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Effect of climate on the recovery in crop and soil of ^{15}N-labelled fertilizer applied to wheat

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Abstract

Data was assembled from experiments on the fate of ^{15}N-labelled fertilizer applied to wheat (*Triticum* spp.) grown in different parts of the world. These data were then ranked according to the annual precipitation-evaporation quotient for each experimental location calculated from the average long-term values of precipitation and potential evaporation. Percentage recovery of ^{15}N fertilizer in crop and soil varied with location in accordance with the precipitation-evaporation quotient. In humid environments more ^{15}N fertilizer was recovered in the crop than in the soil, while in dry environments more ^{15}N fertilizer was recovered in the soil than in the crop. Irrespective of climatic differences between locations 20% (on average) of the ^{15}N fertilizer applied to wheat crops was unaccounted for at harvest. Most of the ^{15}N fertilizer remaining in the soil was found in the 0-30 cm layer. The most likely explanation of these differences is that wheat grown in dry environments has a greater root:shoot ratio than wheat grown in humid environments and, further, that the residue of dryland crops have higher C/N ratios. Both factors could contribute to the greater recovery of ^{15}N fertilizer in the soil in dry environments than in humid ones.

Introduction

Application of ^{15}N-labelled fertilizer to a crop not only enables the amount of fertilizer recovered in the crop or remaining in the soil to be quantified, but the percentage recovery of the fertilizer can also be calculated (Hauck & Bremner, 1976). This technique has been applied to many crops, particularly cereals, grown in locations with a wide range of climatic conditions. This paper collates data from field experiments with ^{15}N-labelled fertilizer applied to wheat (*Triticum* spp.) in different parts of the world, under different climatic conditions and in different years.

The purpose in assembling this data was to test the hypothesis that climate has a major influence on the partitioning of ^{15}N-labelled fertilizer between crop and soil. Mechanisms are proposed which might explain this relationship.

Data selection and sources

Various forms of ^{15}N labelled fertilizer were applied at different stages of growth to rainfed crops of wheat grown in many locations (Table 1). The data includes all forms of fertilizer (urea, ammonium sulphate, ammonium nitrate or nitrate salts of sodium, potassium and calcium), rates of application (13-240 kg N ha^{-1}), and levels of enrichment (1.61-84.5 atom%) of the N fertilizer applied to the wheat crop. The study does not distinguish between the different times of application or the mode of application (solution or powder) used in each experiment. However, data from pot experiments were not used. Similarly, data from field experiments which used cylinders inserted into the soil were not included if the internal diameter of the cylinder was less than 20 cm (e.g. Craswell & Martin, 1975). The reasoning for this was that cylinders with a smaller internal diameter are unrepresentative of conditions in the field because they contain too few plants and because the edge effects are too large. Consequently, the data came mostly from unconfined microplots of

Table 1. Rates, timing and form of ^{15}N-labelled fertilizers applied to wheat in different experiments

Location	Time	Form[a]	Rate (kg N ha^{-1})	Reference
USA				
Kansas (Manhattan)	Autumn	AS	50 & 100	Olson et al. (1979)
	Spring	AS	50 & 100	
	Autumn	AS	80	Olson (1982)
	Spring	PN	13.3	Wagger et al. (1985)
Washington (Pullman)	Spring	AS	112 & 168	Fredrickson et al. (1982)
Alabama	Autumn	U	134	Bronson et al. (1991)
	Spring	U	134	
N.FRANCE	Tillering	U, AN	80	Recous et al. (1992)
	Tillering	U, AN	50	Recous et al. (1988)
	Stem Elongation	U, AN	110	
GERMANY	Tillering	AN	80,	Matzel & Lippold (1990)
	Shooting	AN	60	
ISRAEL	Sowing	PN	60 & 180	Feigenbaum et al. (1983, 1984)
AUSTRALIA				
Tatura	Tiller, Early	AS	20 & 22	Smith & Whitfield (1990)
	Boot, Heading	AS		
Merredin	Sowing	U, AS, DAP, AN	30	Fillery & McInnes (1992)
Wunghnu	Tillering	U	N/A	Fillery & McInnes (1992)
	Ear Initiation	U		
Cobram	Tillering	U	N/A	Fillery & McInnes (1992)
	Ear Initiation	U		
Toowoomba	Pre-sowing	U	60 & 80	Strong et al. (1992)
Roseworthy	Sowing	U	25, 50 & 75	Ladd & Amato (1986)
	Sowing	AS	50	
	Sowing	PN	50	
Griffith	Sowing, Tillering, Ear Initiation	U	60	Bacon & Freney (1989)
SYRIA	Sowing	U, AS	30	Pilbeam (unpublished data)
	Tillering		30 & 60	
BELGIUM	Tillering	PN, AS	75	Van Cleemput & Baert (1984)
	Flag Leaf	PN, AS	75	
	Flowering	PN, AS	30	
	Tillering, Stem Extension, Flag leaf emergence	SN	45 & 60 at each time	Destain et al. (1989)

Table 1. Contd.

	Tillering	SN, AS	35	Riga et al. (1988)
	Heading	SN, AS	45	
	Flowering	SN, AS	20	
	Tillering	PN	20	Van Cleemput et al. (1981)
	Sowing, Tillering, First Node, Flag Leaf	SN, AS	100(Split in 2 or 3 stages)	Riga et al. (1980)
UK				
Broadbalk	Spring	AN	47.3-181.6	Powlson et al. (1986b)
E.England	Autumn	PN, AN	44.2-48.4	Powlson et al. (1986a)
E.England	Spring	AN, PN	32.4-234	Powlson et al. (1992)
Faringdon	Spring	CN	80	Dowdell & Crees (1980)
Boxworth	Spring	AS	80, 160 & 240	Leitch & Vaidyanathan (1983)
E.England	Spring	AN	173-228	Jenkinson (Unpublished data)

[a] Forms of N fertilizer: AS-Ammonium Sulphate; AN-Ammonium Nitrate; PN-Potassium Nitrate; CN-Calcium Nitrate:; SN-Sodium Nitrate; DAP-Diammonium Phosphate; U-Urea.

more than 1 m^2, although some is from large confined microplots, defined as above.

All the studies were without irrigation and the wheat was harvested at maturity. The shoot material (grain, straw and stubble) was dried, weighed and analyzed for total N and ^{15}N. Soil samples were also taken in all of the studies, either by sampling the cylinder after excavation, or by taking cores from the unconfined microplot. In some cases (e.g. Recous et al., 1988, 1992), roots were washed from the soil samples, analyzed for N and ^{15}N. Soil samples were always taken to a depth of at least 30 cm (except in 2 cases (Dowdell & Crees, 1980; Olson, 1982)), often to a depth of 50 cm (Destain et al., 1989; Fredrickson et al., 1982; Leitch & Vaidyanathan, 1983; Powlson et al., 1992, 1986a, 1986b; Van Cleemput & Baert, 1984; Van Cleemput et al., 1981) and occasionally to a depth of at least 1 m (Bacon & Freney, 1989; Olson et al., 1979). These soil samples were weighed and the total N and ^{15}N enrichments were determined. The bulk density of the soil in each layer was also measured.

From these data the percentage recoveries in the crop and in the different soil layers of the applied ^{15}N fertilizer were calculated. The percentage unaccounted for was calculated by subtraction of the percentage recovery in the crop plus soil from 100. Mean values of these parameters and their standard errors were calculated for each location. The percentage recovery in the crop included the recovery in the root, if it was measured. Usually, the root material contained less than 5% of the applied fertilizer, and frequently less than 2%, except for an experiment in France (Recous et al., 1992) in which it contained between 5 and 13%. The mean percentage recovery of ^{15}N fertilizer in the crop was plotted against the mean percentage recovery in the soil for each experimental site.

Meteorological data were not reported for all of the experiments, so an average annual precipitation-evaporation quotient was calculated for each experimental site from the long-term average values of precipitation and potential evaporation for the location nearest to the experimental site (FAO, 1987; Müller, 1982). Values close to 1 indicate that annual precipitation and potential evaporation totals are approximately equal, while values less than 1 indicate that potential evaporation exceeds precipitation. The percentage recovery of ^{15}N fertilizer in crop or soil at each experimental site was ranked according to the value

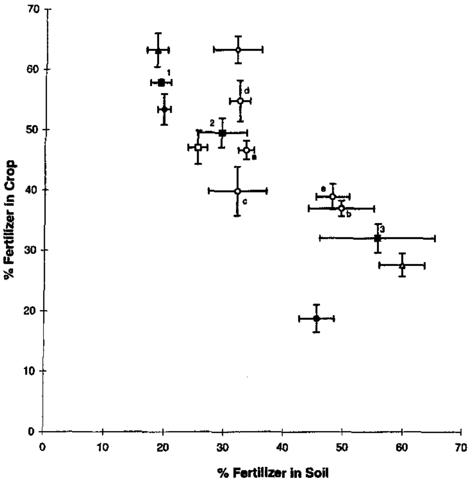

Figure 1. Mean percentage fertilizer recovered in the crop and soil at harvest for wheat crops grown in UK (♦), Belgium (▲), France (□), Germany (◇), Syria (●), Israel (△), USA (■; ^{1}Alabama,^{2} Kansas, ^{3} Washington) and Australia (○ ; ^{a}Roseworthy, ^{b}Toowoomba, ^{c}Tatura, Cobram and Wunghnu, ^{d}Griffith, ^{e}Merredin). Bars represent a standard error of the mean.

of the average precipitation-evaporation quotient for the nearest location. The values of this quotient for the different locations are: 0.14, Israel; 0.20, Syria; 0.23, Merredin, Australia; 0.32, Griffith, Australia; 0.40, Tatura, Wunghnu and Cobram, Australia; 0.45, Toowoomba, Australia; 0.59, Roseworthy, Australia; 0.65, Washington, USA; 0.89, Germany; 0.91, France; 1.09, Kansas, USA; 1.25, UK; 1.28, Belgium; 1.32, Alabama, USA.

Results

Distribution of ^{15}N fertilizer

Recovery of ^{15}N fertilizer in the crop ranged from more than 60% in Belgium to less than 20% in Syria (Figure 1). Conversely, recovery of ^{15}N fertilizer in the soil ranged from less than 20% in Belgium to more than 60% in Israel (Figure 1). Regional differences in the recovery of ^{15}N fertilizer in both crop and soil are evident. Generally, more fertilizer was recovered in the crop (>45%) than in the soil (<30%) for countries in N.W. Europe, while more fertilizer was recovered in the soil (>45%) than in the crop (<30%) for countries in the Middle East. Data from various locations in Australia or USA fall between these extremes.

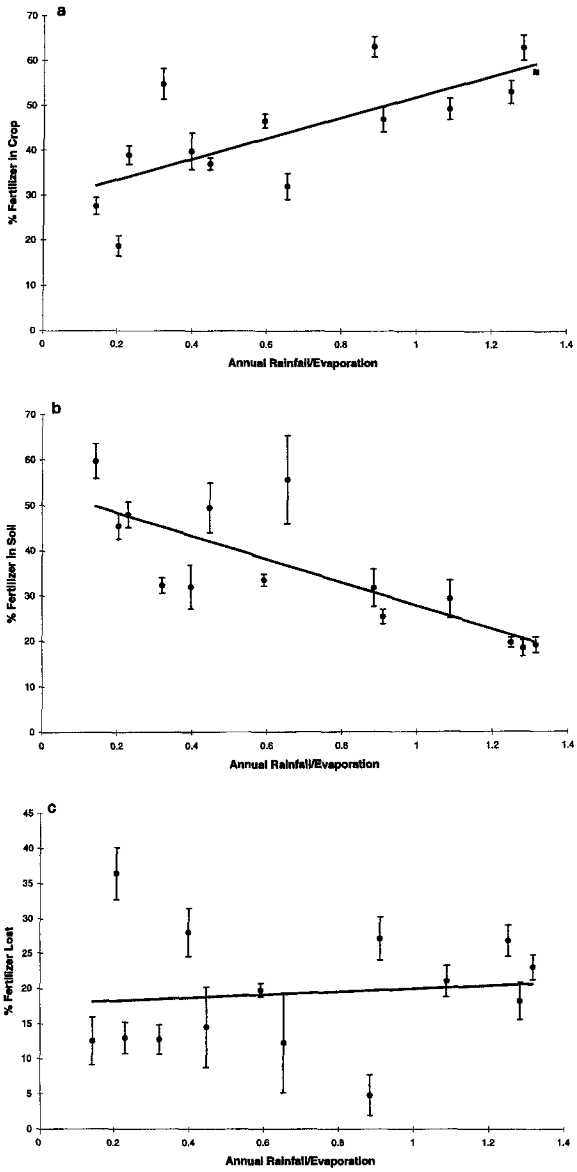

Figure 2. **a,b,c.** Relationship between the precipitation-evaporation quotient and the percentage recovery of ^{15}N-labelled fertilizer in (a) the crop (% recovery = 23.3(quotient) + 28.87; r^2=0.55), (b) the soil (% recovery = −25.8(quotient) + 53.39; r^2=0.64), and (c) unaccounted for (% recovery = 2.2(quotient) + 17.83; r^2=0.01) of ^{15}N-labelled fertilizer applied to wheat grown in different locations

Impact of climate on ^{15}N partitioning

As the precipitation-evaporation quotient increased from 0.14 to 1.32 the percentage recovery of ^{15}N in the crop increased from less than 30% to more than 60% (Figure 2a). Using the precipitation-evaporation quotient as an index of aridity, Figure 2b shows that a greater percentage of the applied ^{15}N fertilizer

Table 2. Proportion in various soil layers of the percentage N fertilizer recovered in the soil at harvest following the application of ^{15}N-labelled fertilizer to wheat in different locations

Location	Depth (cm) 0-10	0-20	0-30
Belgium	0.44	0.66	0.84
UK		0.85[a]	
USA (Kansas)	0.70	0.82	0.88
France	0.62		
USA (Washington)			0.74
Australia (Griffith)			0.96
Syria		0.78	

[a] 0-23 cm soil layer

remained in the soil in dry areas than in humid areas. This index also reconciled the differences between locations within Australia or USA. For instance, Alabama is more humid than either Kansas or Pullman, and less ^{15}N fertilizer was recovered in the soil.

In those experiments in which soils were sampled in layers to at least 0.5 m (but also including data from Syria where sampling occurred to 0.4 m) more than 74% of the ^{15}N fertilizer recovered in the soil was in the 0-30 cm layer (Table 2). Often considerably less than 20% of the ^{15}N fertilizer recovered in the soil was below 30 cm (Table 2). The data shows that the N fertilizer moved down the profile as the precipitation-evaporation quotient increased. Less N was in the 0-10 cm layer in Belgium (44%) than in Kansas (70%). However, this may be partially confounded by the use of different fertilizers in the two locations: nitrate was used in Belgium (Destain et al., 1989; Van Cleemput & Baert, 1984), whereas ammonium was used in Kansas (Olson et al., 1979).

The percentage of ^{15}N fertilizer that was unaccounted for ranged between 10 and 30% irrespective of location and the corresponding value of the precipitation-evaporation quotient (Figure 2c). Apparent losses of ^{15}N fertilizer were almost as great in dry areas as they were in wet areas. Overall losses averaged almost 20%.

Discussion

In drier climates most of the ^{15}N fertilizer remained in the soil while in humid climates most of the ^{15}N fertilizer was recovered in the crop (Figure 1). The differential partitioning of ^{15}N -labelled fertilizer between crop and soil in response to variation in climatic conditions might arise from differences between locations in crop growth patterns, soil characteristics and any interaction between them.

In dry areas wheat tends to mature earlier than in humid environments. Consequently, more N fertilizer would be expected to remain in the soil in dry locations than in more humid ones, if the same amounts of N fertilizer were applied in both locations to wheat crops at the same growth stage. For example, more ^{15}N was recovered in the soil when ^{15}N fertilizer was applied at tillering to wheat grown in Syria (44%, on average) than when it was applied at the same stage to wheat grown in the UK (20%, on average). Similarly, more ^{15}N will be found in the crop where the duration of crop growth is longer. For example, recovery in the crop of ^{15}N fertilizer applied at sowing was greater for wheat grown in either South (Ladd & Amato, 1986) or Western (Fillery & McInnes, 1992) Australia than for wheat grown in Israel (Feigenbaum et al., 1983). The observed differences in Figure 1 might be because of differences in the duration of crop growth following the application of the ^{15}N-labelled fertilizer. If this were true, applications of ^{15}N fertilizer at sowing, rather than at some later growth stage, should result in a greater recovery of fertilizer in the crop and less in the soil for wheat crops grown in any single location. The data do not support this. On average, 33% of the fertilizer applied at sowing remained in the soil in an experiment in N.S.W., Australia (Bacon & Freney, 1989). An identical percentage (33%) was recovered in the soil from a fertilizer application at tillering. Furthermore, recoveries in the soil of ^{15}N fertilizer applied at tillering were greater than recoveries of ^{15}N fertilizer applied at stem extension in both France (Recous et al., 1988) and Belgium (Destain et al., 1989). Therefore, the partitioning of applied ^{15}N fertilizer between crop and soil is not simply a function of the duration of crop growth and the timing of fertilizer application.

Besides the presence of an active microbial population, immobilization also requires the input of quantities of residues with a high C/N ratio. Immobilization can be caused by high C/N ratios of crop residues, or by high C/N ratios of the sloughed-off roots and root exudates of the growing crop. In those cases where the previous crop was given, the crops most frequently grown prior to the experimental wheat crop were cereals (56% of cases) and other non-legume crops (18% of cases), such as sugar beet and potatoes. Legumes preceded the experimental wheat crop in only 8% of cases, while in 18% of cases the wheat crop followed a fallow, in a cereal-fallow rotation. The C/N ratio of the stubble and roots of wheat is greater in drier environments. Assuming a carbon content of 40-45% for wheat stubble, then the C/N ratio of wheat stubble for experiments in Eastern England was 56-73 (Powlson et al., 1986a, 1986b, 1992). The actual value for wheat stubble in Syria was 114-171, or twice as large. The values for Syria compare with the C/N ratio of wheat straw from other dry areas; notably 210 at Pendleton, Oregon (Douglas et al., 1980), and over 200 assuming a C content of 40% for low rates of N fertilizer application (i.e. less than 100 kg N ha^{-1}) at Toowoomba, Queensland, Australia (Strong et al., 1987). Remobilization of N from vegetative tissues (stubble and roots) to reproductive tissues (ears) occurs in wheat experiencing N deficient conditions during grain filling (Dalling et al., 1976; Simpson et al., 1983). It is likely therefore that higher C/N ratios will be found in the stubble and roots of wheat crops grown in soils deficient in N at grain filling. Such conditions are more common in dry areas where less fertilizer N is applied because water often limits yield, and where the mobility of N in soil is low and mineralization is limited. Consequently, N fertilizer applied to, or after a wheat crop, is more likely to be immobilized in a dry environment than in a humid environment because C/N ratios of crops and residues are higher in dry environments.

Crops grown in dry areas compared to humid areas have higher root:shoot ratios, and receive lower rates of N fertilizer. Both may contribute to the greater recovery of ^{15}N-labelled fertilizer in the soil in dry areas compared to humid ones. Hamblin et al. (1990) noted not only that the root:shoot ratio of wheat crops were greater in dry conditions than in wet ones, but that the amount of root was also greater. Thus more ^{15}N fertilizer may be found in the soil in dry areas because the analysis for total soil ^{15}N will include root materials (e.g. fine roots, root exudates and sloughed-off roots).

At any particular location as the rate of fertilizer application increased by 50 kg N ha^{-1} from a low rate of application (<55 kg N ha^{-1}) the recovery of ^{15}N fertilizer in the soil decreased by about 30%, on average (Ladd & Amato, 1986; Olson et al., 1979; Powlson et al., 1986a; Recous et al., 1988). This may be expected if the rate of mineralization-immobilization turnover (MIT) in the soil is unaffected by the level of N fertilizer application. Assuming the same rate of MIT, proportionally more ^{15}N will be retained in the soil following the application of a smaller rather than a larger amount of comparably enriched ^{15}N-labelled fertilizer. Consequently the lower rates of N fertilizer application, typical for wheat production in dry environments, may favour a greater percentage recovery of N fertilizer in the soil.

Losses of N fertilizer from the crop-soil system represent an economic and an environmental cost. These data indicate that between 10 and 30% of the N fertilizer applied to wheat crops is lost (Fig. 2c) irrespective of climatic differences between locations. While the percentage lost may not change from one location to another, the mechanisms by which this loss occurs may differ. At Rothamsted Experimental Station in the UK, the amount of ^{15}N fertilizer lost by leaching and denitrification was shown to be linearly related to the amount of rainfall in the 3 weeks following application (Addiscott & Powlson, 1992). Generally, leaching is not the dominant loss process, because rainfall following fertilizer application is rarely sufficient to leach nitrate below the rooting depth. This is particularly so in dry areas such as Syria, where there is no drainage through the soil profile. In the experiments reported here losses of ^{15}N were often attributed to denitrification, although measurements supporting this assertion were rare. While denitrification may readily occur in wetter environments, it may also occur in drier ones where incidental heavy rainfall and the decomposition of C-rich organic residues combine to create anaerobic microsites (Vlek et al., 1981). In addition, losses of N through ammonia volatilization will occur where the soil pH is high, as it is in Syria.

In this study, the partitioning of ^{15}N-labelled fertilizer between crop and soil varied widely in response to differences in precipitation and evaporation between locations. Caution is therefore necessary when comparing data from locations with different climatic characteristics. In contrast, the proportion of applied ^{15}N fertilizer that was unaccounted for (presumed lost) was independent of any climatic variation between locations.

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