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Fertilizer-Nitrogen Absorption Determined by the ^{15}N Isotopic and Difference Methods

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Abstract
Reported values of percent fertilizer-N absorption (PNA) by crops grown in the fields are somewhere in between 30 and 70%, although there are many extremes. In some crops, such as rice, winter wheat, pearl millet and sugarbeet, the PNA values based on the difference method are generally larger than those on the ^{15}N method, while, in other crops such as spring wheat, maize and sorghum, the trend is opposite. In the other group of crops, such as potato and sudangrass, the PNA shows little difference between those two methods. Among various causes, root-development characteristics, being specific to each crop species, seems to play an important role on the PNA difference by the two methods, since the PNAs are often larger in the pot tests than in the field experiments. There are, however, great variations among the crops in the relative contributions of root development and growth characteristics to the PNA as well as in their N responses. It is concluded that in pursuing the PNA difference caused by those two methods, the following matters will have to be further studied: (a) identification of all aspects of the fertilizer-N distribution in fields, including plant absorption, demineralization and losses through gases and leaching; and (b) concurrent influences of environmental conditions.

Discipline: Soils, fertilizers and plant nutrition
Additional key words: field crops, percent fertilizer-N absorption, residual fertilizer-N, soil-N

Introduction

A great increase of yield has taken place in various field crops for the past few decades, and part of it may attribute to an increased amount of fertilizer application. Among fertilizer elements, nitrogen (N) has been the most important nutrient in determining the crop yield in many farming systems. Percent fertilizer-N absorbed by crops (PNA) is, however, not necessarily high under the present cultural practices.

To identify the fate of fertilizer-N applied to the field, a great number of studies have been conducted with an extensive use of ^{15}N. Among those studies, several scientists[12,38] demonstrated the discrepancy of PNA between the ^{15}N isotopic (tracer, direct) method and the difference (non-isotopic, indirect) method; i.e. the estimated values with the latter method was larger than the other. In contrast, however, some others[17,33] suggested no apparent difference between those two methods.

The PNA and related subjects have already been reviewed by several scientists[1,8,14]. The objective of this paper is to further examine those PNA values that were obtained exclusively from field trials and to discuss the implications of the difference caused by those estimation methods.

Various terms on PNA are presented in reference; e.g. 'recovery of fertilizer N'[5,6,8,16,33], 'percentage of N in the crop derived from fertilizer'[2,7,12,27], 'N use efficiency'[29] and 'percentage uptake of fertilizer N'[28]. All of them are synonymous; the term of PNA is adopted in the present paper.

Observed PNA values in some selected crops

Table 1 shows the reported values of PNA, including recalculated ones, determined by the above-noted two methods. In some crops such as rice, winter wheat, pearl millet, perennial ryegrass and sugarbeet, the PNA values based on the difference method are larger than those on the ^{15}N method, while, in other crops, such as spring wheat under

Table 1. Reported values of percent fertilizer-N absorbed by crop (PNA) in references[a)]

Crop	Fert.-N applied (kgN/ha)	Source of Fert.-N[b)]	Treatment	PNA (%)[c)] ^{15}N	PNA (%)[c)] Diff.	Soil-N[d)] (kgN/ha)	Place	Reference number
Rice (submerged)	38	$(NH_4)_2SO_4$	—	17	37*	37	Bangkhen, Thailand	20
	75		—	19	47*			
	70	$(NH_4)_2SO_4$	Early planting	25	49	102	Miyagi, Japan	35
	150			26	43			
	70		Normal planting	26	48	100		
	150			27	41			
	50	$(NH_4)_2SO_4$		32*	87*	86	Los Baños, Philippines	42
	75–100	$(NH_4)_2SO_4$	(3-yr mean)	32	50	70	Sapporo, Japan	40
	150–300			36	35			
Wheat[e)] (winter)	100	$NaNO_3$	—	47–57	63–75*	118	Gembloux, Belgium	28
		$(NH_4)_2SO_4$		46–64	65–94*			
	42–84	Urea	—	52#	79#	62	Gezira, Sudan	2
	75–100	$(NH_4)_2SO_4$	(3-yr mean)	48	75	137	Sapporo, Japan	40
	150–300			28	34			
Wheat (spring)	21	KNO_3	Natural rainfall (dry)	56*	26*	58	Saskatchewan, Canada	5
	41			56*	43*			
	62			66*	43*			
	82			63*	41*			
	123			41*	28*			
	164			31*	27*			
	21	KNO_3	Irrigated (wet)	74*	176*	93	Saskatchewan, Canada	5
	41			66*	124*			
	62			76*	91*			
	82			84*	79*			
	123			85*	75*			
	164			63*	53*			
Barley	152	$(NH_4)_2SO_4$	1974	27*	19*	83	Ottawa, Canada	19
	150	$NaNO_3$	1976	40*	63*	76		
		$(NH_4)_2SO_4$		30*	72*			
		AS + N-serve		9*	11*			
Maize	56	$(NH_4)_2SO_4$	—	65*	65*	165	Nebraska, USA	3
	112			61*	52*			
	168			56*	39*			
	50	$(NH_4)_2SO_4$	1976	46	40	196	Kansas, USA	24
	150			48	33			
	50		1977	38	42	117		
	150			49	54			
	75–100	$(NH_4)_2SO_4$	(3-yr mean)	36	23	176	Sapporo, Japan	40
	150–300			24	13			

(continue)

(Table 1, continued)

Crop	Fert.-N applied (kgN/ha)	Source of Fert.-N[b)]	Treatment	PNA (%)[c)]		Soil-N[d)] (kgN/ha)	Place	Reference number
				^{15}N	Diff.			
Sorghum	28–84	Urea	—	21#	10#	62	Gezira, Sudan	2
Sorghum–Sudangrass hybrid[f)]	56–168	Urea	1966	48–54	83–87	117	Illinois, USA	38
		Oxamide		46–57	69–99			
		Urea	1967	68–109	92–138	163		
		Oxamide		95–101	114–161			
Sudangrass[g)]	336	$NaNO_3$		42–46	43–46	?	Alabama, USA	6
		$(NH_4)_2SO_4$		40–50	42–52			
	672	$NaNO_3$		23–24	22–25			
		$(NH_4)_2SO_4$		29–36	28–36			
Pearl millet	90	Urea	—	36*	67*	34	Bambey, Senegal	13
	150			38*	45*			
Perennial ryegrass[h)]	394–418	$Ca(NO_3)_2$	—	43–54	57–70*	69–73	Sonning, UK	11
Potato	75–100	$(NH_4)_2SO_4$	(3-yr mean)	39	39	76	Sapporo, Japan	40
	150–300			34	41			
Sugarbeet	135	$(NH_4)_2SO_4$	—	36#	77*	141	Davis, USA	40
	56	$(NH_4)_2SO_4$	—	42	63*	158	Davis, USA	16
	112			47	59*			
	168			46	52*			
	224			43	46*			
	280			39	41*			
	75–100	$(NH_4)_2SO_4$	(3-yr mean)	42	51	144	Sapporo, Japan	40
	150–300			43	64			

a): Exclusively the data from field trials. Fertilizer-N (Fert.-N) is incorporated into the soil as basal application for most of annual crops except winter wheat.
b): AS: Ammonium sulfate.
c): ^{15}N: Isotopic method by using either of enriched or depleted ^{15}N. Diff.: Difference method. *: Calculated on the basis of the result reported. PNA is mostly determined at maturity. #: Mean of various combinations of fertilizer application method with or without P application (wheat), time of fertilizer application (sorghum), and 1–3 split applications (sugarbeet). Rank of PNA values by and large corresponds each other between the two methods, when the values are shown in a range (winter wheat, sudangrass, sorghum-sudangrass hybrids and perennial ryegrass).
d): Amount of soil-N absorbed by crop without fertilizer-N applications. ?: Unknown.
e): PNA is larger in 3-split applications than in 2-split applications.
f): Variation of PNA is due to N application rates of 56, 112 and 168 kgN/ha.
g): Variation of PNA is due to the pH range of 4.5–5.0, 5.5–6.0 and 6.5–7.0, tending to be larger with an increase of pH.
h): Herbage is cut six times during the growing season.

natural rainfall, maize in Sapporo and sorghum, the trend is opposite. There is another group of crops, such as sudangrass, potato with lower N levels and sugarbeet at high N levels, which show little difference between the two methods.

These comparisons however give rise to some difficulties in identifying whether the PNA difference by the two methods is specific to crop species or not, since the number of examples for each crop and detailed experimental information are limited. In rice plants under a submerged condition, however, the PNAs by the ^{15}N method are consistently smaller than those by the difference method and its values per se (17–36%) are smaller than PNAs in the other crops. The reason is to be identified yet. However, it is presumed that the submerged condition for rice, being different from dry land for other crops, might contribute partly to the smaller PNAs with the ^{15}N method in rice plants. Another possible reason is that rice plants are more dependent on soil-N (48–87% with an average of 68%) even under the relatively highly fertilized condition (70–150 kg N/ha)[20].

Many scientists have often suggested that as the N application rate is increased, the PNA be reduced proportionally. Such a general tendency may also be observed in the results in Table 1. However, there are several exceptions; e.g. rice in Bangkhen and Sapporo, maize in Kansas (1977) and sugarbeet in Sapporo show larger PNAs at the higher N levels. In spring wheat, the largest PNA by the ^{15}N method is obtained at the medium N level. In case where the difference method is adopted, larger PNAs are frequently obtained at the lower N levels with a decrease under a higher level of fertilizer-N application; the decrease is larger than that by the ^{15}N method. As a consequence, the difference in PNAs between the two methods becomes smaller at the high N level.

From the information available, it may be concluded that no simple explanation could be given in regard to the relationship between the PNA difference caused by the two methods and its association with N source, indigenous soil-N level (estimated as crop absorption of soil-N without N application), environmental conditions of the experiment including soil type and climate, and other relevant treatments.

Table 1 includes the data obtained only in the field trials, since the PNAs in pot experiments are usually larger than those in the field trials. According to the results of the pot experiments employing the ^{15}N method, PNAs are 84%[42] and 67%[29] in submerged rice, 59–71%[25] and 60–64%[9] in wheat, 73% in barley[26], 51% in ryegrass[36], 31–81% in sudangrass[23], and 72–76% in Rhodes grass[15]. The variations may be caused by differences in the cultural conditions such as fertilizer treatments (rate, source, placement and method of application), soil type and moisture content. The larger PNA values usually observed in the pot experiments might possibly be caused by the smaller quantity of soil used because of the limited size of pots. Therefore, any discussion on the PNA difference between the two methods is not valid, if the comparisons are made on the mixed results of pot and field experiments.

PNA and root development

When a PNA by the difference method is larger than that by the ^{15}N method, the soil-N uptake under the fertilized condition is larger than that without N application.

Hauck and Bremner[14] suggested that the addition of fertilizer-N to soil cause several apparent effects to soil-N transformation and plant N uptake as follows: (1) mineralization of soil organic matter is increased through stimulation of microbial activity, (2) immobilization of added and perhaps mineralized N is increased, (3) plant growth is increased, which situation augments the volume of soil explored by the plant roots, and (4) the plant becomes healthier, thereby absorbing and using more N. Environmental factors such as moisture and temperature also affect N transformation directly through their influences on plant growth and N uptake. This concept is widely accepted by many scientists [1,8,18,33,37]. Such an increase of N derived from soil following fertilizer addition is referred to a 'priming effect'. It is recognized that a plant itself is not an essential element in a priming effect, and that a larger amount of N is often liberated in the soil incubated with added N than that without N addition.

Among the various causes of N added to the soil in relation to PNA changes, root development seems to play an important role in the field, since PNAs obtained in the pot experiments are generally larger. Maize and winter wheat are both typical deeply-rooted crops, and rice and potato are shallowly-rooted crops[39]. Root development itself is not, however, directly linked to the PNA difference by the two methods. It is observed that larger PNA differences take place in rice than in potato, and also in winter wheat than in maize, while some differences are seen between shallowly-rooted rice and deeply-rooted wheat. Soil-N uptake without fertilizer-N is larger in maize (120–200 kgN/ha) and sugarbeet (140–160 kgN/ha) than in other crops (Table 1), which status might be associated with their deeply-rooted systems. In justifying this, however, chemical properties of the soils used also have to be taken into account, though no sufficient information on

Table 2. Some examples of residual fertilizer-N (residual-N)[a] reported in references

Crop	Fert.-N applied (kgN/ha)	Source of Fert.-N[b]	Treatment	Residual-N in soil (%)	Soil depth (cm)	Reference number
Rice (submerged)	40[c]	NH_4Cl	Surface appl.	48	20	41
			Incorporated	52	20	
Rice (upland)	137	$(NH_4)_2SO_4$	—	18	64	34
		KNO_3	—	11	64	
Wheat (winter)	100[d]	KNO_3	—	46	50	7
	96	$Ca(NO_3)_2$	—	12–43[f]	60	10
	100	$NaNO_3$	—	8[g]	70	28
		$(NH_4)_2SO_4$	—	14	70	
Wheat (spring)	21–164	KNO_3	Natural rain	26–57[h]	120	5
			Irrigated	14–21	120	
	120	$Ca(NO_3)_2$	—	24[i]	100	30
Barley	152	$(NH_4)_2SO_4$	1974	42	75	19
	150	$NaNO_3$	1976	22	75	19
		$(NH_4)_2SO_4$		24	75	
		AS + N-serve		56	75	
Maize	56–168	$(NH_4)_2SO_4$	Basal appl.	24–25	150	3
			Top-dress.[e]	6–13	150	
	50	$(NH_4)_2SO_4$	—	30	240	24
	150			27	240	

a): Residual fertilizer-N: Percent fertilizer-N remaining in soil after a single crop. Exclusively the data from field trials. Fertilizer-N (Fert.-N) is incorporated to soil at sowing, and residual-N in soil is determined at full maturity, unless mentioned.
b): AS: Ammonium sulfate.
c): Fertilizer-N is applied at transplanting and residual-N is determined at 84 days after transplanting.
d): Including split-application of non-labelled NH_4NO_3 (80 kgN/ha).
e): Top-dressed at 45 cm plant height.
f): Value is larger under the lower rainfall than the higher one.
g): Average over 2- and 3-split applications; no significant difference.
h): Tending to be larger with an increase of N application rate.
i): Remained 3% as nitrate and 21% as nonsoluble form.

this matter is available in the respective references.

The PNA is closely associated with plant N absorption, which is defined by two components; dry matter production and N content. Both components are greatly affected by genetic and environmental factors, and each component possesses different response to fertilizer-N levels[31, 32]. In addition, even if only the root development is taken into account, no definite data are available in concluding that more roots develop in the field under a fertilizer application[2,39]. Root growth itself is strongly influenced by various cultural and climatic conditions, which also affect plant growth. In other words, the comprehensive understanding of the factual cause and effect of the incidences indicated in Table 1 is very difficult without additional information on plant growth, cultural practices including fertilizer management, soil characteristics and other environmental conditions.

Residual fertilizer-N

Fertilizer-N is not entirely utilized by crops in a single growing season. As a matter of fact, a considerable amount remaining in the soil as an immobilized form is absorbed by crops in the subsequent growing seasons.

Some examples of percent fertilizer-N remaining in the field after a single cropping are shown in Table 2. Residual-N is estimated at in between 20 and 40% of fertilizer-N applied, although a wide variation (6–57%) exists. Soil depth at which the residual-N is determined does not seem to be an important factor, since the majority of residual-N is often retained only in an upper soil layer[24]. In regard to the yearly absorption of residual-N by succeeding crops, great variations are reported as follows: approximately 1% against the initial fertilizer-N applied during the five-year period[17]; 2.7% in the 2nd year[26]; 5–10% and 1–2% in the 2nd and 3rd year, respectively and less than 1% in the 5th year[11]; 1–4%[21]; and 1.3–1.7%, 1.0–2.0% and 0.5–1.0% in the 2nd, 3rd and 4th year, respectively, and half-life of residual fertilizer-N was estimated at 5–13 years[28]. These values vary with changes in cultural conditions such as organic matter application[26]. Total recovery of residual-N by the subsequent crops is estimated to be 10%[9] and 3–4%[28] of the quantity initially applied.

Allison[1] indicated that the determination of PNA with a long-term use of the difference method generally gave the results that agreed closely with those by the ^{15}N method, providing that crops were also grown in subsequent years and they were not subjected to extremely low-N rates. Therefore, in determining PNAs under the field conditions, implications of the fertilizer application as well as of the indigenous soil-N level have to be taken into consideration.

Conclusion

It may be said that the existing information are not sufficient to draw a definite conclusion on the fate of fertilizer-N applied to the field as well as on the issue whether the difference method gives a larger value of PNA than the ^{15}N method. Further studies on these subjects would be required. For this purpose, determinations on all aspects of the fertilizer-N distribution may be helpful: according to the review made by Kundler[22] on the ^{15}N experiments, it is summarized that 10–40% are fixed in a soil organic matter, 10–30% are lost in a gaseous form, 5–10% are lost through leaching and only 30–70% retrieved in crop plants.

It should be added that the conventional PNA determination (e.g. the difference method) is still valid to get information on the fertilizer-N efficiency, in particular when comparisons are made among the widely variable cultural conditions of cropping systems and among the crop species with different growth habits.

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