

Modeling long-term crop response to fertilizer and soil nitrogen

I. Model description and application

J. WOLF¹, C.T. DE WIT² and H. VAN KEULEN³

¹Centre for World Food Studies, c/o CABO, P.O. Box 14, 7600 AA Wageningen, The Netherlands;

²Department of Theoretical Production Ecology, Agricultural University, P.O. Box 430, 6700 AK Wageningen, The Netherlands and ³CABO, P.O. Box 14, 6700 AA Wageningen, The Netherlands

Received 1 November 1988. Revised June 1989

Key words: fertilizer recommendations, long-term fertilizer recovery, nitrogen uptake, simulation model, soil nitrogen cycle

Abstract

A simple nitrogen balance model to calculate long-term changes in soil organic nitrogen, nitrogen uptake by the crop and recovery of applied nitrogen, is presented. It functions with time intervals of one year or one growing season. In the model a labile and a stable pool of soil organic nitrogen are distinguished. Transfer coefficients for the various inputs of nitrogen are established that specify the fractions taken up by the crop, lost from the system, and incorporated in soil organic nitrogen.

It is shown how input data, model parameters and initial pool sizes can be derived and how the model can be used for calculating long-term changes in total soil organic nitrogen and uptake by the crop. For nitrogen applied annually as fertilizer or organic material the time course of nitrogen uptake and recovery of applied nitrogen is calculated. To test the sensitivity of the model, calculations have been performed for different environmental conditions with higher or lower risks for losses. The model has also been applied to establish fertilizer recommendations for a certain target nitrogen uptake by the crop. Finally, for agricultural systems where periods of cropping alternate with periods of green fallow the time course of nitrogen uptake by the crop is calculated.

Introduction

Nitrogen is present in soils in different organic forms and in two inorganic forms, *i.e.* ammonium and nitrate. The behaviour of nitrogen in soils is therefore complex and many processes influence uptake by the crop. For example, ammonium may volatilize, it can be adsorbed at the cation exchange complex or it can be converted into nitrate. Nitrate may be lost through denitrification or can be leached to the subsoil. Both ammonium and nitrate can be converted into organic nitrogen by microorganisms; organic nitrogen can be mineralized. The net balance of inorganic nitrogen determines availability of nitrogen for the crop.

Comprehensive simulation models describing many of these processes and distinguishing different organic compounds have been developed (*cf.* Frissel and van Veen, 1980; van Keulen and Seligman, 1987). Practical application of such models is difficult, however, due to their extensive data requirements. Moreover, validation of such models is problematic. For approximative prediction of long-term changes in soil organic nitrogen and crop-available nitrogen, a summary model will often suffice (Lucas *et al.*, 1977; Parton *et al.* 1987). For that purpose a simple nitrogen balance model was developed that describes the main processes in a schematic way and operates with time steps of one year or one growing season.

Model structure

In the model two pools of soil organic nitrogen are distinguished, labile organic N and stable organic N (LON and SON in Fig. 1). Annual conversion of these pools is described as fixed fractions of the pool sizes at the start of the year. The numerical values of these fractions are the reciprocals of the time constants of conversion.

Mineralization depletes the labile pool only and depletion of the stable pool occurs by transfer to the labile pool. This simplifies the calculation of initial pool sizes and time constants of conversion. There is also transfer from the labile to the stable pool, representing all processes rendering soil nitrogen more stable.

The pools of stable and labile nitrogen, as defined in the model, cannot be identified with specific organic compounds in the soil. The initial sum of the stable and the labile pool is set equal to the total amount of soil organic nitrogen, with the exception of inert organic matter. The rates of change of the pools are calculated on the basis of nitrogen transformations and external sources.

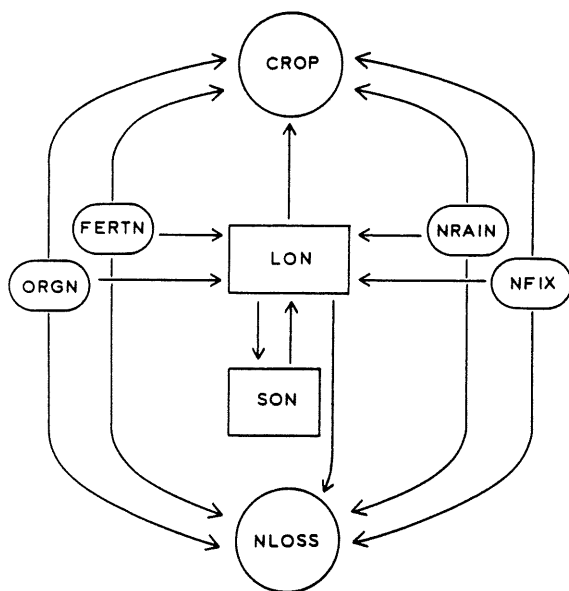


Fig. 1. The structure of the model. Two pools of stable and labile organic nitrogen (SON, LON) are distinguished. Nitrogen inputs from biological fixation (NFIX), fertilizer (FERTN) and organic material application (ORGN), rainfall and flood water (NRAIN), and from mineralization of labile organic matter are distributed over crop uptake (CROP), incorporation in the labile organic pool, and losses (NLOSS).

Four external sources of nitrogen are distinguished (Fig. 1): rainfall (NRAIN) which includes irrigation and flood water, biological fixation (NFIX) by blue-green algae, symbiotic and free-living bacteria, inorganic fertilizer (FERTN) and organic materials (ORGN) such as straw, stubble, green manure and animal manure. For each of these components the nitrogen input is partitioned among uptake by the crop, incorporation in the labile pool and losses. The same applies to nitrogen mineralized from the labile pool. The stable pool is assumed to exchange with the labile pool only, so in total 16 partitioning or transfer coefficients have to be estimated (Table 1).

Input data

The data required for the model are the rates of nitrogen applied in inorganic fertilizers and organic materials, the supply of nitrogen via rainfall, flood and irrigation water, and via biological fixation, the initial sizes of the labile and the stable pool, and the time constants of conversion of both pools. The latter are derived from the initial nitrogen uptake by the crop. For each of the external sources and for the nitrogen mineralized from the labile pool, partitioning between uptake by the crop, incorporation in the labile pool, and losses due to denitrification, leaching, *etc.* is required.

Application rates of nitrogen in fertilizer and organic material have to be specified by the user. The supply via rainfall and flood water has sometimes been measured, but total natural supply

Table 1. Transfer coefficients required in the model for the following inputs: inorganic fertilizer nitrogen (FERTN), organic nitrogen (ORGN), biologically fixed nitrogen (NFIX), nitrogen in rainfall and flood water (NRAIN), and nitrogen mineralized from labile (LON) and stable (SON) pools of soil organic nitrogen

Input	Transfer coefficients to			
	Crop	Loss	Labile pool	Stable pool
FERTN	+	+	+	
ORGN	+	+	+	
NFIX	+	+	+	
NRAIN	+	+	+	
LON	+	+		+
SON			+	

from biological fixation and rainfall can generally only be derived from results of long-term trials on unfertilized fields, where nitrogen uptake by the crops and losses are balanced by natural supply. If only crop yields have been determined, nitrogen uptake may be derived from crop-specific limiting nitrogen contents (van Keulen and van Heemst, 1982).

To calculate the initial pool sizes of soil organic nitrogen, a number of assumptions must be made. Soil nitrogen content is generally given for a plough layer of about 0.2 m, however in deep soils crops may deplete soil nitrogen to a greater depth. In such situations available nitrogen from mineralization may be double the amount in the plough layer alone (Wolf and van Keulen, 1989). However, in the calculations presented, only soil organic nitrogen in a plough layer of 0.2 m is taken into account.

As depletion of the stable pool only takes place by transfer to the labile pool and crop uptake and losses of mineralized nitrogen only occur at the expense of the labile pool, uptake and loss fractions for total soil organic matter can be used as transfer coefficients for the labile pool. In addition to uptake by the crop and losses, part of the nitrogen mineralized from the labile pool is incorporated in the stable pool. This latter fraction is fixed at 0.15 on the basis of model calculations, explained below.

The time constant of conversion of the labile pool can be calculated from its mineralization rate which is equal to that of total soil organic nitrogen, and pool size (Fig. 1). It is impossible to derive in a direct way the time constant of conversion of the stable pool. However, a ratio between the time constants of conversion of the stable and the labile pool of 20 for dryland soils and 30 for wetland soils worked satisfactorily in simulations of long-term field trials under a range of environmental conditions (Wolf and van Keulen, 1989). Also in simulations of the course of soil organic matter content in fallow fields (Dam Kofoed, 1982; Kortleven, 1963; Persson, 1981), a ratio between the time constants of 20 appeared to be appropriate. Therefore, these ratios are assumed to be generally applicable for the present study.

From total initial soil organic nitrogen and the equilibrium ratio between both pools, the sizes of the separate pools are calculated. Assuming that

initially the transfer rates between both pools are identical, the equilibrium ratio can be calculated from the ratio between the time constants of conversion and the transfer coefficient from the labile to the stable pool. The equilibrium ratio between the size of the stable pool and that of the labile pool for dryland soils becomes $((0.15 * 1/1) \div 1/20 =) 3$. The equivalent ratio is 4.5 for wetland soils.

In temperate zones about 0.70 of the nitrogen applied in organic material such as straw, animal manure or green manure is partitioned to the labile pool. It may vary, however, from almost 1.0 for materials with a relatively low nitrogen content (Verveda, 1984) to 0.50 or less for materials with a high nitrogen content (Sluijsmans and Kolenbrander, 1977). In tropical areas where higher temperatures cause higher rates of decomposition, the fraction transferred to the labile pool is only about 0.50.

The remaining fraction is partitioned between uptake by the crop and losses. This partitioning can be derived from representative field experiments. As mineralization proceeds continuously, thus also outside the growing season, the partitioning depends mainly on environmental conditions and the corresponding risks for losses. If no experimental data are available, indicative values for the ratio between uptake and losses may be used, estimated at 1.0 for environmental conditions with moderate risks for losses, 2.0 for conditions with low risks (*i.e.* deep groundwater, limited leaching, high soil water and nutrient holding capacity), and 0.5 for conditions with high risks (*i.e.* high groundwater level, substantial leaching, low soil water and nutrient holding capacity). The resulting transfer coefficients are given in Table 2.

The partitioning of applied fertilizer nitrogen among uptake by the crop, losses, and the labile pool should be derived from representative local fertilizer experiments. The fraction partitioned to the labile pool is set to 0.20, representing nitrogen in organic material ploughed in after harvest and immobilized in soil organic matter. This fraction may vary between 0.15 and 0.25, for conditions with high and low risks for fertilizer losses and it may vary among crops. If field data are not available, the ratio between uptake by the crop and losses may be estimated from environmental conditions and the corresponding risks for losses

Table 2. Indicative numerical values for fractions transferred to crop, to labile and stable pool, and lost in agricultural systems with low, moderate and high risks for losses. For explanation of acronyms see Table 1

Input	Low risks				Moderate risks				High risks			
	Crop	Loss	Labile pool	Stable pool	Crop	Loss	Labile pool	Stable pool	Crop	Loss	Labile pool	Stable pool
FERTN	0.50	0.25	0.25		0.40	0.40	0.20		0.28	0.57	0.15	
ORGN	0.20	0.10	0.70		0.15	0.15	0.70		0.10	0.20	0.70	
NFIX	0.20	0.10	0.70		0.15	0.15	0.70		0.10	0.20	0.70	
NRAIN	0.50	0.25	0.25		0.40	0.40	0.20		0.28	0.57	0.15	
LON	0.57	0.28		0.15	0.425	0.425		0.15	0.28	0.57		0.15
SON			1.00				1.00				1.00	

(Table 2). However, as that ratio is also affected by the method of fertilizer application, its variation may be much larger, ranging from about 0.2 to about 10.

Nitrogen in rainfall and flood water mainly occurs in inorganic form. The fraction transferred to the labile pool is therefore set equal to that for inorganic fertilizer, *i.e.* 0.20. The distribution between uptake by the crop and losses depends on the risk for losses defined above.

For biologically fixed nitrogen the transfer coefficients are set identical to those for applied organic material. Jenkinson and Rayner (1977) in their model for decomposition of organic matter used about an identical value (0.34) for the annually mineralized fraction of biomass as used here for the fraction transferred to crop and losses (Table 2).

Mineralization from the labile pool of soil nitrogen is defined in net terms. Thus, mineralized nitrogen is distributed between uptake by the crop, losses, and the stable pool. The distribution between uptake by the crop and losses depends again on the risks for losses, and is similar to that for the other nitrogen sources (Table 2).

Calculation of N uptake by the crop and fertilizer N recovery

Starting point for the calculations is a steady state situation for an annually cropped soil not receiving fertilizer N (Fig. 2). It is a steady state because the state variables are constant and the sum of outputs (crop, losses) equals the sum of external inputs via biological fixation and rainfall.

Table 3 presents input data and illustrates derivation of model parameters and initial pool

sizes for a situation with moderate risks for losses (Fig. 2b). The sizes of the labile and the stable pool are calculated from total initial soil organic nitrogen and the equilibrium ratio between both pools. The equilibrium ratio is calculated from the ratio of the time constants and the transfer coefficient from the labile to the stable pool.

Initial nitrogen uptake by the crop is derived from a representative trial on an unfertilized field. The contribution of mineralized nitrogen to total crop uptake is obtained by subtracting the inputs from rain and biological fixation. The time constants of conversion are derived from mineralized nitrogen and the pool sizes.

Subsequently, the transfers and changes are calculated. This is illustrated in Table 4 for the first two years for a situation with fertilizer application. Mineralized nitrogen and nitrogen in rain and applied fertilizers are partitioned among crop uptake, the labile pool and losses. Simulations of long-term field trials (Wolf and van Keulen, 1989) have shown that biological fixation is considerably reduced if large amounts of nitrogen are applied as fertilizer and/or organic material. To simplify the calculations, biological fixation is set to zero if nitrogen is applied. Consequently, transfer of nitrogen to the labile pool is smaller than the rate of mineralization and the pool is rapidly depleted. This results in lower nitrogen mineralization and lower crop uptake in the second year (Table 4).

The initial situation without nitrogen application was assumed to be a steady state, *i.e.* annual nitrogen uptake by the crop is constant with time. For conditions with moderate risks for losses the value is $22.5 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (Fig. 2b). For conditions with low and high risks for losses different transfer coefficients are used (Table 2). Consequently, the

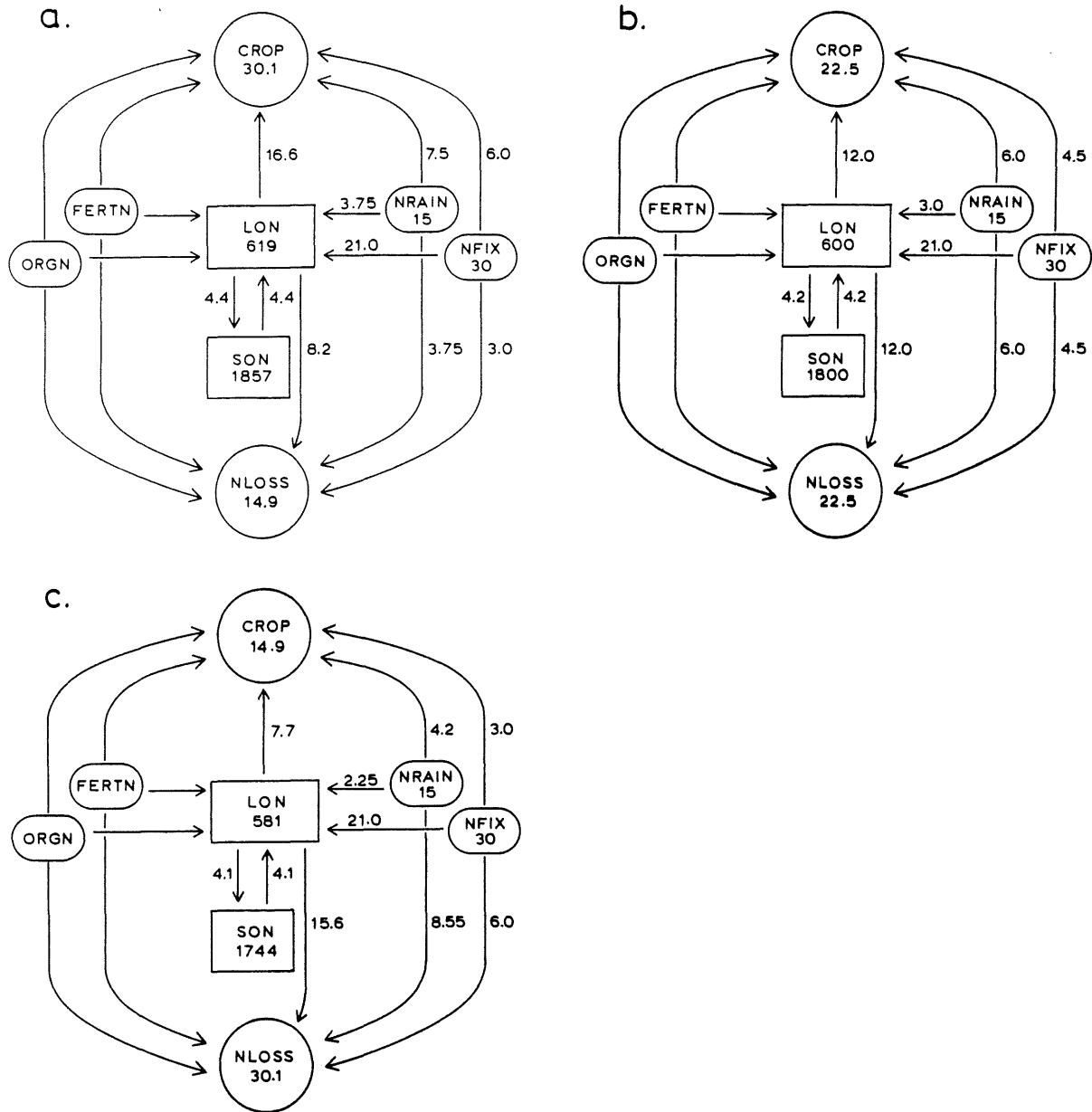


Fig. 2. Initial steady state situation for arable land. Pool sizes (SON, LON) are in kg ha^{-1} , all other variables in $\text{kg ha}^{-1} \text{yr}^{-1}$. Transfers apply to situations with low (a), moderate (b) and high (c) risks for losses. Risks are defined in the text. Nitrogen input into the system occurs via rainfall and biological fixation.

transfer of nitrogen in rain to the labile pool changes, as does the initial size of the pools (Fig. 2a, 2c). With low risks for losses that results in a value for nitrogen uptake of $30.1 \text{ kg ha}^{-1} \text{yr}^{-1}$. With high risks for losses uptake is only $14.9 \text{ kg ha}^{-1} \text{yr}^{-1}$.

The size of the labile pool, nitrogen uptake by the crop, and apparent recovery of applied nitrogen for conditions with moderate risks for losses for a period of 15 years are given in Table 5. Annually, 50 kg N ha^{-1} was applied as inorganic fertilizer or

Table 3. Input data, model parameters, and calculation of initial pool sizes and time constants of conversion

Description	Calculation	Value
<i>Initial situation</i>		
Soil nitrogen content (kg N kg ⁻¹ soil)		0.00086
Weight soil layer ^a of 0.20 m depth (kg soil ha ⁻¹)		2.8 * 10 ⁶
Amount of nitrogen in layer of 0.20 m depth (kg N ha ⁻¹)		2400
Size of labile pool ^b (kg N ha ⁻¹)		600
Size of stable pool ^b (kg N ha ⁻¹)		1800
Crop uptake (kg N ha ⁻¹ yr ⁻¹)		22.5
<i>Input data, parameters</i>		
Nitrogen in rainfall and flood water (kg N ha ⁻¹ yr ⁻¹)		15.0
Nitrogen from biological fixation (kg N ha ⁻¹ yr ⁻¹)		30.0
Nitrogen from organic material application (kg N ha ⁻¹ yr ⁻¹)		0
Nitrogen from fertilizer nitrogen application (kg N ha ⁻¹ yr ⁻¹)		0
Transfer coefficients, see values in Table 2		
for moderate risks for losses		
Transfer of nitrogen in rainfall to crop, (kg N ha ⁻¹ yr ⁻¹)	(15.0 * 0.4 =)	6.0
Transfer of biologically fixed nitrogen to crop, (kg N ha ⁻¹ yr ⁻¹)	(30.0 * 0.15 =)	4.5
Transfer of mineralized soil nitrogen to crop, (kg N ha ⁻¹ yr ⁻¹)	(22.5 - 6.0 - 4.5 =)	12.0
Time constant of conversion of the labile pool, (years)	(600/(12.0/0.425) =)	21.25
Time constant of conversion of the stable pool, (years)	(20 * 21.25 =)	425

^a Bulk density = 1400 kg m⁻³.

^b The applied assumption is discussed in the text.

in organic material. The results for the unfertilized situation are given for comparison. Without nitrogen amendments the initial steady state situation persists. When fertilizer is applied, additional uptake by the crop is (0.4 × 50 =) 20 kg ha⁻¹ in the first year. As biological fixation is set to zero if nitrogen is applied, the apparent recovery is only 15.5 kg ha⁻¹. In the course of time the labile pool decreases from 600 to 485 kg N ha⁻¹ in year 15, and consequently nitrogen uptake by the crop decreases from 38.0 to 35.7 kg ha⁻¹ and apparent nitrogen recovery decreases from 15.5 to 13.2 kg ha⁻¹ over the same period. If organic material is applied, the recovery increases from 3.0 kg N ha⁻¹ in the first year to 5.9 in year 15, due to the increase in size of the labile pool, resulting in higher mineralization than in the unfertilized situation.

Cumulative apparent recoveries for annual applications of 50 kg N ha⁻¹ in inorganic fertilizer or organic material are presented in Fig. 3 for conditions representing higher or lower risks for losses. For inorganic fertilizer the values range from 278 to 401 and 503 kg N ha⁻¹ for high,

moderate and low risks for losses, respectively over the period of 30 years. For nitrogen in organic material the values range from 114 to 172 and 230 kg N ha⁻¹, respectively. The total apparent recovery fraction of applied nitrogen over a period of 30 years ranges from 0.19 to 0.34 for inorganic fertilizer and from 0.08 to 0.15 for organic material.

Fertilizer rate required for target

The model may also be formulated in a target-oriented way. The target may be a yield level determined either by crop characteristics and level of irradiation, water availability, or phosphorus supply. The target yield multiplied by the N content, yields the target N uptake. To allow comparison of the fertilizer requirements for different environmental conditions, the required nitrogen rates are established for a target increase in N uptake, set at 30 kg ha⁻¹ yr⁻¹ which would suffice for an increase in grain yield of maize of 1500 kg ha⁻¹ (van Keulen and van Heemst, 1982).

Table 4. Calculation of nitrogen uptake by the crop and pool sizes during the first and the second year after the start of the calculations. Annually 50 kg ha⁻¹ fertilizer nitrogen is applied and inputs via rainfall and biological fixation are 15 and 0 kg N ha⁻¹, respectively

Description	Calculation	Value ^a
<i>1st year</i>		
Transfer from stable to labile pool	(1800/425 =)	4.2
Transfer from labile to stable pool	(0.15 * 600/21.25 =)	4.2
Transfer from labile pool to crop	(0.425 * 600/21.25 =)	12.0
Transfer from labile pool to losses	(0.425 * 600/21.25 =)	12.0
Transfer of rainfall N to labile pool	(0.20 * 15 =)	3.0
Transfer of rainfall N to crop	(0.40 * 15 =)	6.0
Transfer of rainfall N to losses	(0.40 * 15 =)	6.0
Transfer of fert. N to labile pool	(0.20 * 50 =)	10.0
Transfer of fert. N to crop	(0.40 * 50 =)	20.0
Transfer of fert. N to losses	(0.40 * 50 =)	20.0
N uptake by the crop	(12.0 + 6.0 + 20.0 =)	38.0
Cumulative crop uptake	(0.0 + 38.0 =)	38.0
Change in labile pool	(4.2 + 3.0 + 10.0 - 600/21.25 =)	-11.0
Final size of labile pool	(600 - 11.0 =)	589.0
Change in stable pool	(4.2 - 4.2 =)	0.0
Final size of stable pool	(1800 + 0.0 =)	1800.0
Annual losses	(12.0 + 6.0 + 20.0 =)	38.0
Cumulative losses	(0.0 + 38.0 =)	38.0
<i>2nd year</i>		
Transfer from stable to labile pool	(1800/425 =)	4.2
Transfer from labile to stable pool	(0.15 * 589.0/21.25 =)	4.2
Transfer from labile pool to crop	(0.425 * 589.0/21.25 =)	11.8
Transfer from labile pool to losses	(0.425 * 589.0/21.25 =)	11.8
Transfer of rainfall N to labile pool	(0.20 * 15 =)	3.0
Transfer of rainfall N to crop	(0.40 * 15 =)	6.0
Transfer of rainfall N to losses	(0.40 * 15 =)	6.0
Transfer of fert. N to labile pool	(0.20 * 50 =)	10.0
Transfer of fert. N to crop	(0.40 * 50 =)	20.0
Transfer of fert. N to losses	(0.40 * 50 =)	20.0
N uptake by the crop	(11.8 + 6.0 + 20.0 =)	37.8
Cumulative crop uptake	(38.0 + 37.8 =)	75.8
Change in labile pool	(4.2 + 3.0 + 10.0 - 589.0/21.25 =)	-10.5
Final size of labile pool	(589.0 - 10.5 =)	578.5
Change in stable pool	(4.16 - 4.24 =)	-0.1
Final size of stable pool	(1800 - 0.1 =)	1799.9
Annual losses	(11.8 + 6.0 + 20.0 =)	37.8
Cumulative losses	(38.0 + 37.8 =)	75.8

^a Sizes of pools, cumulative crop uptake and cumulative losses are expressed in kg N ha⁻¹, and transfers, changes in pools, uptake by the crop and annual losses are expressed in kg N ha⁻¹ yr⁻¹.

To illustrate the effect of some relevant factors on the required fertilizer rate, results for six different situations are shown in Fig. 4 and Table 6. In all cases, nitrogen inputs via rain and biological fixation and the time constants of conversion are identical, but the initial pool sizes and initial crop uptake without fertilizer application vary. The values for the time constants and transfer coefficients are identical to those described in Tables 2 and 3.

The calculations are discussed for Column B

(Table 6) representing the standard case, with application of inorganic fertilizer and environmental conditions representing a moderate risk for losses. In the first year nitrogen uptake without fertilizer application is 22.5 kg ha⁻¹. As the transfer coefficient from applied fertilizer to the crop is 0.40 and biological fixation is zero if nitrogen is applied, the required nitrogen application to attain a target increase in uptake of 30 kg N ha⁻¹ is $(30.0 + 0.15 * 30.0)/0.4 = 86.3$ kg ha⁻¹. As most of the crop material produced is removed from the

Table 5. Time courses of labile pool size at the beginning of the indicated years, N uptake and apparent recovery⁴ from annual applications of 50 kg N ha⁻¹ in fertilizer (Fert.) or organic material (Org.). Input via rainfall is 15 kg N ha⁻¹ yr⁻¹. Input through biological fixation is 30 kg N ha⁻¹ yr⁻¹ in the unfertilized situation (Unfert.) and is set to zero if nitrogen is applied in fertilizer or organic material. Transfer coefficients apply to situation with moderate risks for losses

Year	Labile pool			N uptake			Recovery of applied N			
	Unfert.	Fert.	Org.	Unfert.	Fert.	Org.	Fert.		Org.	
							Per year	Cumulative	Per year	Cumulative
1	600	600	600	22.5	38.0	25.5	15.5	15.5	3.0	3.0
2	600	589	614	22.5	37.8	25.8	15.3	30.8	3.3	6.3
3	600	579	627	22.5	37.6	26.0	15.1	45.9	3.5	9.8
4	600	569	640	22.5	37.3	26.3	14.8	60.7	3.8	13.6
5	600	559	652	22.5	37.2	26.6	14.7	75.4	4.1	17.7
6	600	550	664	22.5	37.0	26.7	14.5	89.9	4.2	21.9
7	600	541	675	22.5	36.8	27.0	14.3	104.2	4.5	26.4
8	600	533	685	22.5	36.7	27.2	14.2	118.4	4.7	31.1
9	600	525	695	22.5	36.5	27.4	14.0	132.4	4.9	36.0
10	600	518	705	22.5	36.3	27.6	13.8	146.2	5.1	41.1
11	600	511	714	22.5	36.2	27.8	13.7	159.9	5.3	46.4
12	600	504	723	22.5	36.1	28.0	13.6	173.5	5.5	51.9
13	600	497	731	22.5	36.0	28.1	13.5	187.0	5.6	57.5
14	600	491	739	22.5	35.8	28.3	13.3	200.3	5.8	63.3
15	600	485	746	22.5	35.7	28.4	13.2	213.5	5.9	69.2

⁴ Apparent recovery is defined as the ratio of the difference in N uptake with and without fertilizer application and the rate of fertilizer application.

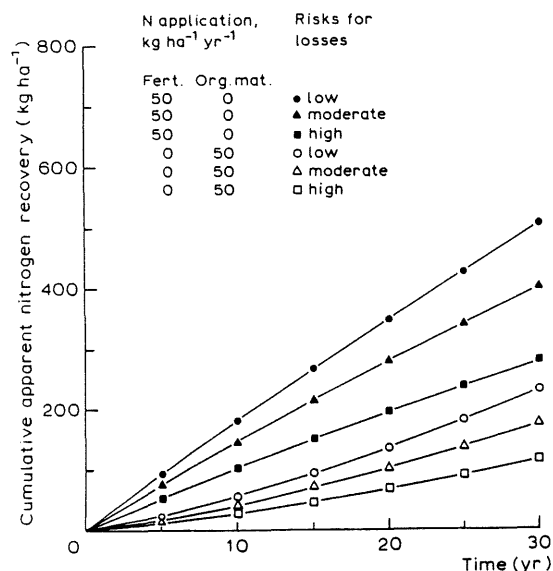


Fig. 3. Cumulative apparent nitrogen recovery from annually applied inorganic fertilizer or organic material for different environmental conditions and corresponding risks for losses and transfer coefficients.

field, application of only inorganic fertilizer will result in a decrease in soil organic nitrogen with time. Particularly the labile pool decreases by about 60 kg ha⁻¹ over a period of 50 years, with an associated decrease in nitrogen uptake to 21.3 kg ha⁻¹. The required nitrogen application rate for the target increases over that period to 89.4 kg ha⁻¹. These results demonstrate the implications of continuous cropping for soil organic nitrogen content and soil nitrogen supply in agricultural systems where no organic material is applied.

In case A (Fig. 4; Table 6) the risk for losses is low, so the fraction of applied fertilizer nitrogen transferred to the crop is higher than in case B. Consequently, the required nitrogen application rate to reach the target is lower, *i.e.* $(30.0 + 0.20 * 30.0)/0.5 = 72.0$ kg ha⁻¹. The labile pool, initially 619 kg N ha⁻¹ decreases by about 50 kg ha⁻¹ over the 50 year period. Nitrogen uptake without fertilizer application decreases to 28.8 kg ha⁻¹ in year 50, and the required nitrogen

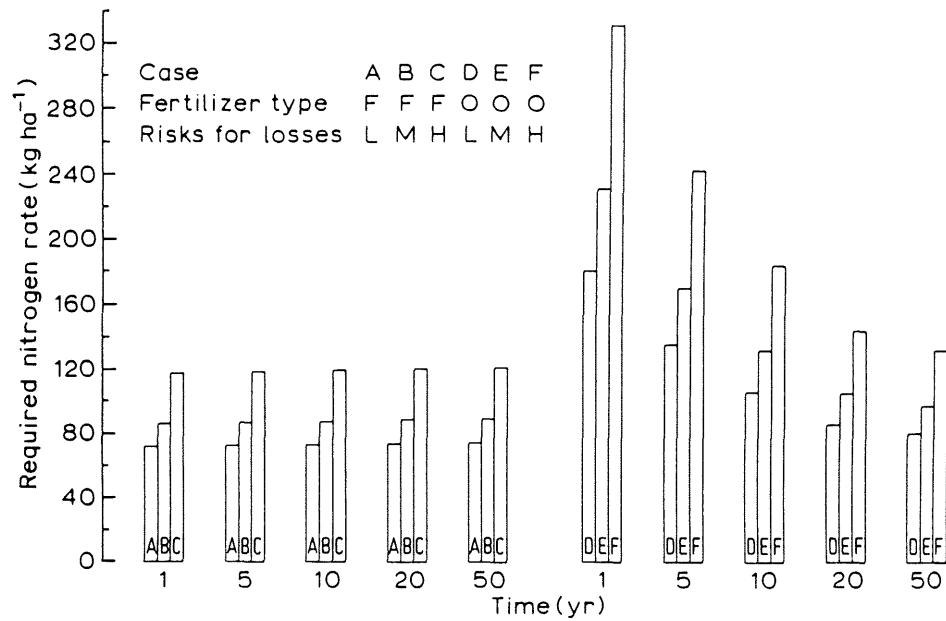


Fig. 4. Time course of required nitrogen rate, applied as inorganic fertilizer (F) or organic material (O), for a target increase in N uptake of $30 \text{ kg ha}^{-1} \text{ yr}^{-1}$ and for environmental conditions with low (L), moderate (M) and high (H) risks for losses. For the different conditions the initial values for pool sizes and for crop uptake without fertilizer application (Table 6) and the transfer coefficients (Table 2) vary depending on the risks for losses. Input via rainfall is $15 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ and input through biological fixation is $30 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in the unfertilized situation and zero if nitrogen is applied.

Table 6. The unfertilized crop uptake, the labile pool size at the beginning of the indicated year, and the required application rate of nitrogen for a target increase in nitrogen uptake of $30 \text{ kg ha}^{-1} \text{ yr}^{-1}$ for six different sets of parameters in year 1, 10 and 50 after the starting point of calculations. Input via rainfall is $15 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ and input through biological fixation is $30 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in the unfertilized situation and is set to zero if nitrogen is applied

Case	A	B	C	D	E	F
Type of N application ^a	F	F	F	O	O	O
Risks for losses ^b	L	M	H	L	M	H
Transfer coeff. of fertilizer to crop	0.50	0.40	0.28	—	—	—
Transfer coeff. of org. mat. to crop	—	—	—	0.20	0.15	0.10
<i>1st year</i>	kg N ha ⁻¹					
Size of labile pool	619	600	581	619	600	581
Crop uptake without N application	30.1	22.5	14.9	30.1	22.5	14.9
Required application rate for target	72.0	86.3	118.0	180.0	230.0	330.4
<i>10th year</i>						
Size of labile pool	598	573	557	1174	1342	1700
Crop uptake without N application	29.5	22.0	14.5	45.0	37.3	29.6
Required application rate for target	73.1	87.6	119.1	105.5	131.1	183.0
<i>50th year</i>						
Size of labile pool	571	538	524	1366	1601	2096
Crop uptake without N application	28.8	21.3	14.1	50.1	42.5	34.8
Required application rate for target	74.6	89.4	120.7	79.8	96.6	130.8

^a F = N applied in inorganic fertilizer; O = N applied in organic material.

^b L = Low, M = moderate, H = high risks for losses.

application rate for the target increases to 74.6 kg ha^{-1} . In case C, with higher risk for losses, the size of the labile pool is smaller and the required nitrogen application rates for the target are higher.

In cases D, E, and F nitrogen is applied in organic material. That implies that the fraction of applied nitrogen transferred to the crop is small, as the main part is incorporated in soil organic nitrogen. In case E, comparable to the standard case B, that fraction is only 0.15. The required nitrogen application for a target increase in uptake of 30 kg N ha^{-1} is in the first year: $(30.0 + 0.15 * 30.0)/0.15 = 230 \text{ kg ha}^{-1}$, compared to 86.3 kg ha^{-1} for case B. As the main part of the nitrogen applied is transferred to the labile pool, this pool increases rapidly to $1601 \text{ kg N ha}^{-1}$ in year 50.

Crop uptake without fertilizer application reaches a value of 42.5 kg ha^{-1} in year 50 and the required nitrogen application rate for the target decreases to 96.6 kg ha^{-1} . Hence, in year 50 the required application rate is about identical to that

for case B. In cases D and F with low and high risks for losses, the required application rates for the target are lower and higher, respectively than in case E. They decrease with time, as crop uptake without fertilizer application increases with increasing size of the labile pool.

Regeneration during fallow periods

In regions where population density is not too high, soil fertility is low and application of chemical fertilizers is not profitable, shifting cultivation is often practised. It is a system in which cropping is alternated with fallow periods to restore soil fertility. Such a cropping system can also be described by the present model. As an example it is applied to a system with 5 years of cropping alternated with 10 years of natural vegetation (green fallow). It is assumed that nitrogen taken up during the green fallow is completely recycled, *i.e.* all nitrogen in the vegetation is returned in the subsequent year in

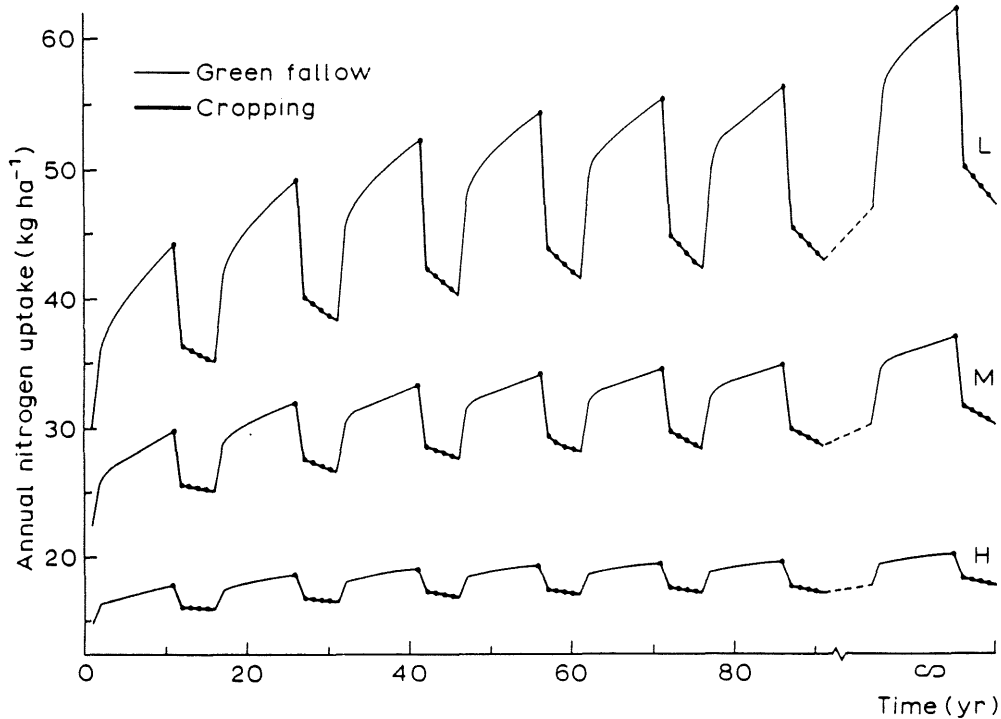


Fig. 5. Time course of nitrogen uptake by the crop and the natural vegetation under shifting cultivation with 5 years of cropping alternated with 10 years of green fallow, calculated for environmental conditions with low (L), moderate (M), and high (H) risks for losses and corresponding values for initial pool sizes and transfer coefficients. Input via rainfall is $15 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ and input through biological fixation is $30 \text{ kg N ha}^{-1} \text{ yr}^{-1}$.

organic form. Nitrogen input into the system via rainfall is $15 \text{ kg ha}^{-1} \text{ yr}^{-1}$ and via biological fixation by symbiotic and/or free-living microbes $30 \text{ kg ha}^{-1} \text{ yr}^{-1}$, values derived from observations in Broadbalk, UK (Wolf and van Keulen, 1989). The values for initial pool sizes, transfer coefficients and time constants of conversion are those of Tables 2, 3 and 6. Identical values are used for years of green fallow and years of cropping.

In the standard case with moderate risks for losses, nitrogen uptake by the vegetation during the first fallow period increases from 22.5 to 29.4 kg ha^{-1} due to crop recycling (Fig. 5). In the first year of cropping, nitrogen uptake by the crop is relatively high at 29.8 kg ha^{-1} due to recycling of the natural vegetation. In the subsequent years of cropping nitrogen uptake decreases to 25.2 kg ha^{-1} , reflecting the depletion of the labile pool. In the subsequent cropping/fallow sequences maximum crop uptake at the end of the fallow period gradually increases, as does the minimum uptake at the end of the cropping cycle. Finally, an equilibrium situation is reached, where soil nitrogen accumulation during the fallow period is equal to the depletion during the cropping period. Nitrogen uptake then increases from 30.2 to 36.7 kg ha^{-1} during the fallow period and decreases from 36.9 to 30.5 kg ha^{-1} during the cropping period. In that situation average nitrogen uptake during the cropping period is $32.2 \text{ kg ha}^{-1} \text{ yr}^{-1}$, which is much higher than under continuous cropping without fertilizer application.

With low risks for losses the increase in nitrogen uptake between successive cropping periods is much higher (Fig. 5). Build-up of the soil nitrogen pools is much faster and allows higher nitrogen uptake during the periods of cropping. In the equilibrium situation average nitrogen uptake during the period of cropping is $51.6 \text{ kg ha}^{-1} \text{ yr}^{-1}$. For conditions with high risks for losses the opposite applies. In the equilibrium situation average nitrogen uptake during the cropping period is $18.4 \text{ kg ha}^{-1} \text{ yr}^{-1}$, *i.e.* only slightly higher than under continuous cropping without fertilizer application. Soil nitrogen accumulation during the period of green fallow is limited and in that situation shifting cultivation is not very effective.

If during the fallow period the risks for losses are much lower than during cropping, for example because the natural vegetation covers the soil

during a larger part of the year and its root system is deeper and denser than that of annual crops and consequently may prevent nitrogen leaching more effectively, regeneration of the soil nitrogen pools may occur much faster. The model can then also be applied, but with adapted transfer coefficients during the fallow period.

Conclusions

The model presented in this paper can be used for several practical purposes. Examples are:

- calculation of the direct and residual effects of applied nitrogen in inorganic fertilizer or organic material,
- calculation of the fertilizer requirement for a target nitrogen uptake, *i.e.* a target yield or a target increase in yield,
- calculation of the dynamics of soil nitrogen pools and nitrogen uptake by the crop for various environmental conditions and levels of nitrogen input,
- calculation of nitrogen uptake by the crop in a shifting cultivation system.

References

- Dam Kofoed A 1982 Humus in long-term experiments in Denmark. *In* Soil Degradation. Eds. D Boels, D B Davies and A E Johnston. pp 241–258. Balkema, Rotterdam, The Netherlands.
- Frissel M J and Veen J A van (Eds.) 1980 Simulation of Nitrogen Behaviour of Soil-Plant Systems. Pudoc, Wageningen, The Netherlands. 277 p.
- Jenkinson D S and Rayner J H 1977 The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Sci.* 123, 298–305.
- Keulen H van and Seligman N G 1987 Simulation of Water Use, Nitrogen Nutrition and Growth of a Spring Wheat Crop. Simulation Monographs, Pudoc, Wageningen, The Netherlands. 310 p.
- Keulen H van and Heemst H D J van 1982 Crop Response to the Supply of Macronutrients. Agric. Res. Rep. 916, Pudoc, Wageningen, The Netherlands. 46 p.
- Kortleven J 1963 Kwantitatieve Aspecten van Humusopbouw en Humusafbraak. Versl. Landbk. Onderz. 69.1, Pudoc, Wageningen, The Netherlands. 109 p.
- Lucas R E, Holtman J B and Connor L J 1977 Soil carbon dynamics and cropping practices. *In* Agriculture and Energy. Ed. W Lockeretz. pp 333–351. Academic Press, New York, USA.

22 *Model of crop response to nitrogen*

- Parton J W, Schimel D S, Cole C V and Ojima D S 1987 Analysis of factors controlling soil-organic matter levels in Great Plains grasslands. *Soil Sci. Soc. Am. J.* 51, 1173-1179.
- Persson J 1981 Influence of mineral and organic fertilizers on the humus balance and humus formation. *In Colloque Humus-Azote*. pp 82-89. Reims, France.
- Sluijsmans C M J and Kolenbrander G J 1977 The significance of animal manure as a source of nitrogen in soils. *In Proc. Int. Sem. Soil Environment and Fert. Management in Intensive Agric.* pp 403-411. Tokyo, Japan.
- Verveda H W 1984 Opbouw en Afbraak van Jonge Organische Stof in de Grond en de Stikstofhuishouding onder een Vierjarige Vruchtwisseling met Grasgroenbemester. Agric. Univ., Dep. of Soil Science and Plant Nutrition, Intern. note 58, Wageningen, The Netherlands, 101 p.
- Wolf J and Keulen H van 1989 Modeling long-term crop response to fertilizer and soil nitrogen. II. Comparison with field results. *Plant and Soil* 120, 23-38.