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Modeling long-term crop response to fertilizer and soil nitrogen

II. Comparison with field results

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Abstract

Results from a simple model for computing long-term changes in soil organic nitrogen and crop uptake and crop recovery of nitrogen applications were compared with results of previously published long-term field trials. In these trials a rotation of sugar beet, barley, potatoes and wheat was practiced in the German Democratic Republic and continuous production of wheat and rice in the United Kingdom and Japan, respectively. The agreement between observed values for the change in soil nitrogen and nitrogen uptake and the computed values is in general satisfactory. The number of input data required for application of the model is kept as restricted as possible. Nevertheless, part of the required information may not be available in many situations. The quality of the predictions of the model will then be limited particularly by the lack of suitable input data.

Introduction

Extensive literature exists on the many processes affecting the soil nitrogen balance and their influence on crop uptake of soil nitrogen. Many field experiments have been carried out to establish the recovery of nitrogen applied as inorganic fertilizer or organic material. The number of experiments reported that deal with long-term changes in total amount of soil organic nitrogen and nitrogen uptake by the crop is, however, limited. Experimental results suitable for testing the model developed by Wolf *et al.* (1989) are therefore scarce. Serious problems may still arise in using these results, because nitrogen uptake by the successive crops is seldom measured continuously, and seasonal effects are often so strong that it is difficult to recognize regular patterns. In this paper data from long-term field trials from the German Democratic Republic, United Kingdom and Japan are used to test the model.

Experimental designs

German Democratic Republic

The experiment reported by Ansorge (1965) was established in 1902 at Lauchstädt on a mollisol developed in a loess loam layer of 1.5 m. The effects of different soil amendments on crop yields and nitrogen uptake were measured from 1903 to 1962 for a rotation comprising sugar beet, summer barley, potatoes and winter wheat. The amendments included NPK, PK, and N fertilizers and a control, both with and without application of animal manure to potatoes and sugar beet. Total soil nitrogen contents (Kjeldahl) in the 0–0.2 m soil depth were established in 1902, 1930 and 1956.

United Kingdom

In the Broadbalk experiments, wheat has been grown under a manurial regime that almost has not changed from the start in 1843. In 1968 a new wheat variety was introduced. The annual amendments varied from zero to 35 tons ha^{-1} of animal manure containing about 225 kg N, in combination with various fertilizer nitrogen doses (0, 48, 96 and 144 kg N ha^{-1}, respectively) and PKMg fertilizers (35 kg P, 90 kg K and 10 kg Mg per hectare). Total soil nitrogen contents for the 0–0.23 m soil depth were determined in 1865, 1881, 1893, 1914, 1944 and 1966 using the Kjeldahl method except for the first two occasions, when the soda-lime method was used. Those data have been transformed in Kjeldahl values (Jenkinson, 1977) by multiplying with the (N Kjeldahl)/(N soda-lime) ratio derived from the 1893 Broadbalk samples (Dyer, 1902). Average nitrogen uptake by the crop under different treatments was established for a number of sampling periods.

Another part of the field, the Broadbalk Wilderness, in which wheat had been grown without manure since 1843, was fenced off in 1883 and allowed to revert to wilderness. For that part of the Broadbalk Wilderness where emerging saplings were removed regularly by stubbing and which was covered by a mixed herbaceous vegetation, the change in total soil nitrogen content with time was followed. More information about these experiments and their nitrogen balances is given by Jenkinson (1977).

Japan

Field experiments covering 21 years of flooded rice cultivation with one crop per year, have been carried out at Aomori experimental station (Koyama and App, 1979). The annual amendments were constant throughout the period and consisted of various levels of manure application, containing 0, 28.6, 57.2 and 95.4 kg N ha^{-1}, with or without chemical N fertilizer at 56.3 kg ha^{-1}. For the different treatments the initial and final total soil nitrogen and the cumulative nitrogen uptake by the crop were established.

Experimental results

German Democratic Republic

Average annual nitrogen uptake from the unfertilized soil varied substantially for the four crops in the rotation (Ansorge, 1965). If the value for winter wheat is set at 100, those for sugar beet, potatoes and summer barley are 137, 69 and 61, respectively. The recovery fractions of nitrogen applied as chemical fertilizer or manure are also different for the four species. For fertilizer the long-term recovery fraction is 0.65 for potatoes, 0.69 for winter wheat, 0.80 for summer barley and 0.91 for sugar beet. As such differences in nitrogen uptake and fertilizer recovery cannot be reproduced by the present simple model, the model is applied for an 'average' crop and for 'average' application rates. Actually these rates also vary among the different species and they change with time due to limited changes in fertilizer rate and in manure-N application (Fig. 1).

For comparison with computed long-term results, total soil nitrogen contents in the 0–0.2 m soil depth established in 1902 and 1956 were used. Total soil nitrogen contents for 1930 were also available, but as the average annual rate of change in soil nitrogen can be established more accurately over a longer period of time, these data were not used. Bulk density in the experimental fields was 1400 kg m^{-3} and the change in total nitrogen in the 0.2–0.6 m soil layer was about identical to that in the 0–0.2 m soil layer (Ansorge, 1957; Ansorge, 1965). From these data total soil nitrogen and its average annual rate of change can be calculated (Table 1).

The nitrogen inputs from seed potatoes and grains and from rain were estimated by Ansorge (1965) at 3 to 4 and about 15 kg ha^{-1} yr^{-1}, respectively. For all treatments the average amounts of nitrogen applied annually in fertilizer and/or manure and the average nitrogen uptake by the crop were specified for a period of 60 years (Ansorge, 1965). With the average rate of change in total soil nitrogen given in Table 1, balances of nitrogen inputs and outputs can be established for the various treatments (Table 2).

United Kingdom

Total soil nitrogen hardly changed over a period of 125 years of continuous wheat cropping in the plots where no nitrogen or only inorganic nitrogen has been applied. In the plots where manure has been applied, however, total soil nitrogen in the 0–0.23 m soil depth rapidly increased by

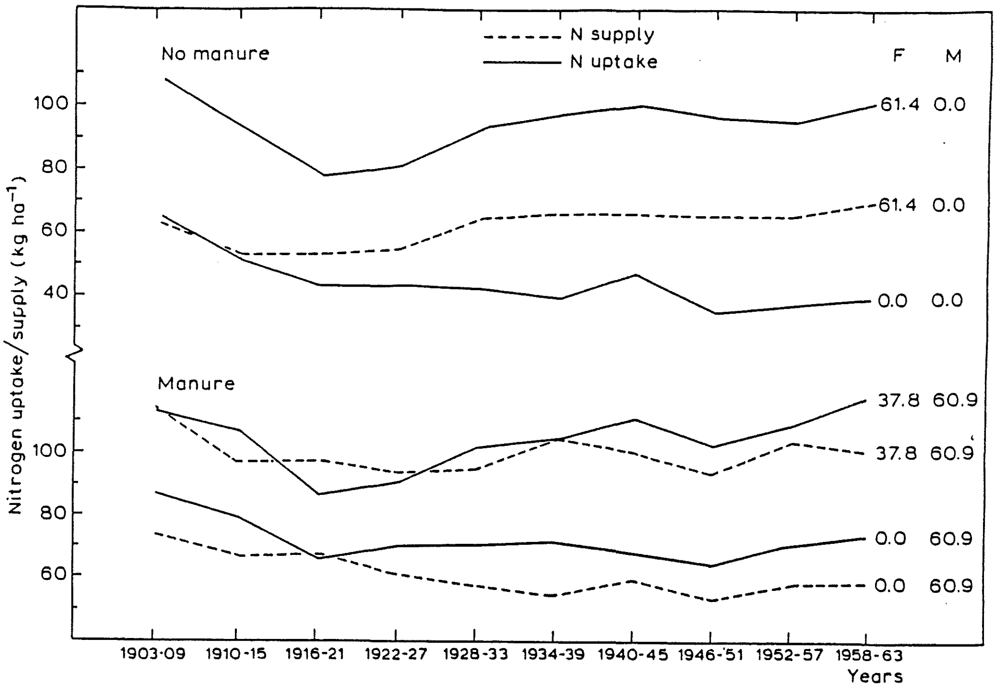

Fig. 1. Courses of actual nitrogen supply and measured nitrogen uptake by an 'average' crop in the rotation on the Lauchstädt fields over the period 1903–1963 (source: Ansorge, 1965). *Numbers* indicate the average amount of nitrogen (kg ha^{-1}) applied annually as fertilizer (F: NPK or 0 treatment) and/or manure (M).

Table 1. Total soil nitrogen contents, total soil nitrogen in layers of 0.20 m and 0.60 m depth, and annual change in soil nitrogen in Lauchstädt fields between 1902 and 1956

Treatment	Soil nitrogen content (0–0.2 m) 1902	1956	Total soil nitrogen (0–0.2 m) 1902	1956	Total soil nitrogen (0–0.6 m) 1902	1956	Annual change in soil nitrogen (0–0.6 m)
	(kg N kg^{-1})		(kg N ha^{-1})				
With manure							
NPK	0.00160	0.00173	4480	4844	8960	9688	13.5
N	0.00160	0.00165	4480	4620	8960	9240	5.2
PK	0.00160	0.00162	4480	4536	8960	9072	2.1
O	0.00160	0.00160	4480	4480	8960	8960	0.0
Without manure							
NPK	0.00160	0.00146	4480	4088	8960	8176	−14.5
N	0.00160	0.00144	4480	4032	8960	8064	−16.6
PK	0.00160	0.00133	4480	3724	8960	7448	−28.0
O	0.00160	0.00131	4480	3668	8960	7336	−30.1

96 kg ha^{-1} yr^{-1} on average during the first 22 years and by about 31 kg ha^{-1} yr^{-1} on average over the total period of 125 years (Fig. 2). As no data were available on changes in soil organic nitrogen below the plough layer, it is assumed that the same approach as for Lauchstädt (Table 1) can be applied. In that case the annual changes in total organic nitrogen in the 0–0.6 m soil layer are on average 167 and 54 kg ha^{-1} during the first 22 years and during the total period of 125 years, respectively. In the Broadbalk Wilderness on average 48 kg N ha^{-1} accumulated annually in the top 0.23 m (Fig. 2). Relatively little nitrogen accumulated in the soil below that depth (Jenkinson, 1977), probably because of the absence of soil tillage.

In addition to the varying nitrogen inputs via fertilizer and/or manure, other annual inputs, estimated at 3 kg ha^{-1} in grains, at 5 kg ha^{-1} in rain and at 10 kg ha^{-1} in dry deposition of ammonia

Table 2. Annual balances of nitrogen inputs and outputs (kg ha^{-1}) for various treatments on Lauchstädt fields averaged for the four different crops in the rotation over a period of 60 years (1903–1962)

	With manure				Without manure			
	NPK	N	PK	O	NPK	N	PK	O
N-inputs								
Seeds	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Rainfall	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Fertilizer	37.8	37.8	0.0	0.0	61.4	61.4	0.0	0.0
Manure	60.9	60.9	60.9	60.9	0.0	0.0	0.0	0.0
Total	117.2	117.2	79.4	79.4	79.9	79.9	18.5	18.5
N-outputs								
Crop uptake	104.4	102.2	72.4	72.1	93.5	85.5	45.4	44.2
Change Soil-N[a]	13.5	5.2	2.1	0.0	−14.5	−16.6	−28.0	−30.1
Total	117.9	107.4	74.5	72.1	79.0	68.9	17.4	14.1
Balance[b]	−0.7	9.8	4.9	7.3	0.9	11.0	1.1	4.4

[a] Value established for period of 54 years.
[b] This value represents the losses for the various treatments.

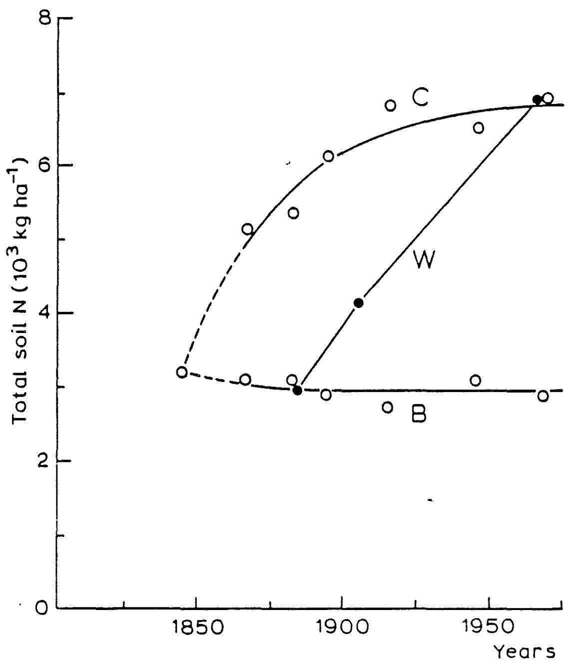

Fig. 2. Course of total soil nitrogen in the 0–0.23 m soil depth in the stubbed section in Broadbalk Wilderness (**W**), the control plot of the Continuous Wheat experiment on Broadbalk (**B**), and the plot of the Continuous Wheat experiment receiving 35 t ha^{-1} of manure annually (**C**)(source: Jenkinson, 1977).

(Jenkinson, 1977), are identical for all treatments.

The data in Table 3 suggest that nitrogen uptake by the crop is about constant with time, although according to Jenkinson (1977) yields and probably also nitrogen uptake reached minimum values in the early 1920's. From data for the first sampling periods (1852–1871) the recovery fraction of nitrogen applied in manure is calculated to be about 0.14 and that applied in fertilizer about 0.34. In 1968 a more modern wheat variety was introduced and the fertilizer application method was changed, resulting in substantial increases in nitrogen uptake without nitrogen application and in recovery fraction of applied nitrogen.

Annual losses of nitrogen by leaching for all treatments, except the manure treatment, were established by Lawes, Gilbert and Warington (1882) for a period of 30 years. As total soil nitrogen and nitrogen uptake by the crop are practically constant with time, these values probably apply until 1968 (Jenkinson, 1977).

Annual balances of nitrogen inputs and outputs have been compiled for the various treatments (Table 4). For the 0 and PKMg treatments the input of nitrogen via seeds, rain and dry deposition (18 kg ha^{-1} yr^{-1} in total) is much smaller than the output via uptake by the crop and leaching. As total soil nitrogen is approximately constant, an additional input of nitrogen of about 18 to 23 kg ha^{-1} yr^{-1} must be assumed which probably results from biological fixation (Dart and Day, 1975).

Losses by denitrification have not been established, but they may be estimated as described by Jenkinson (1977). The total nitrogen input in the

Table 3. Uptake of nitrogen in wheat grains and straw in $kg\,ha^{-1}\,yr^{-1}$ for the various treatments in the Broadbalk experiment, Rothamstead (source: Jenkinson, 1977)

Sampling period	Wheat variety	O	PKMg	N1PKMg	N2PKMg	N3PKMg	Manure
1852–61	Red Rostock	26	32		64		59
				42		71	
1862–71	Red Rostock	20	22		56		57
1966–67	Squarehead's Master	25	26	41	64	78	63
1970–72	Capelle-Desprez	34	35	66	104	130	144

Table 4. Annual balances of nitrogen inputs and outputs ($kg\,ha^{-1}$) for various treatments on Broadbalk fields averaged for a period of 125 years (1843–1967)

	O	PKMg	N1PKMg	N2PKMg	N3PKMg	Manure
N-inputs						
Seeds	3	3	3	3	3	3
Rainfall	5	5	5	5	5	5
Dry deposition	10	10	10	10	10	10
Biol. fixation[a]	18(28)	23(35)	0(15)	0(12)	0	10(0)[b]
Fertilizer	0	0	48	96	144	0
Manure	0	0	0	0	0	225
Total	36(46)	41(53)	66(81)	114(126)	162	253(243)
N-outputs						
Crop uptake	24	27	42	61	73	60
Leaching	12	14	21	35	48	75[d]
Denitrification	0(10)[c]	0(12)[c]	3(18)[c]	18(30)[c]	41	64[d](129)[b]
Change Soil-N	0	0	0	0	0	54[e]
Total	36(46)	41(53)	66(81)	114(126)	162	253(243)

[a] Biological fixation calculated as the final term in the balance.
[b] Biologically fixed nitrogen set to zero and consequently total losses reduced.
[c] Denitrification calculated under the assumption that the ratio of leaching and denitrification losses calculated for N3PKMg also applies to the other treatments.
[d] The ratio of nitrogen applications in the manure and N3PKMg treatments (225/144) is used to calculate these losses from those found for N3PKMg.
[e] Change in soil nitrogen calculated for the 0–0.6 m soil depth. Applied calculation method, see text.

N3PKMg treatment is $162\,kg\,ha^{-1}\,yr^{-1}$, *i.e.* much higher than the total of nitrogen uptake by the crop and losses by leaching (Table 4). The difference of $41\,kg\,ha^{-1}\,yr^{-1}$ may probably be ascribed to denitrification. Denitrification losses can be estimated assuming that they are proportional to the NO_3-N content which in turn is assumed to be proportional to the leaching losses. For example, for the control treatment that yields: $12/48 * 41 = 10\,kg\,N\,ha^{-1}\,yr^{-1}$. The input via biological fixation must be higher by the same amount to close the balance.

For the N1PKMg and N2PKMg treatments the nitrogen outputs via uptake by the crop and leaching are lower than the inputs, even if biological fixation is assumed to be zero. As total soil nitrogen is approximately constant, additional losses must occur, probably via denitrification. If denitrification losses are calculated proportionally to leaching losses, a higher nitrogen input via biological fixation must be assumed to close the balance.

Leaching losses have not been measured for the manure treatment. A first estimate of the losses was obtained by multiplying the leaching and denitrification losses in the N3PKMg treatment by the ratio of the nitrogen applications in the manure and the N3PKMg treatments (225/144).

Japan

The data available are total nitrogen uptake by rice during the period of 21 years and the initial and final amounts of organic nitrogen in the soil. Unfortunately, the time courses of these variables are not available. In the absence of fertilizer and manure application, average annual nitrogen uptake by the crop is 45.2 kg ha^{-1}, which results in an annual depletion of the total soil nitrogen store of 20.2 kg ha^{-1} (Table 5). If 56.3 kg ha^{-1} of fertilizer nitrogen is applied, average annual uptake increases to 65.9 kg ha^{-1}, but at the expense of a more rapid depletion of total soil nitrogen at a rate of 34.7 kg ha^{-1} yr^{-1}. If 57.2 kg ha^{-1} of nitrogen is applied as manure, average annual values of nitrogen uptake by the crop and total soil nitrogen increase are 62.0 and 1.6 kg ha^{-1}, respectively. The results of the other treatments where smaller or larger amounts of manure nitrogen are applied, indicate that increased manure–nitrogen application results in higher nitrogen uptake by the crop and a smaller decrease or larger increase in total soil nitrogen.

The amount of nitrogen added annually via irrigation water is 10.1 kg ha^{-1} for all treatments. No other nitrogen inputs are reported by Koyama and App (1979), except the various applications in fertilizer and/or manure (Table 5). The nitrogen recovered by the crop represents probably the net amount, as nitrogen input from sowing or planting material is not explicitly accounted for, but complete information on this aspect is lacking.

From the differences in crop nitrogen uptake in the various treatments (Table 5), the cumulative recovery fraction of applied nitrogen can be calculated and appears to be 0.35 for fertilizer nitrogen and 0.25 for manure nitrogen over the period of 21 years.

Annual balances of nitrogen inputs and outputs have been compiled for the various treatments (Table 5). If no nitrogen is applied, the output via crop uptake minus the decrease in total soil nitrogen is 25 kg ha^{-1} annually, which is higher than the input of 10.1 kg ha^{-1} with irrigation water. As also losses occur, for which no measured data were available, an additional nitrogen input, probably biological fixation, is required which is estimated at 30 kg ha^{-1} yr^{-1}. If 56.3 kg ha^{-1} of fertilizer nitrogen is applied, the nitrogen output via uptake by the crop minus the decrease in total soil nitrogen is 31.2 kg ha^{-1} yr^{-1}, which is much smaller than the input via fertilizer and irrigation water, *i.e.* 66.4 kg ha^{-1} yr^{-1}. Hence, biological fixation is set to zero if fertilizer nitrogen is applied. If 57.2 kg ha^{-1} of nitrogen is applied as manure, the nitrogen output via uptake by the crop and the increase in total soil nitrogen is 63.6 kg ha^{-1} yr^{-1}, *i.e.* about identical to the input of 67.3 kg ha^{-1} yr^{-1} via manure and irrigation water. As the losses will

Table 5. Annual balances of nitrogen inputs and outputs (kg ha^{-1}) for various treatments on Aomori fields averaged over a period of 21 years (source: Koyama and App, 1979)

	Fertilizer Manure				No fertilizer Manure			
	N0	N1	N2	N3	N0	N1	N2	N3
N-inputs								
Irrigation	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
Biol. fixation[a]	0	0	0	0	30	30	30	30
Fertilizer	56.3	56.3	56.3	56.3	0.0	0.0	0.0	0.0
Manure	0.0	28.6	57.2	95.4	0.0	28.6	57.2	95.4
Total	66.4	95.0	123.6	161.8	40.1	68.7	97.3	135.5
N-outputs								
Crop uptake	65.9	70.7	80.7	86.3	45.2	52.4	62.0	69.0
Change Soil-N	−34.7	−29.2	−12.2	13.7	−20.2	−3.1	1.6	52.8
Total	31.2	41.5	68.5	100.0	25.0	49.3	63.6	121.8
Balance[b]	35.2	53.5	55.1	61.8	15.1	19.4	33.7	13.7

[a] Estimated values, see text.

[b] This value represents the losses for the various treatments.

be higher than in the unfertilized situation, an additional input via biological fixation must be assumed, which is estimated at 30 kg ha^{-1} yr^{-1}, if no fertilizer nitrogen is applied.

Results of modeling

German Democratic Republic

For the deep soils and low rainfall (annual average of 482 mm) at Lauchstädt it may be assumed that losses by leaching and denitrification are negligible, which is substantiated by the annual balances of nitrogen inputs and outputs (Table 2). For the nitrogen input via rain only an estimate by Ansorge (1965) is available. Assuming that nitrogen losses are negligible under these conditions, nitrogen input via rain as derived from the balances in Table 2 for the PK and the O treatments without manure application, is 12 kg ha^{-1} yr^{-1}.

From the field data the long-term average recovery fractions of nitrogen in fertilizer and manure during the crop rotation are calculated at 0.72 and 0.45, respectively, although large variations exist among crops. As the residual effect of fertilizer nitrogen is generally small and that of manure nitrogen large, in the model the fractions transferred to the crop in the first year are estimated at 0.70 and 0.30, respectively. As no losses occur, the complementary fractions are transferred to the labile pool of soil nitrogen (Table 6, case A). As explained by Wolf *et al.* (1989), a fraction of about 0.15 of the nitrogen mineralized from the labile pool is transformed into a more stable form and is not available for the crop, and the partitioning between crop and labile pool for nitrogen in rain is identical to that for fertilizer, as rain water mainly contains inorganic nitrogen.

For simulating the nitrogen cycle, time constants of conversion of the labile and the stable pool are required (Wolf *et al.*, 1989). Their values are best estimated from the control treatment with only manure application, where total soil nitrogen is constant with time (Table 7). Actual uptake by the

Table 6. Annual inputs of nitrogen (kg ha^{-1}) via rain (NRAIN) and biological fixation (NFIX) and the fractions transferred to crop, labile and stable pool, and lost of nitrogen inputs via inorganic fertilizer (FERTN), organic material (ORGN), biological fixation (NFIX) and rain and of nitrogen mineralized from soil organic matter (LON), used in the simulation of the nitrogen cycle in Lauchstädt, German Democratic Republic, and Broadbalk, United Kingdom

Input	Crop	Loss	Labile pool	Stable pool	NRAIN	NFIX	Crop	Loss	Labile pool	Stable pool	NRAIN	NFIX
	Lauchstädt, case A						Lauchstädt, case B					
FERTN	0.70	0.00	0.30		12.0	0.0	0.60	0.05	0.35		14.0	0.0
ORGN	0.30	0.00	0.70				0.15	0.05	0.80			
NFIX	0.30	0.00	0.70				0.15	0.05	0.80			
NRAIN	0.70	0.00	0.30				0.60	0.05	0.35			
LON	0.85	0.00		0.15			0.85	0.00		0.15		
	Broadbalk, case A						Broadbalk, case B					
FERTN	0.30	0.50	0.20		15.0[a]	0.0	0.35	0.45	0.20		15.0[a]	0.0
ORGN	0.10	0.20	0.70			or	0.15	0.15	0.70			or
NFIX	0.10	0.20	0.70			15.0	0.15	0.15	0.70			20.0
NRAIN	0.27	0.53	0.20			or	0.35	0.45	0.20			or
LON	0.28	0.57		0.15		35.0[b]	0.425	0.425		0.15		35.0[b]
	Broadb. Wilderness, cases W1 and W2						Broadb. Wilderness, case W3					
ORGN	0.15	0.15	0.70		15.0[a]	35.0	0.20	0.00	0.80		15.0[a]	35.0
NFIX	0.15	0.15	0.70			or	0.20	0.00	0.80			
NRAIN	0.35	0.45	0.20			95.0[c]	0.65	0.00	0.35			
LON	0.425	0.425		0.15			0.85	0.00		0.15		

[a] Total nitrogen in rain and in dry deposition of ammonia.

[b] NFIX set at 35 kg ha^{-1} yr^{-1} if no nitrogen is applied, 20 or 15 kg ha^{-1} yr^{-1} if 48 kg ha^{-1} fertilizer nitrogen is applied, and zero if 144 kg ha^{-1} fertilizer nitrogen or 225 kg ha^{-1} manure nitrogen is applied.

[c] NFIX set at 35 and 95 kg ha^{-1} yr^{-1} for cases W1 and W2, respectively.

Table 7. Annual change in total soil nitrogen in the 0–0.6 m soil depth, annual nitrogen uptake averaged for the four different crops in the rotation, and losses of nitrogen in the Lauchstädt fields, both measured and computed ($kg\,ha^{-1}\,yr^{-1}$) for the various treatments during a period of 60 years (1903–1962)

	Manure				Without manure			
	NPK	N	PK	O	NPK	N	PK	O
Measured								
Crop uptake	104.4	102.2	72.4	72.1	93.5	85.5	45.4	44.2
Change Soil-N[a]	13.5	5.2	2.1	0.0	−14.5	−16.6	−28.0	−30.1
Computed, case A								
Crop uptake	104.7		74.0		89.5		39.6	
Change Soil-N	9.5(9.9)[a]		2.4(2.5)[a]		−12.6(−13.1)[a]		−24.1(−25.1)[a]	
Losses	0.0		0.0		0.0		0.0	
Computed, case B								
Crop uptake	101.8		73.4		89.5		43.4	
Change Soil-N	8.8(9.2)[a]		1.2(1.3)[a]		−14.3(−15.0)[a]		−26.6(−27.9)[a]	
Losses	5.6		3.7		3.8		0.7	

[a] Value established for period of 54 years.

crop minus the nitrogen transferred to the crop from seed, rain and manure, yields the amount of nitrogen for crop uptake from mineralization of the labile pool: $72.1 - 3.5 - 0.7 * 12 - 0.3 * 60.9 = 41.9\,kg\,ha^{-1}$. As initial soil organic nitrogen is $8960\,kg\,ha^{-1}$ (Table 1) and a fraction of 0.15 of the nitrogen mineralized is transferred to the stable pool, the relative mineralization rate is: $(41.9/0.85)/8960 = 5.5 * 10^{-3}\,yr^{-1}$. It is impossible to establish the time constant of conversion of the stable pool directly. Therefore, the ratio of the time constants of conversion of the stable and the labile pool, derived from comparison of results of computer simulations with the actual time courses of pool sizes and uptake by the crop, is used as an intermediate. Ratios of 20 for dryland soils and 30 for wetland soils appeared to work well for various long-term field trials and are therefore assumed to be generally applicable in the present approach. Hence, in wetland soils the proportion of soil organic nitrogen in the labile pool is relatively smaller and long-term applications of organic material result in larger increases in nitrogen uptake by the crop. These ratios of the time constants have only an empirical basis, but the higher ratio for wetland soils might be explained by the limited rooting depth of flooded rice in puddled soil. Assuming that initially the labile pool and the stable pool are in equilibrium, the ratio of their sizes can be calculated from the ratio of their time constants of conversion and turns out to be 3 for dryland soils and 4.5 for wetland soils (Wolf *et al.*, 1989). So, the time constant of conversion of the labile pool becomes $(1/5.5 * 10^{-3})/4 = 45$ years and that of the stable pool 900 years.

With the parameter values derived, uptake by the crop and total soil nitrogen were simulated over a period of 60 years for the various treatments (Table 7, case A). The agreement between computed and measured values is acceptable for most treatments, except those without manure and without fertilizer nitrogen. In judging the results of the model, the differences in experimental results between the treatments with and without PK application should be considered. Such differences, which may result from a more efficient use of soil and fertilizer nitrogen due to faster initial crop growth and higher crop production with PK fertilizer cannot be explained with this model.

For the treatment without manure and fertilizer nitrogen the decrease in soil nitrogen and nitrogen uptake by the crop are underestimated in the model. To obtain a better agreement between computed and measured values the parameter values were recalculated (case B). The calculated decrease in soil nitrogen and uptake by the crop will increase if the mineralization rate of the labile pool is assumed to be higher. The time constants of conversion of the labile and the stable pool then become 37 and 740 years, respectively. Nitrogen uptake by the crop without application is higher now and to retain agreement in the case of nitrogen amendments, the recovery fractions of applied fertilizer and manure nitrogen have been reduced to

0.60 and 0.15, respectively. From Table 2 it can be deduced that the nitrogen balance is slightly more positive if fertilizer and manure nitrogen are applied than without nitrogen application. This means that a small part of the nitrogen amendments is lost, estimated at 0.05 of the total (Table 6, case B). Assuming that the same value applies to nitrogen in rain and that the average annual decrease in soil nitrogen over a period of 60 years is somewhat lower than the value determined over 54 years, evaluation of the nitrogen balance leads to a nitrogen input via rain of about 14 kg ha^{-1}. The agreement between computed and measured results is now satisfactory (Table 7, case B).

If only manure is applied, the computed sizes of the labile and the stable pools of soil organic nitrogen over a period of 60 years are about constant, as is nitrogen uptake by the 'average' crop in the rotation (Fig. 3). The observed nitrogen uptake by the crop is also about constant with time, at an identical value of about 70 kg ha^{-1} (Fig. 1). Only in the first years nitrogen uptake is higher, which may have been the result of the land use prior to the experiment (*i.e.* natural vegetation, fertilizer or manure application *etc.*). When also fertilizer nitrogen is applied, the computed pool sizes increase with time and as a result, nitrogen uptake by the crop increases from about 95 to about 105 kg ha^{-1} over the 60-year period. Observed nitrogen uptake also increases with time but the pattern is different. Nitrogen uptake in the first years is relatively high as in the manure treatment. In the period 1916–1921 it is rather low, probably as a result of relatively low rainfall (Ansorge, 1965), and from then on uptake increases from about 90 to about 110 kg ha^{-1}, *i.e.* somewhat faster than computed, probably due to the increase in fertilizer rate.

The computed pool sizes in the control treatment decrease rapidly with time, as does the nitrogen uptake by the crop (Fig. 3). Observed nitrogen uptake (Fig. 1) shows a similar decline from about 65 to about 35 kg ha^{-1}, although the slope of the uptake curve is somewhat steeper in the beginning, perhaps due to the dry years 1916–1921. If only fertilizer nitrogen is applied, computed pool sizes also decrease rapidly and with it uptake by the crop from about 100 to about 85 kg ha^{-1} over the 60-year period. Observed nitrogen uptake decreases from over 100 kg ha^{-1} initially to less than 80 in the dry years 1916–1921, a pattern similar to that in the other treatments. Subsequently, nitrogen uptake increases again and from 1928–1933 till the end of the 60-year period it remains between 95 and

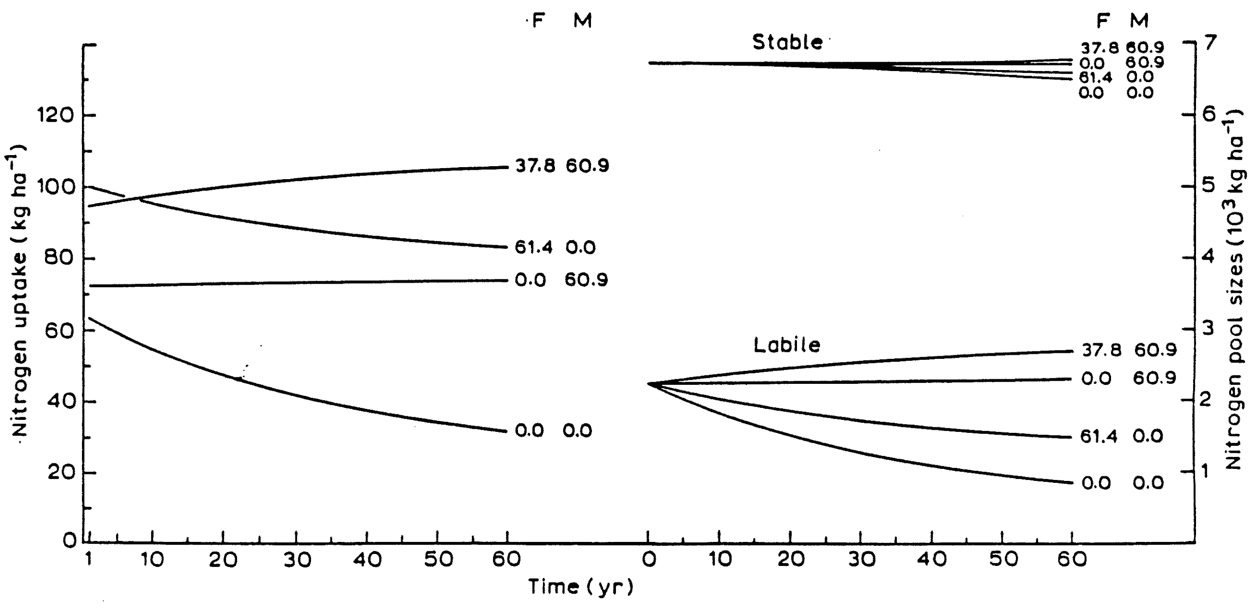

Fig. 3. Calculated courses of nitrogen uptake by an 'average' crop in the rotation and of the size of the labile and stable pools of soil organic nitrogen in the Lauchstädt fields over a period of 60 years. Parameters and input values used for computer simulation are those of case B. *Numbers* indicate the average amount of nitrogen (kg ha^{-1}) applied annually as fertilizer (F) and/or manure (M).

100 kg ha^{-1}. The difference with the computed pattern can only partly be explained by the increase in fertilizer rate in the period 1928–1933. The observed average nitrogen uptake in the N treatment is lower (85.5 kg ha^{-1}) than in the NPK treatment (93.5 kg ha^{-1}, Table 7). As for the N treatment the time course of nitrogen uptake was not reported, it cannot be judged whether that curve corresponds better with the computed curve. On the whole, the agreement between observed and computed time courses of pool sizes and nitrogen uptake by the crop is satisfactory, considering that variations in weather conditions and soil amendment regimes were neglected in the model calculations.

United Kingdom

The recovery fractions of nitrogen applied in fertilizer and manure are calculated from Table 3 as 0.34 and 0.14, respectively. As in these recovery fractions residual effects are included, in the model the fractions transferred annually to the crop are estimated at 0.30 and 0.10, respectively. The fractions of inorganic nitrogen (in fertilizer and rain) and organic nitrogen (in manure and from biological fixation) transferred to the labile pool may be estimated at 0.20 and 0.70, respectively and assuming moderate risks for losses, the fractions of fertilizer and manure nitrogen lost become 0.50 and 0.20. The ratio between uptake by the crop and losses for nitrogen in manure depends on environmental conditions and the associated risks for losses and is assumed to be identical for the nitrogen input via rain, biological fixation and mineralization of the labile pool. The resulting transfer coefficients used for simulation of the Broadbalk experiments are given in Table 6, case A.

In the nitrogen balance, values for the various sources of nitrogen are given (Table 4). For the N3PKMg treatment the total loss by leaching and denitrification is calculated from available experimental data. From this value denitrification losses alone are derived and used to estimate denitrification losses for the other treatments. To close the nitrogen balance input via biological fixation must be estimated, for which values of 35 kg ha^{-1} yr^{-1} if no nitrogen is applied, 15 for the N1PKMg treatment and zero for the N3PKMg and the manure treatments are assumed (Table 6). In the control and the PKMg treatments total soil nitrogen in the 0–0.23 m soil depth is about 3000 kg ha^{-1} and is invariable with time (Fig. 2). From this value total soil nitrogen in the 0–0.6 m soil depth is estimated similarly to that for Lauchstädt and amounts to 5220 kg ha^{-1}. Subsequently, the initial sizes of the labile and the stable pool of soil nitrogen are calculated at 1305 and 3915 kg ha^{-1} and the time constants of conversion at 23 and 460 years, respectively. These values are used in the simulations of the nitrogen cycle.

Comparison of computed and observed values for the change in total soil nitrogen and for nitrogen uptake by the crop (Table 8, case A) clearly indicates that the estimated mineralization rate is too high. As a result, computed total soil nitrogen gradually decreases and calculated losses are too high resulting in underestimation of crop uptake. To obtain better agreement, the transfer coefficients have been recalculated (Table 6, case B) assuming lower losses, and as a consequence the time constants of conversion of the labile and stable pools change to values of 45 and 900 years, respectively. The agreement between observed and computed results (Table 8, case B) is satisfactory now for the control and for the fertilizer nitrogen treatments. In N1PKMg and N3PKMg initial soil nitrogen is somewhat higher than calculated for the control and the PKMg treatments (Jenkinson, 1977). Use of these values in the model leads to even better agreement with the observed values (Table 8).

Observed nitrogen uptake in the manure treatment is about constant over the period of 125 years (Table 3), but total soil nitrogen increases rapidly (Fig. 2; Table 8). The computed increase in soil nitrogen closely resembles the observed values, but the consequence is a rapid increase in nitrogen uptake by the crop from 55 kg ha^{-1} in the first year to 109 kg ha^{-1} in year 125 (Fig. 4). In reality, uptake does not exceed 63 kg ha^{-1} (Table 3), and the nitrogen additionally available in the model is probably lost. In 1968, after introduction of a more modern wheat variety, nitrogen uptake increases to 144 kg ha^{-1}, *i.e.* 32% higher than the computed value of 109 kg ha^{-1}. For the control and the PKMg treatments the relative increases in nitrogen uptake from the moment that the new wheat variety was introduced, are about identical (Table