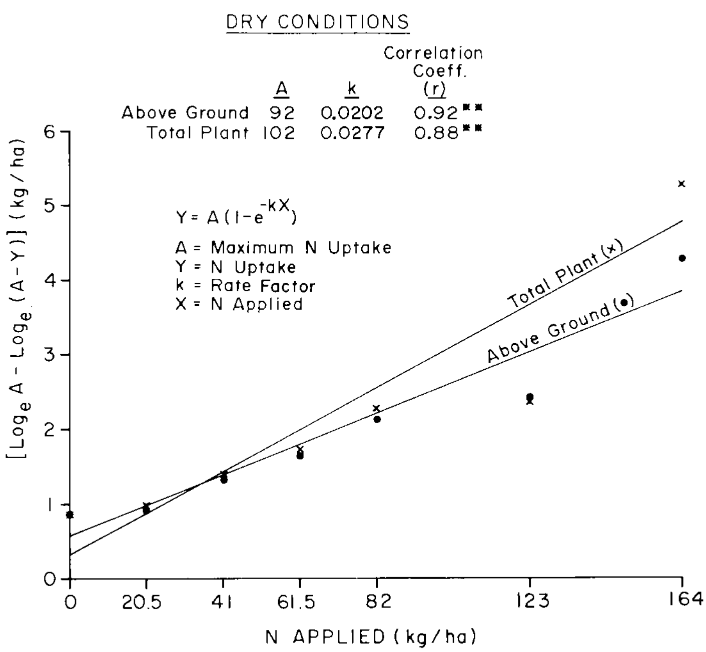

Fig. 1a. Quantitative effect of fertilizer N and moisture on uptake of N in total plant and aboveground parts — dry conditions.

In a review of how different variables affect A-values, Broadbent (1970) noted that A-values may increase, decrease, or remain constant with increased rate of fertilizer N. Our results showed that there was an interaction between A-value and rate of N applied (Table 3). A-values generally tended to decrease with increasing fertilizer to 82 kg N/ha (dry) or 123 kg N/ha (wet) and then increased considerably under dry conditions. In most growth chamber studies (Aleksic et al. 1968; Legg and Stanford 1967; Smith and Legg 1971), the A-values tended to remain constant even though N uptake from soil tended to increase with N applied. In our study, A-values and soil N uptake curves were similar up to a point [e.g. r = 0.64* (dry); 0.78* (wet)]; however, while the A-values indicated an increased availability of soil N at high rates of fertilizer under dry conditions, the NDFS response to fertilizer did not reveal this. As will be shown later, this increase in A-values coincided with treatments where the greatest amount of residual fertilizer N was left in the soil. It was interesting to note that there was no indication of increased soil N availability when a "difference" method such as that used earlier to determine net mineralization (Table 1) was

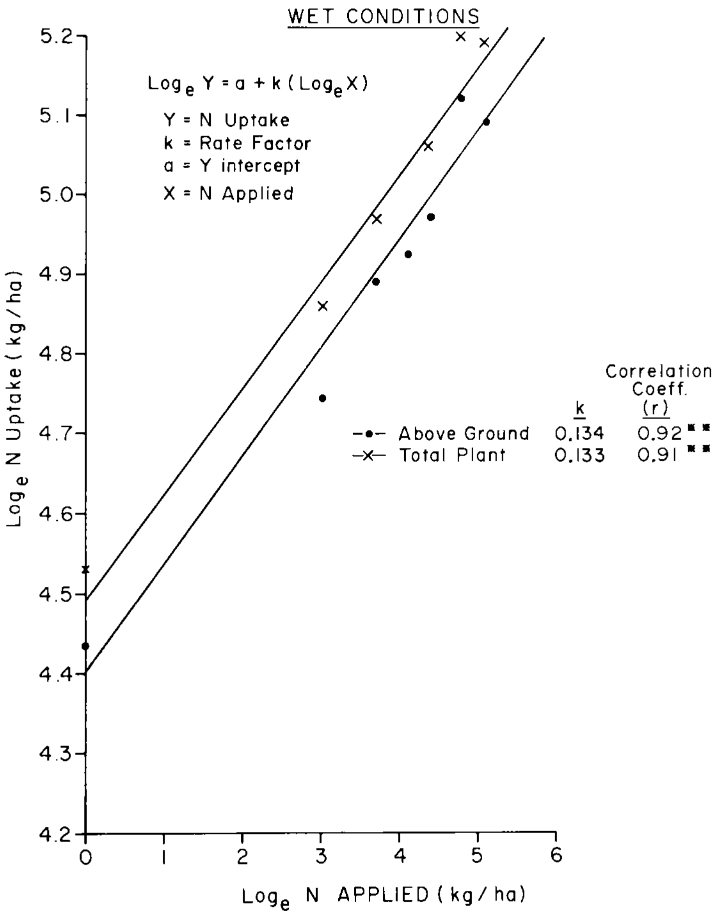

Fig. 1b. Quantitative effect of fertilizer N and moisture on uptake of N in total plant and aboveground parts — wet conditions.

employed. Our results do not provide an answer as to which mechanism is responsible for the increase in soil N availability. Laura (1976) has suggested that a protolytic mechanism might be responsible, while Broadbent and Nakashima (1971) have suggested that this increase may be due to osmotic effects.

The proportion of the fertilizer N which was recovered by the total plant varied from 31 to 65% under dryland, and from 63 to 84% under irrigation (Table 3). The recovery was related to the influence of fertilizer N on dry matter production up to fertilizer rates of 61.5 kg N/ha under dryland conditions, and up to 123 kg N/ha under irrigation (see dry matter response, Campbell et al. 1977a). The decreasing recovery at high rates of N reflect the fact that although the applied ^{15}N was increasing, plant ^{15}N content (NDFF) remained constant at or above these high levels of N. But, under dryland, N (^{15}N + ^{14}N) tended to increase at high N rates (Table 2) due to increased use of the native soil ^{14}N (NDFS, Table 3). The latter would therefore tend to indicate that this increased availability of soil N was at least partly responsible for the decrease in the recovery of fertilizer N by the plant at the highest rate of fertilizer application.

When the "difference method" was used to calculate the efficiency of fertilizer recovery by the plants, recovery decreased with increasing rate of fertilizer (Campbell et al. 1977b). The values varied from 35% at 41 kg N/ha to 23% at 164 kg N/ha (dry conditions) and from 120 to 49% at similar rates under wet conditions. These results are opposite to those obtained by using the isotope method. We therefore concur with the sentiments of Rennie and Fried (1971), and Terman and Brown (1968) who concluded that the "difference method" provides results which are difficult to interpret, and should be used with extreme caution. Allison (1973), using results from a growth chamber study, reported that much lower recovery values were obtained by the ^{15}N procedure than by difference. Although Allison points out that either low or high values may be obtained by the difference

Table 3. Effects of fertilizer N and moisture on the amount of each source of N found in aboveground parts, on A-values, and on the proportion of the fertilizer N found in the total plant and in soil at maturity

Moisture treatment	N applied (kg/ha)							$\omega(P<0.05)$‡	
	0	20.5	41	61.5	82	123	164	Moisture	N
				Nitrogen derived from fertilizer (NDFF)†(kg/ha)					
Dry	-	11.0	21.8	38.4	49.6	47.2	47.2	4.9	13.1
Wet	-	15.3	25.3	44.4	64.8	100.2	97.9		
				Nitrogen derived from soil (NDFS)† (kg/ha)					
Dry	52.5	43.2	45.0	35.5	31.6	36.0	43.6	5.4	13.7
Wet	83.7	102.4	107.8	92.2	79.2	66.7	63.8		
				A-value†(kg/ha)					
Dry	-	109	116	78	72	132	211	30	52
Wet	-	187	239	175	137	112	148		
				Proportion of fertilizer N recovered in plant (%)					
Dry	-	57	55	65	63	41	31	6	15
Wet	-	75	67	76	83	84	63		
				Proportion of fertilizer N recovered in soil (%)					
Dry	-	28	31	28	26	37	57	2	4
Wet	-	15	15	14	14	15	21		

†Based on N in aboveground parts only.
‡$\omega(P<0.05)$ is the difference required for significance at the 5% level of probability according to Tukey's method.

method under "well-understood" conditions, he also states that the two methods give generally similar recovery values. We believe Allison's results were due to the fact that they were obtained in pot experiments. These differences underline the difficulty in transposing results from the laboratory to the field.

Residual Fertilizer N in the Soil

About 28% of the fertilizer N was left in the soil profile following rates of application up to 82 kg N/ha on dryland; at higher rates as much as 57% of the applied N was left in the soil (Table 3); only 15–21% was left in the soil under irrigation. The fate of the residual N is uncertain. Several workers (Jansson 1963; Legg et al. 1971; Broadbent and Nakashima 1967; Shields et al. 1973) have shown that under both growth chamber and field conditions most of this N becomes immobilized or changed into a form which, though temporarily more available than humus N, is only slowly available to plants and has a half life of 20–50 yr. Crops may continue to respond to the residual fertilizer N for several years. Non-tracer work with forages seems to indicate that this may occur (Power et al. 1973; Read 1974; Leyshon and Kilcher 1976). Under irrigation the increased plant growth improves the chances of recovering most of the fertilizer N from the profile.

At rates of fertilizer N equal to or less than 82 kg/ha, 73% or more of the residual N was located in the top 30 cm of the soil profile under dryland conditions (Table 4). At higher rates of N, 50% of the residual N was leached into the 30- to 60-cm segment by heavy rains which occurred between anthesis and maturity. Since the plants had made more thorough use of the fertilizer N under irrigation, very little residual N was left for leaching when the rains came; consequently, only at 164 kg N/ha was there appreciable movement of residual fertilizer N into the 30- to 60-cm segment (Table 4). There was an average of 4% of the residual fertilizer N located in the 60- to 90-cm segment and none below this depth. Thus there was no leaching loss.

Nitrogen Balance

The fertilizer N recovery data were averaged over the levels of applied N to provide a mean balance sheet (Fig. 2). The original replicate data for the various treatments were used to calculate the confidence limits ($\pm t_{.01} \times S_{\bar{x}}$) at the 1% level of probability for the average total N recovery; this was found to be ±6%. There was considerably more of the fertilizer N left in the dryland soil (34.6%) than in the irrigated soil (15.4%); and there was much less fertilizer N recovered in the grain of dryland wheat (37.3%) than in the grain of irrigated wheat (58.3%). Both of these responses were directly related to dry matter production (Campbell et al. 1977b). Moisture had a minimal effect on the average fertilizer N recovery in straw and roots. The average proportion of the fertilizer N that was not accounted for in the plant plus the soil (to 105 cm) was 7% for dryland and 4% under

Table 4. Location of residual fertilizer N in soil profile

N applied (kg/ha)	Distribution of residual fertilizer N in soil profile (cm)							
	Dryland				Irrigation			
	0–30	30–60	60–90	90–105	0–30	30–60	60–90	90–105
	%							
41	89	10	1	0	80	15	5	0
82	73	13	13	0	78	19	2	0
123	43	54	2	0	86	8	5	0
164	17	81	0	2	51	46	2	1

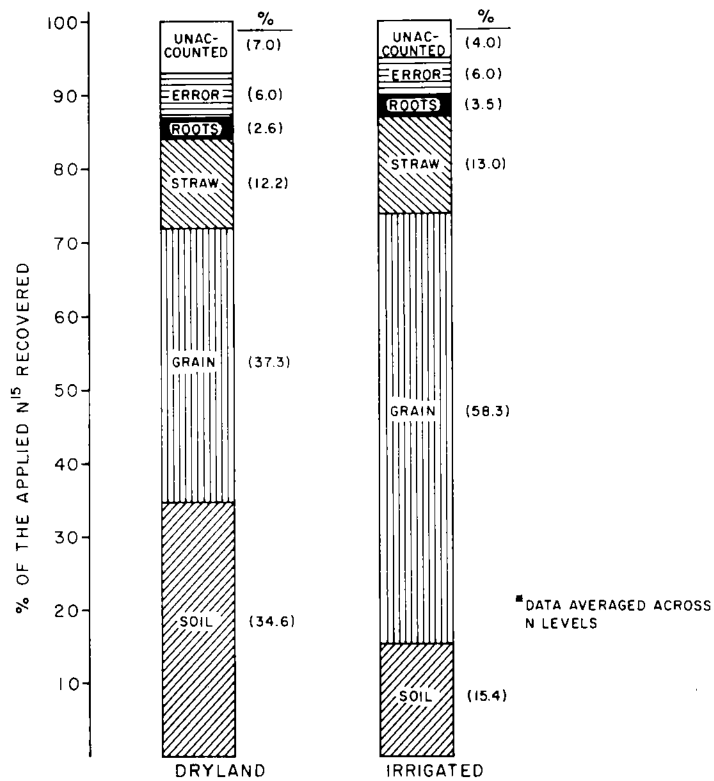

Fig. 2. Average balance sheet of ^{15}N (error refers to confidence limits at $P < 0.01$).

irrigation. These amounts, unaccounted for, were assumed to have been denitrified, although there is the possibility that some of the loss could be due to the shedding of pollen (Rumberg and Sneva 1970). We can also assume that there was no effect of irrigation on denitrification in this experiment. Water was applied with this objective in mind.

Kundler (1970) has reported that 1st yr recoveries under a variety of experimental conditions indicate N recovery in the plant to range between 30 and 70% (we recovered 53–75%), with 10–40% left in the soil (we found 15–35%), 5–10% lost by leaching (we had none) and 10–30% unaccounted for (we found about 4–7% unaccounted for). The low losses via denitrification are in contrast to the findings of numerous workers who report extensive losses by this means (Broadbent and Clark 1965), but agree with those of Craswell and Martin (1974) who reported very little denitrification in a well-structured clay soil at moisture content up to 90% (by weight).

Under dryland farming conditions usually only the N in grain and that lost by denitrification are removed from the system; thus, of the N applied, an average of 56% (dry) and 38% (wet) would be left to replenish the soil organic matter. The roots and straw contained about 16% of the fertilizer N and they would go directly into the active organic matter pool of N.

CONCLUSIONS

In contrast to reports in the literature, we found that uptake of soil N and A-values generally decreased with increasing fertilizer N, while increased availability of native soil N only occurred at the highest rates of fertilizing, particularly under dryland conditions. We also found a plateau for fertilizer N uptake. In our opinion, one of the main contributors to this difference in results was that most results in the literature accrue from pot-culture studies and these often do not provide a realistic simulation of response under field conditions. For example, it distorts root distribution, results in a much lower soil N/fertilizer N ratio than exists in the field, and it usually permits much greater dry matter production, which in turn provides a much greater sink for N assimilation.

A considerable proportion of the fertilizer remained in the soil under dryland conditions (28–57%). The nature of this N was not determined but it seems reasonable to assume that this residual N would represent a greater pollution potential if the field was summer-fallowed rather than cropped the following year. The very low residual N and denitrification and leaching losses experienced under the irrigated system indicate that it is fallacious to assume that irrigation will necessarily result in greater pollution. The rate and timeliness of irrigation, the rate and type of fertilizer applied, the amount and rate of crop growth, and the soil type will interact to determine the amount and distribution of the fertilizer N that appears in the soil, plant, air or groundwater.

Ideally, minimum pollution will occur if soil moisture is good in the spring so as to promote rapid growth and uptake of N; plants take up most of their N at an early growth stage (Viets 1965; Campbell et al. 1977b). This should be followed by good rainfall when the plant is making its maximum growth to allow continued plant development and N uptake and reduce leaching and denitrification losses. If too much rainfall occurred, or too much irrigation was administered at too early a stage, NO_3-N could be leached out of the root zone before it could be assimilated. On the other hand, if the soil became very dry, and especially if this occurred at an early growth stage, dry matter production will be reduced (small N sink) and this may even result in the exudation of plant N into the soil (Allison 1973; Campbell et al. 1977a).

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