The effect of the rate and method of nitrogen application on nitrogen uptake and utilization by broccoli (*Brassica oleracea* var. *italica*)

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Abstract

The effect of the rate and method of nitrogen application on nitrogen uptake and utilization by broccoli (*Brassica oleracea* var. *italica*) was studied in four field experiments. The methods of application were broadcast application vs band placement and split application. Maximum uptake of nitrogen by the crop was around 300 kg ha^{-1}. In one experiment band placement positively influenced nitrogen uptake. Split application did not influence nitrogen uptake. Nitrogen application resulted in a higher head dry matter production, but the efficiency of nitrogen utilization for the production of head dry matter decreased with higher amounts of nitrogen applied. Nitrogen application decreased the dry matter content of the heads. In half of the experiments band placement of nitrogen fertilizer resulted in extra head dry matter production and lower head dry matter contents. At the optimum rates of band placed nitrogen application, the nitrogen harvest index in the experiments ranged from 27 to 30 percent.
The amount of mineral nitrogen in the soil at harvest generally increased with increasing amounts of nitrogen applied. Band placement resulted only in one experiment in lower amounts of mineral nitrogen in the soil at harvest. The mineral nitrogen in the soil at harvest can be unevenly horizontally distributed, both with broadcast application and band placement of nitrogen fertilizer. The amount of nitrogen unaccounted for at harvest increased with increasing amounts of nitrogen applied, but was always less than the amount of nitrogen in crop residues. At the optimum rates of band placed nitrogen application, the amount of nitrogen in crop residues ranged from 120 to 155 kg ha^{-1}. With broccoli cultivation, the nitrogen in the crop residues forms the single largest source of potential loss of nitrogen to the environment.

Keywords: broccoli, *Brassica oleracea* var. *italica*, nitrogen fertilization, band placement, broadcast application, nitrogen uptake, nitrogen utilization, nitrogen harvest index, crop residues, soil nitrogen distribution.

Introduction

In view of the need to develop methods to prevent the unnecessary loss of nitrogen in agricultural production (Wehrmann & Scharpf, 1989; Greenwood, 1990), data on crop uptake of nitrogen and on the amount of nitrogen left in crop residues and in the soil after harvest are needed. Few such data are available for broccoli (*Brassica oleracea* var. *italica*). Kowalenko & Hall (1987b) reported that broccoli took up 175 and 269 kg of nitrogen per hectare with a nitrogen application of 125 or 250 kg per hectare, respectively. Mineral nitrogen in the soil layer 0–60 cm at harvest was 48 and 90 kg per hectare (Kowalenko & Hall, 1987a). Around 60 percent of the nitrogen taken up was left in the field with crop residues after harvest (Kowalenko & Hall, 1987b). Shelp & Liu (1992) mentioned a crop uptake of 185 kg nitrogen per hectare at 130 kg per hectare nitrogen applied. Weier *et al.* (1994) reported a maximum uptake of 237 kg nitrogen per hectare with 72 kg per hectare mineral nitrogen in the soil (0– 60 cm) at planting and 278 kg nitrogen applied in a three-fold split application. Uptake of nitrogen by the crop was highest when most of the nitrogen was applied at planting (Weier *et al.*, 1994).

Nitrogen uptake and the amount of nitrogen left in crop residues and soil at harvest is likely to vary with soil conditions, nitrogen application rate and method, and nitrogen harvest index. Therefore, in field experiments under the local conditions (Everaarts & De Willigen, 1999), the effect of the rate and method of nitrogen application on, (i) nitrogen uptake and utilization by the crop, (ii) the amount of nitrogen left in crop residues and soil at harvest, and (iii) the amount of nitrogen unaccounted for at harvest, was studied. The aim of the observations was to provide a better understanding of the effects of nitrogen application on fresh product yield (Everaarts and De Willigen, 1999) and to assess the potential for loss of nitrogen to the environment with broccoli cultivation.

Materials and methods

General

From 1990–1992 eight experiments were carried out in which the effect of nitrogen and the method of application on yield and quality of broccoli (*Brassica oleracea* var. *italica*, cv. Emperor) was studied (Everaarts & De Willigen, 1999). Experiments 1 to 4 described here were originally Experiments 2, 4, 5 and 8 in that series. Nitrogen was applied broadcast or band placed at planting (Table 1). Banded fertilizer was placed in a hand-drawn furrow, about 5 cm deep, about 5 cm on one side of the row, after which the furrow was closed again. The second application with the split application was applied broadcast at 28, 41, 36 and 27 days after planting for Experiments 1, 2, 3 and 4 respectively. Planting distance was 0.50 × 0.45 m. Details on layout of the experiments are given by Everaarts & De Willigen (1999). Statistical analysis was done with the Genstat 5 statistical package (Anonymous, 1993). The significance indicated in the tables for Experiment 4 only applies to treatments in

Table 1. The amount of mineral nitrogen in the soil at planting and the amount of nitrogen applied (kg ha^{-1}).

Expt	Mineral nitrogen soil layer (cm)		Nitrogen applied					
	0–30	0–60	0	*N*	2*N*	3*N*	4*N*	2*N* + *N*
1	20	32	0	56	112	168	224	112 + 56
2	21	35	0	55	110	165	220	110 + 55
3	17	39	0	53	106	159	212	106 + 53
4	16	30	0	93	186	279	372	186 + 93

which nitrogen was applied. In Experiment 2 the crop was damaged by pigeons six days after planting. Crop growth slowly resumed thereafter.

Plant sampling

When about fifty per cent of the plants had been harvested, in each plot the above-ground part of five randomly chosen, marketable plants was harvested. The fresh and dry weight (after oven drying for 48 h at 70 °C) of the marketable part of the inflorescence (hereafter referred to as the head), the leaf-blades, the leaf-stalks, side-shoots and the stem of these plants was determined. In the plant material of Experiment 1 nitrogen Kjeldahl and in Experiment 2 total nitrogen was determined (BLGG Laboratory, Oosterbeek), both after drying at 105 °C. No correction was made for the difference of drying at 70 °C. In the plant material of Experiments 3 and 4 (in three of four replicates in Experiment 4) total nitrogen based on drying at 70 °C was determined by the indophenolblue method (Walinga *et al.*, 1995).

Soil sampling

At the locations of the five randomly chosen plants, at the same time as the plant sampling, samples were taken of the soil layers 0–30 and 30–60 cm according to the scheme in Figure 1 and pooled for each bore-hole 1, 2, 3 and 4. The method of soil sampling was the same for both methods of fertilizer application. A reliable impression of the spatial distribution of the mineral nitrogen in the soil is expected with this method of sampling (Van Noordwijk *et al.*, 1985). With the treatments *N*, 3*N* and 2*N*+*N*, a composite soil sample of all bore-holes was made for each soil layer. For Experiment 3 only data on total mineral nitrogen, without spatial distribution, are given. Mineral nitrogen was determined colorimetrically after extraction of soil with KCl (Vierveijzer *et al.*, 1979). A density of 1.3 kg per dm^3 was used for the conversion of mineral nitrogen in mg per kg soil to kg per hectare.

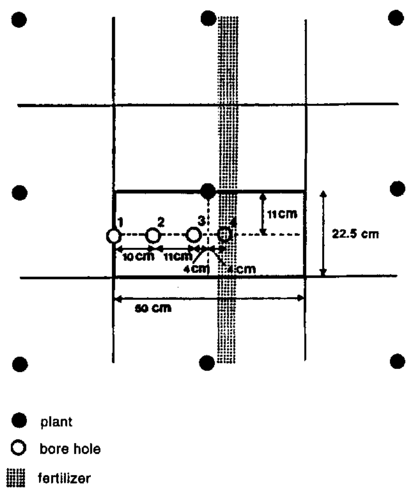

Figure 1. The location of the soil samples taken.

Results

Uptake of nitrogen and head dry matter production

Uptake of nitrogen by the crops without nitrogen application ranged from 55 to around 90 kg per hectare (Figure 2a). In all experiments the amount of nitrogen taken up increased with application of nitrogen. Only in Experiment 3 band placement had a significant ($P = 0.001$) positive effect on nitrogen uptake. Split application did not influence nitrogen uptake in any experiment (data not shown). Maximum uptake of nitrogen was around 300 kg per hectare, in Experiment 4. In general, the positive slope of the lines in Figure 2(a) indicates that, nitrogen uptake might still have increased with higher amounts of nitrogen applied.

The efficiency of nitrogen utilization was evaluated by comparing the amount of head dry matter produced per kg of nitrogen taken up. In Experiment 4, without nitrogen application 12.7 kg head dry matter was formed per kg of nitrogen taken up and this amount decreased to 6.8 and 5.0 kg respectively with $2N$ and $4N$ band placed. Similarly for band placement in Experiments 1 and 3, the amount of head dry matter per kg of nitrogen taken up decreased from 11.8 and 10.2 without nitrogen application, to 6.7 and 6.2 at $4N$ applied respectively. With increasing nitrogen uptake the efficiency of the utilization of nitrogen taken up in the production of head dry matter thus decreased. On average band placement significantly ($P = 0.035$) reduced the efficiency of nitrogen utilization in Experiment 4. No effects of the method of fertilizer application on nitrogen utilization efficiency were observed in the Experiments 1, 2 and 3.

In Experiment 2 with band placement only 9.9 kg head dry matter was produced per kg nitrogen at the zero nitrogen level and this amount decreased to 4.9 kg at $4N$ applied. The pigeon damage in this experiment resulted in a visibly reduced leaf area, whereby probably photosynthesis and, as a consequence, nitrogen utilization

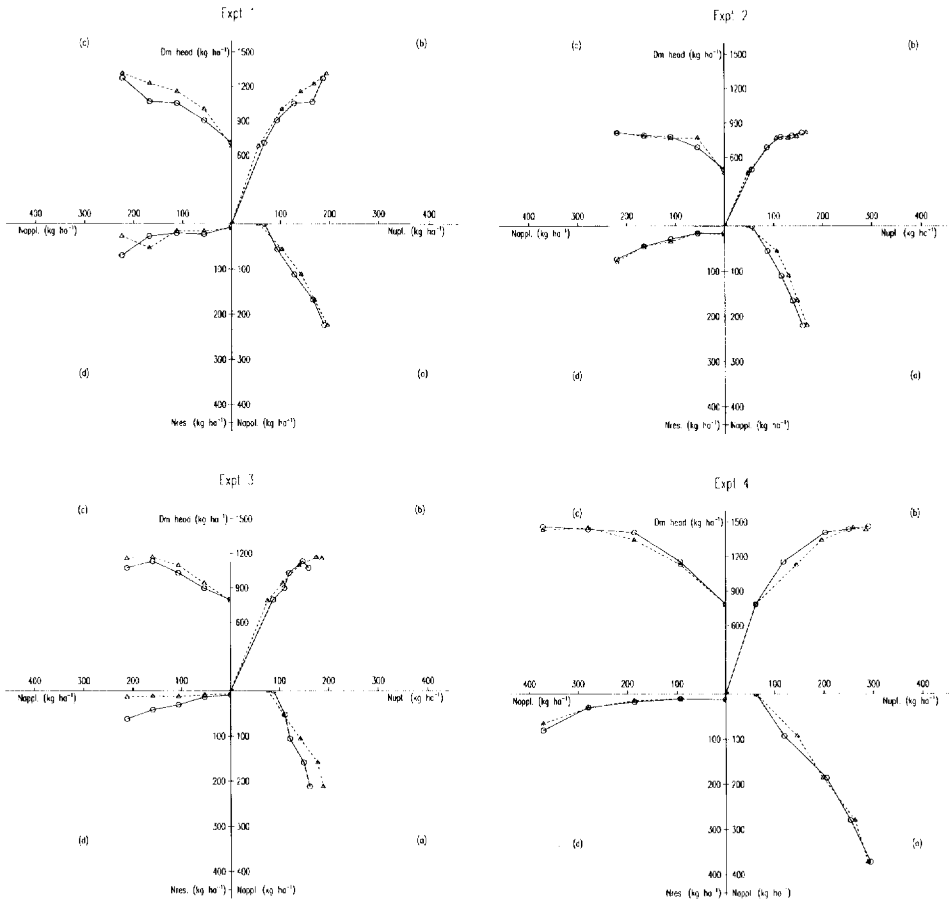

Figure 2. The relation between nitrogen application (Nappl.) and nitrogen uptake (Nupt.) (a), between nitrogen uptake and head dry matter (DM head) (b), between head dry matter and nitrogen application (c), and between nitrogen application and residual mineral nitrogen in the soil layer 0–60 cm at harvest (Nres.) (d), for broadcast application (○) and band placement (△)

was limited. Thus, while with increasing amounts of nitrogen applied the uptake of nitrogen still increased in this experiment (Figure 2a), the efficiency of nitrogen utilization was low. This resulted in high nitrogen concentrations in the crop, ranging from 26 to 44 g kg^{-1}.

Band placement significantly increased head dry matter production in Experiment 1 ($P = 0.018$) and Experiment 3 ($P = 0.013$). The higher head dry matter production with band placement in Experiment 1 (Figure 2c), is the result of a combination of small positive effects on uptake and utilization of nitrogen. In Experiment 3 the higher head dry matter production with band placement is mostly the result of a higher uptake of nitrogen, as there was only a limited effect on the utilization of nitrogen in this experiment. As a result of the pigeon damage dry matter production was lowest in Experiment 2. In Experiment 4 no effect of band placement was observed on nitrogen uptake and there was a negative effect on utilization of nitrogen for head dry matter. As a consequence head dry matter production in this experiment with band placement was equal or lower as compared to that with broadcast application.

The dry matter content of the heads generally decreased with an increase in amount of nitrogen applied (Table 2). In Experiments 3 and 4 banding significantly reduced average dry matter content of the heads.

Nitrogen in the head

Generally no effect of the amount of nitrogen was observed on the dry matter harvest indices of treatments where nitrogen was applied. (data not shown). In Experiments 1 and 3 the dry matter harvest indices of the no nitrogen treatments were lower and in Experiments 2 and 4 these indices were higher than the dry matter harvest indices with nitrogen application. The nitrogen harvest index, the amount of nitrogen that is removed from the field with the product as a percentage of the total amount of nitrogen in the crop at harvest, varied between 22 and 37 percent and decreased with increasing amounts of nitrogen applied (Table 3). Only in Experiment 1 did the method of fertilizer application influence the nitrogen harvest index. The average index was higher with band placement. Split application had no effect on the nitrogen harvest index. The optimum rates of nitrogen application in the experiments were 149, 90, 145 and 208 kg ha^{-1}, band placed, for Experiments 1 to 4, respectively (Everaarts & De Willigen, 1999). At these rates the nitrogen harvest index in the experiments ranged from 27 to 30 percent.

Table 2. Dry matter content of the head (%).

Expt	Application method	Nitrogen applied (Table 1)						LSD ($\alpha = 0.05$)
		0	N	$2N$	$3N$	$4N$	$2N+N$	
1	broadcast	11.3	10.9	10.9	10.6	10.7	10.7	0.4
	band placed	11.3	11.4	10.8	10.8	10.8	10.7	
2	broadcast	10.4	10.1	9.9	9.1	8.6	9.3	0.5
	band placed	10.6	9.9	9.6	8.9	8.7	8.9	
3	broadcast	11.6	11.0	10.9	10.4	10.1	10.1	0.5
	band placed	11.5	10.9	10.5	9.8	10.0	10.1	
4	broadcast	12.2	11.6	10.5	9.7	9.2	10.2	0.8
	band placed		10.7	10.0	9.5	9.7	9.2	

Significance	Expt 1	Expt 2	Expt 3	Expt 4
nitrogen	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
application method	ns	ns	$P = 0.033$	$P = 0.031$
nitro. x appl. meth.	ns	ns	ns	ns

Table 3. The nitrogen harvest index (%).

Expt	Application method	Nitrogen applied (Table 1)						LSD ($\alpha = 0.05$)
		0	*N*	2*N*	3*N*	4*N*	2*N* + *N*	
1	broadcast	34	32	30	24	28	26	3
	band placed	35	33	29	29	28	28	
2	broadcast	32	33	31	28	26	26	3
	band placed	36	31	27	26	25	26	
3	broadcast	29	30	33	27	29	30	4
	band placed	31	31	31	29	28	31	
4	broadcast	37	30	26	25	23	24	3
	band placed		29	27	25	22	26	

Significance	Expt 1	2	3	4
nitrogen	$P < 0.001$	$P < 0.001$	$P = 0.022$	$P < 0.001$
application method	$P = 0.027$	ns	ns	ns
nitro. x appl. meth.	ns	$P = 0.011$	ns	ns

Nitrogen in crop residues

The amount of nitrogen left in crop residues in the field after harvest increased with increasing amounts of nitrogen applied (Table 4). Because of the positive effect of band placement on nitrogen uptake in Experiment 3 and the absence of an effect of band placement on the nitrogen harvest index in this experiment, the average amount of nitrogen left in the crop residues in Experiment 3 was higher with band placement of fertilizer as compared to broadcast application. Excluding Experiment 2, because of limited nitrogen uptake, the amount of nitrogen in crop residues at the optimum rate of nitrogen application in the experiments (Everaarts & De Willigen, 1999), varied from 120 to 155 kg ha^{-1}.

Nitrogen in the soil at harvest

Amount

The amount of mineral nitrogen in the soil at harvest generally increased with increasing amounts of nitrogen applied, with the exception of band placed nitrogen in Experiment 3 (Figure 2d, Table 5). The higher uptake of nitrogen with band placement in Experiment 3 resulted in low amounts of mineral nitrogen in the soil at harvest. The higher uptake also contributed to the only limited increase in amounts of mineral nitrogen found in the soil at harvest with increasing amounts of nitrogen applied. Split application of nitrogen generally had no effect on the amounts of mineral nitrogen in the soil at harvest. At the optimum banded nitrogen applications in the

Table 4. The amount of nitrogen in crop residues (kg ha^{-1}).

Expt	Application method	Nitrogen applied (Table 1)						LSD ($\alpha = 0.05$)
		0	N	$2N$	$3N$	$4N$	$2N+N$	
1	broadcast	45	63	90	126	136	133	17
	band placed	36	69	101	120	141	121	
2	broadcast	39	58	80	100	118	108	24
	band placed	31	74	95	110	126	121	
3	broadcast	63	77	81	108	114	107	13
	band placed	53	75	98	126	134	116	
4	broadcast	39	83	151	189	225	181	26
	band placed		103	143	196	223	184	

Significance Expt	1	2	3	4
nitrogen	$P< 0.001$	$P< 0.001$	$P< 0.001$	$P< 0.001$
application method	ns	ns	$P= 0.003$	ns
nitro. x appl. meth.	ns	ns	$P= 0.011$	ns

experiments (Everaarts & De Willigen, 1999), the amounts of nitrogen in the soil layer 0–60 cm at harvest would have been 34, 27, 12 and 19 kg ha^{-1} for Experiments 1 to 4, respectively.

Spatial distribution

In Experiment 2 more nitrogen was found in the soil layer 30–60 cm than in the soil layer 0–30 cm, for both methods of application (Table 5). Such a pattern was not obvious in Experiments 1 and 3. Apparently especially in Experiment 2 nitrogen leached to deeper soil layers. In Experiment 4 considerably more nitrogen was found in the soil layer 0–30 cm as compared to that in the soil layer 30–60 cm. Leaching probably played no, or a much lesser role in this experiment.

The distribution of mineral nitrogen in the soil at harvest with no or broadcast application of nitrogen in Experiments 2 and 4, showed that the uptake of nitrogen by the crop had been rather similar at different distances from the plant (Figure 3). This indicates a horizontally uniformly rooted soil. In Experiment 1 with broadcast application of 4*N* clearly more nitrogen was taken up in the row than between the rows. Apparently the nitrogen present in the inter-row area already satisfied crop demand. With band placement of 2*N* in Experiments 2 and 4 uptake of nitrogen was rather uniform throughout the soil. With band placement of 2*N* and 4*N* in Experiment 1 and 4*N* in Experiments 2 and 4, however, considerably more nitrogen was found where the fertilizer had been placed than between the rows. It thus appears that at the high levels of nitrogen application, broadcast application as well as band placement, can result in an unequal distribution of nitrogen in the soil at harvest.

Table 5. The amount of mineral nitrogen in the soil at harvest (kg ha^{-1}).

Expt	Soil layer (cm)	Application method	Nitrogen applied (Table 1)						LSD (α = 0.05)
			0	*N*	2*N*	3*N*	4*N*	2*N* + *N*	
1	0–30	broadcast	4	10	8	9	37	13	9
		band placed	6	7	7	23	14	10	
	30–60	broadcast	3	9	13	19	33	24	9
		band placed	5	9	9	24	14	20	
2	0–30	broadcast	7	6	8	7	22	7	10
		band placed	8	5	10	9	31	12	
	30–60	broadcast	9	10	21	38	51	24	12
		band placed	11	9	25	35	47	30	
3	0–30	broadcast	5	9	18	25	32	21	8
		band placed	4	6	6	8	8	12	
	30–60	broadcast	4	5	18	24	30	19	13
		band placed	2	4	6	4	7	12	
4	0–30	broadcast	9	8	11	23	68	24	16
		band placed		7	10	24	44	26	
	30–60	broadcast	4	3	6	7	12	6	6
		band placed		3	5	7	21	10	

	Soil layer (cm)							
Significance	0–30				30–60			
Expt	1	2	3	4	1	2	3	4
nitrogen	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001	P=0.012	P<0.001
application method	ns	ns	P<0.001	ns	ns	ns	P<0.001	ns
nitro. x appl. meth.	P<0.001	ns	P<0.001	ns	P=0.017	ns	ns	ns

Loss of nitrogen from the crop+soil system

With an increase in available nitrogen, the amount of nitrogen unaccounted for at harvest, or the 'loss' of nitrogen from the crop+soil system, increased (Figure 4). The 'loss' at the highest broadcast applications in the experiments varied between 13 to 28 percent of available nitrogen. With the highest amounts of nitrogen band placed in the experiments the 'loss' was between 14 and 32 percent of available nitrogen. At the optimum banded nitrogen application in the experiments (Everaarts & De Willigen, 1999), the 'loss' of nitrogen would have been 47, 8, 49 and 52 kg for Experiments 1 to 4, respectively. When the data on 'loss' of all experiments were pooled, the loss of nitrogen was described by y = 0.26x – 18, whereby y is 'loss' and

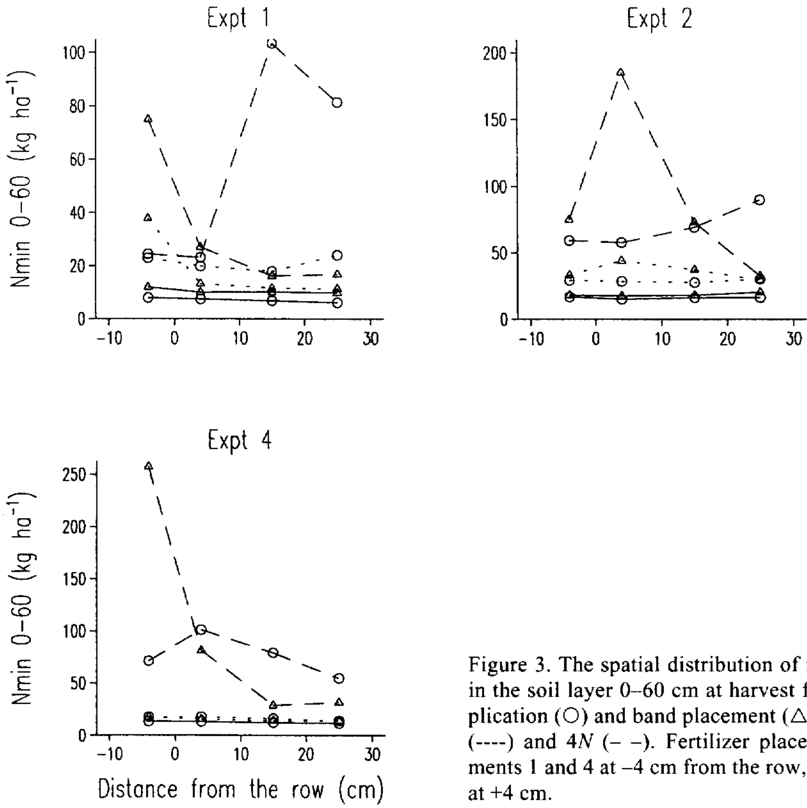

Figure 3. The spatial distribution of mineral nitrogen in the soil layer 0–60 cm at harvest for broadcast application (○) and band placement (△) at 0 N (—), 2*N* (----) and 4*N* (– –). Fertilizer placement in Experiments 1 and 4 at –4 cm from the row, in Experiment 2 at +4 cm.

x is available nitrogen ($r^2 = 0.80$; $P < 0.001$). The method of application, broadcast application vs band placement, had no effect on the 'loss'. Also split application had no obvious effect on the 'loss' of nitrogen.

Discussion

Uptake of nitrogen by broccoli at harvest has been reported to be in the range of 175 to 270 kg per hectare (Kowalenko & Hall, 1987b; Shelp & Liu, 1992; Weier *et al.*, 1994). Our range of uptake with the higher amounts of nitrogen applied compares well with these values. Zebarth *et al.* (1995), however, recorded amounts of nitrogen uptake as high as 345 to 465 kg per hectare. However, the maximum nitrogen application rate in their experiments was 625 kg ha^{-1}. Variation in conditions during growth, different cultivars used and different rates of fertilizer application are likely responsible for the variation reported in the amount of nitrogen in the crop at harvest. After a slow start, the uptake of nitrogen by the crop rapidly increases and continues up to harvest (Shelp & Liu, 1992). This means that also shortly before harvest nitrogen must be available for uptake. At a nitrogen application rate of 279 kg ha^{-1}

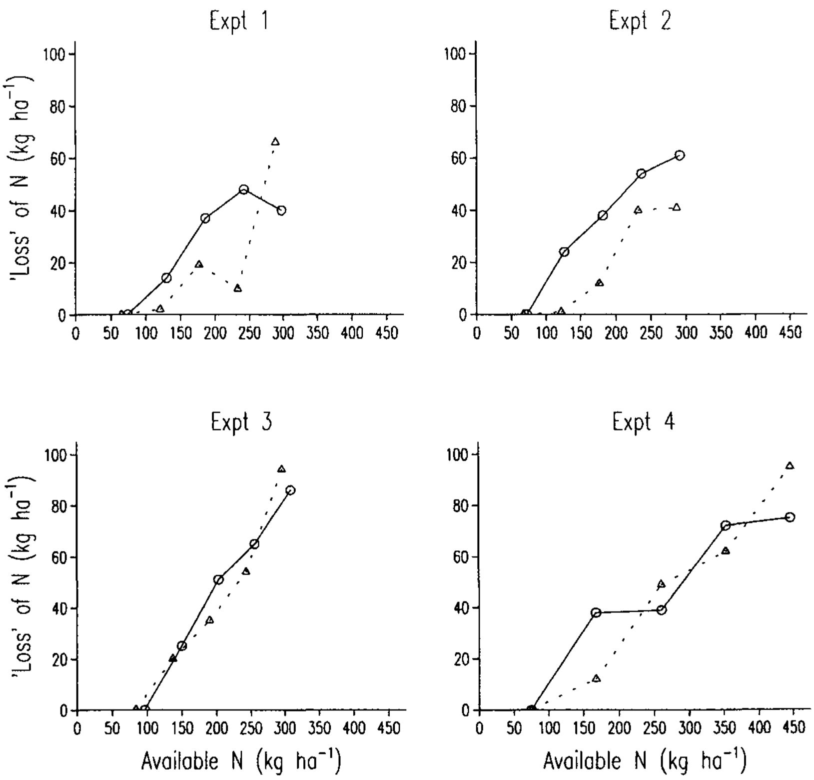

Figure 4. The 'loss' of nitrogen from the crop/soil system in relation to the amount of nitrogen available for broadcast application (O) and band placement (△). 'Loss' = available nitrogen minus nitrogen present in the crop and soil (0–60 cm) at harvest. Available nitrogen is nitrogen present in the crop and soil (0–60 cm) at harvest at 0 N plus fertilizer nitrogen.

band placed at planting, the uptake of nitrogen in Experiment 4 was 261 kg ha^{-1}. With a cultivation period of 52 days, this indicates an average uptake of 5 kg nitrogen ha^{-1} d^{-1} during growth. However, the rate of uptake in the later part of the growing period is much higher than that in the first part of the growing period (Shelp & Liu, 1992; Weier *et al.*, 1994). Band placement may contribute to a better availability of nitrogen, making high uptake rates possible. This perhaps explains why in the majority of the experiments and in the combined analysis of the experiments, a positive effect of band placement of nitrogen fertilizer on fresh product yield was found (Everaarts & De Willigen, 1999).

The dry matter harvest index in our experiments showed no consistent response to nitrogen application. Kowalenko & Hall (1987b) found a significant increase in dry matter harvest index with nitrogen application in one of two trial years. Everaarts (1994) observed no effect of nitrogen application on the dry matter harvest index. Nitrogen application apparently has no consistent effect on dry matter distribution in the above-ground part of the broccoli plant. Kowalenko & Hall (1987a) mentioned that in both trial years the fresh matter harvest index was positively correlated with yield, while dry matter content of the head was negatively correlated with yield. The latter observation is corroborated by our data. With an increase in nitrogen application rate the dry matter content of the head decreased, while yield increased (Everaarts & De Willigen, 1999). The positive effect of nitrogen application on yield, thus, in general, is not just caused by a higher dry matter production, but also by a higher water content.

Kowalenko & Hall (1987b) found no effect of nitrogen application on the nitrogen harvest index. The average nitrogen harvest index in their experiments was 38 and 57 percent respectively. Shelp & Liu (1992) and Abdul-Baki *et al.* (1997) found 17 and 22 percent respectively of the total amount of nitrogen taken up to be located in the head. In our experiments the nitrogen harvest index generally decreased with an increase in nitrogen application rate. At the optimum banded nitrogen application rates (Everaarts & De Willigen, 1999), the nitrogen harvest index ranged from 27 to 30 percent. Apart from conditions during growth, the nitrogen harvest index is likely to be especially strongly influenced by the type of cultivar. The cultivar Emperor is a cultivar that forms quite an amount of leaf-mass (Aalbersberg & Stolk, 1992). The cultivars with less leaf production or the 'crown' types of broccoli, with considerably shorter stems, probably have considerably different nitrogen harvest indices. However, no comparative information on nitrogen harvest indices for broccoli cultivars is available. From the point of view of reducing the amount of nitrogen in crop residues, breeding of cultivars with high nitrogen harvest indices would be advantageous.

As found by Kowalenko & Hall (1987a) and Zebarth *et al.* (1995), the amount of nitrogen in the soil at harvest increased with increased amounts of nitrogen applied. Most of the nitrogen in the soil at harvest in our experiments was found in the 0–30 cm soil layer. A comparable pattern was observed by Kowalenko & Hall (1987a). At the optimum banded nitrogen applications in the experiments (Everaarts & De Willigen, 1999), the amounts of nitrogen in the soil layer 0–60 cm at harvest ranged from 12 to 34 kg ha^{-1}. The amount of mineral nitrogen in the soil at harvest apparently does not necessarily have to be high to obtain good yields. This despite the high nitrogen demand of the crop in the period shortly before harvest (Shelp & Liu, 1992; Weier *et al.*, 1994). The amounts of nitrogen taken up by the crop with no or low nitrogen application in combination with the low amounts of residual mineral nitrogen in the 30–60 cm soil layer with that treatments, support the conclusion that broccoli is able to utilise the mineral nitrogen from the 30–60 cm soil layer (Everaarts & De Willigen 1999). The present data show that depending on the amount of nitrogen applied, both with broadcast application and band placement, the distribution of residual nitrogen in the soil around a plant can horizontally be heterogenous. When sampling the soil for residual nitrogen after harvest, this is to be taken into account (Clay *et al.*, 1995).

The 'loss' of nitrogen at optimum banded application would have been 47, 8, 49 and 52 kg for Experiments 1 to 4, respectively. Denitrification or volatilization of nitrogen during cultivation might have contributed to these 'losses'. In view of the size of the 'losses' this, however, seems unlikely. Leaching is also not likely as a major cause of the 'losses' observed, as under summer conditions evapotranspiration usually exceeds rainfall. Indications for leaching from the uppermost soil layer to deeper soil layers were only found in Experiment 2. Possibly nitrogen not accounted for in the roots and immobilization of nitrogen play an important role in the 'losses' found, as was suggested for onions by Greenwood *et al.* (1992). Abdul-Baki *et al.* (1997) estimated that 14 percent of the total nitrogen uptake by broccoli was located in the roots.

In all cases the estimated 'loss' of nitrogen during cultivation, as measured at harvest, is much less compared to the amount of nitrogen in crop residues left in the field after harvest. At the optimum rates of band placed nitrogen application in the experiments (Everaarts & De Willigen, 1999), the nitrogen in crop residues ranged from 120 to 155 kg ha^{-1}. In reality this amount is higher as no account is taken of nitrogen in leaves shed during growth or of nitrogen in the roots and non-harvested plants. Part of the nitrogen in crop residues, especially when worked into the soil, can quickly mineralise and possibly is lost through leaching during winter (De Neve *et al.*, 1994). As most of the area of broccoli is harvested after August (Everaarts, 1993), catch crops are no option to conserve nitrogen from crop residues, or soil, as the remaining growth period for these crops after August is too short to take up appreciable amounts of nitrogen. Leaching of nitrogen from crop residues might be limited by leaving crop residues untouched in the field and work them into the soil only shortly before (Weier & Scharpf, 1994) or after winter (Wehrmann & Scharpf, 1989). However, from the point of reducing the spread of diseases, working crop residues into the soil shortly after harvest may be preferred. While on heavy soils soil cultivation before winter might even be necessary. Removal of crop residues after harvest may then be another option to consider.

Conclusion

Nitrogen application results in a higher head dry matter production and a lower head dry matter content. Band placement of nitrogen fertilizer may further stimulate these effects. The 'loss' of nitrogen during growth is less than the amount of nitrogen left in crop residues at harvest. The nitrogen in the crop residues forms the largest single source of potential loss of nitrogen to the environment with broccoli cultivation.

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