

# 1. Nitrogen balance in tropical agrosystems

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## 1. Introduction

Nitrogen is an essential element for the growth of crops. In the last two decades, it has been considered a key element in attempts to increase the production of food crops to keep pace with the growth of the world's population. Problems associated with these attempts include the high energy demand incurred in the industrial fixation of fertilizer nitrogen, and the inefficiency of fixed nitrogen when used for the increase of crop production. This inefficiency is mainly due to nitrogen losses from the agrosystem to which it is applied, and these are, for the greater part, the direct or indirect result of microbiological processes in the soil. In tropical agrosystems the losses can be high because most microbiological processes are, to a certain limit, accelerated under high temperature conditions [99]. In addition, nitrogen loss due to microbiological reduction (denitrification) is enhanced under the extremely wet soil conditions associated with flooded rice fields, one of the most important agrosystems in the tropics.

In natural ecosystems, nitrogen losses (outputs) are generally fully compensated for by nitrogen gains (inputs). Interference by man, e.g. through the imposition of an agrosystem, disturbs this balance and may cause a decrease in soil nitrogen status. This reduces agricultural production unless it is compensated for by 'artificial' means such as nitrogen fertilizers. However, a decrease in soil nitrogen status is also invariably the reflection of a lowering in soil organic matter content, leading to lower rates of water infiltration and lower water holding capacity, and making the soil more vulnerable to erosion losses. A continuous decrease in soil nitrogen content over time will therefore ultimately result in agriculturally uneconomic land. Thus, changes in soil nitrogen content are sensitive indicators of the balance between inputs and outputs of nitrogen and of the stability or otherwise of an agrosystem. As a result, microbiologists, soil scientists, agronomists and ecologists are concerned with the assessment of nitrogen balances in different agrosystems. Such assessments are particularly appropriate in the tropics because of the instability of soils under annual dryland conditions.

In this chapter we provide an overview of the different inputs and outputs of the soil, plant, and animal pools of tropical agrosystems, and of the changes that can take place in the nitrogen contents of these pools.

## 2. The three main nitrogen pools

In any given agrosystem, the total N can be distributed over the three main pools: soil, plant, and animal (Fig. 1). The N in the soil is mainly in the organic form (between 95 and 100% of the total N). Its concentration is generally highest in the topsoil, reflecting the fact that nearly all N inputs enter the soil through the surface. The total amount of organic N in this layer can be as low as 800 kg ha<sup>-1</sup> and as high as 10,000 kg ha<sup>-1</sup>.

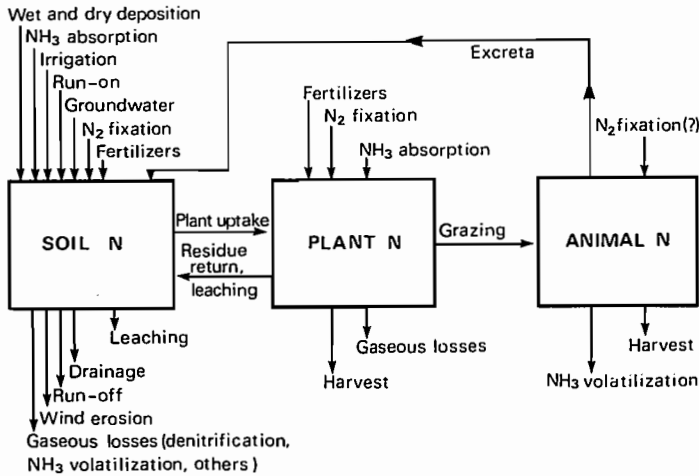


Fig. 1. The three main nitrogen pools and their inputs and outputs.

Mineralization of organic N, a microbiological process, results in temporary accumulation of inorganic N, mainly in the nitrate and partly in the ammonium form. The mineralization coefficient, i.e. the percentage soil organic N in the topsoil that is mineralized per growing season, is generally higher in the tropics (about 5%) than in temperate climates (1–3%) [87]. However, the size of this sub-pool fluctuates strongly over time because of crop uptake of this mineral N. If we assume for the tropics an organic N content of 0.07% in the top 15 cm of a soil with a bulk density of 1.43 and a mineralization coefficient of 5%, then the inorganic N sub-pool can be as high as 70 kg N ha<sup>-1</sup>, assuming no residual accumulation of inorganic N from the previous season.

The plant N pool of an annual crop at sowing is equal to the amount of N contained in the seed. From then on, the pool size increases sigmoidally over time, and reaches a maximum at flowering (Fig. 2). In the case of a non-leguminous crop, the N in the plant pool can originate from mineralized soil organic N or from fertilizer N applied to the soil. In the case of a leguminous crop, a substantial percentage of the total N in the plant can originate from symbiotic fixation of N<sub>2</sub>.

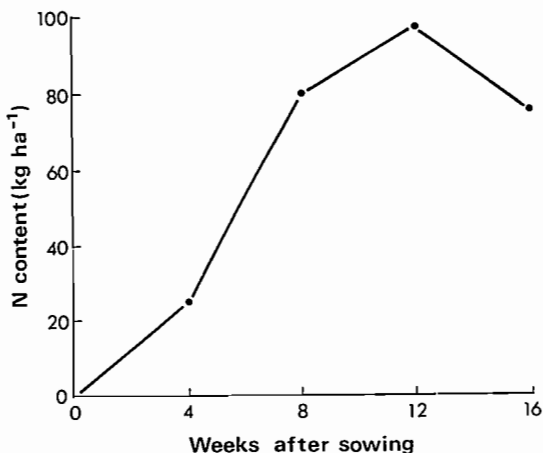


Fig. 2. Time course of plant N content (mean of 6 different fodder crops) in northwest Australia, for the wet season 1956–57, with 105 kg N ha<sup>-1</sup> applied as ammonium sulphate [60].

Where grazing occurs, the size of the animal N pool will depend on the type of animal and the stocking rate. For instance, under the extensive beef cattle grazing conditions in northern Australia, the animal N pool size can be as low as 0.2 kg N ha<sup>-1</sup>. On the other hand, using improved pastures, its size can be increased to about 10 kg N ha<sup>-1</sup> at certain times of the year.

The net changes in the pool sizes ( $\Delta N$ ) can be determined directly or indirectly. In the direct method the amount of N in each pool is assessed at times 0 and  $t$ , and  $\Delta N$  is calculated according to

$$\Delta N = N_t - N_0 \quad (1)$$

For the plant N pool, representative samples can be obtained easily at different times. For the animal N pool,  $\Delta N/\Delta t$  is generally small and a representative sample is difficult to obtain owing to the heterogeneity of the materials that constitute this pool. Similarly, for the soil N pool the changes in  $\Delta N$  per unit time are also small in relation to the pool size; a 5% change per year is high. This is complicated even further by the enormous spatial variation, often more than 15%, in the total N content of the plough layer. Only by increasing  $t$  to 3–5 years or more is it possible to get a reasonable assessment of  $\Delta N/\Delta t$ . An additional complication in the assessment of  $\Delta N$  of the soil N pool is the possibility of change in the bulk density of the topsoil. The way to overcome this complication is not simple, but an elegant solution has been proposed [38], by (i) sampling to two soil depths, (ii) measuring bulk density and percentage N for all samples, (iii) estimating the weight of accumulated organic matter, and (iv) adjusting the results by a proposed iterative procedure.

Alternatively, the changes in the different N pools can be assessed according to the equation

$$\Delta N = \sum_0^t \text{inputs} - \sum_0^t \text{outputs} \quad (2)$$

which assumes that all inputs and outputs of the pool concerned can be measured. This is very rarely the case, especially when effluxes of  $N_2$  are involved. One way to determine such an efflux, or unknown output, would be by combining equations (1) and (2) thus:

$$\sum_0^t (\text{unknown outputs}) = N_0 - N_t + \sum_0^t (\text{inputs}) - \sum_0^t (\text{known outputs}) \quad (3)$$

In this case, the size of the pool is determined at times 0 and  $t$  and all known inputs and outputs are monitored. Such an approach can be useful when using an  $^{15}N$ -labelled input, if all but one output can be measured.

### 3 The soil N pool: inputs and outputs

#### 3.1. Inputs

*3.1.1. Wet and dry deposition.* Nitrogen can be added to the soil from the atmosphere through rain, snow and hail (wet deposition) or dust and aerosols (dry deposition). Few if any estimates of dry deposition have been made in tropical areas, and most deposition estimates must be regarded as a combination of wet and dry ones (Table 1). In such cases, contamination of the deposition collector probably occurred and the data must be interpreted with caution. Furthermore, organic N is seldom included in rainwater analyses, resulting in gross underestimation of the contribution of wet deposition to the soil N pool.

Table 1. Nitrogen content in rainwater for different tropical countries (in many cases, the N contained in dry deposition is likely to have been included)

Country or Region	N (kg ha <sup>-1</sup> yr <sup>-1</sup> )	Reference
Vindhyan plateau, India	23	Singh and Pandey [71]
Chiang Mai, Thailand	13 <sup>a</sup>	Brown [9]
West Malaysia	3–10	Samy and Vamadevan [68]
West Malaysia	20–38	Pushparajah [66]
West Java, Indonesia	7.5	Brotonegoro <i>et al.</i> [8]
Northwest Australia	1 <sup>b</sup>	Wetselaar and Hutton [93]

<sup>a</sup> Wet deposition only; includes organic N.

<sup>b</sup> Wet deposition only; does not include organic N.

On a regional scale, transfer of terrestrial N can occur from one ecosystem to another through wind erosion and subsequent deposition. The absence of reliable

estimates of the deposited N can therefore affect the outcome of a nitrogen balance made for an ecosystem. On a global scale, however, the only true accession of N through deposition is the part contributed by electrical discharge, the amount being only in the order of 0.1 to 0.2 kg N ha<sup>-1</sup> yr<sup>-1</sup> [78, 90, 93].

*3.1.2. Ammonia absorption.* The concentration of ammonia N in the atmosphere immediately above the soil surface varies from 1 to 2 µg m<sup>-3</sup> in unpolluted areas to 200 µg m<sup>-3</sup> close to areas with industrial activity. Ambient ammonia concentrations are higher in the tropics than elsewhere [51]; in general the residence time of this ammonia, mostly only days, will depend on the rainfall frequency.

Absorption of atmospheric ammonia has been shown to occur for a wide range of soil types. Malo and Purvis [52] found this absorption to range between 25 and 100 g ha<sup>-1</sup> d<sup>-1</sup> under field conditions. Under controlled temperature and atmospheric ammonia concentrations, Hanawalt [35] found an average rate of absorption of 240 µg of NH<sub>3</sub>-N 100 g<sup>-1</sup> soil d<sup>-1</sup> at 20 °C at an ammonia concentration of 38 µg N m<sup>-3</sup> for six soils differing in clay content, organic matter and cation exchange capacity, and with a pH range of 5.2 to 6.7. His studies indicate that the sorption rate increases markedly with ammonia concentration and moderately with temperature. According to Malo and Purvis [52] atmospheric ammonia absorption might explain in part why maize yields were maintained in the absence of nitrogen fertilizers in long-term experiments in New Jersey, USA.

In conclusion, the phenomenon is likely to be of importance only for soils of low pH, in the neighbourhood of high industrial activity, and in a warm climate.

*3.1.3. Irrigation, run-on and groundwater.* Irrigation water may contain nitrogen, and this is of particular importance for flooded rice fields, where substantial amounts of water are added to the soil to maintain the required ponding conditions. Estimates of the N added in this way to the soil range from 6 to 16 kg ha<sup>-1</sup> crop<sup>-1</sup> [91].

Run-off from these fields either drains directly into a water way (creek, river, lake, or canal) or runs over less-elevated land. In the latter case, nitrogen in the run-on water might contribute to the soil N content, depending on the speed at which it moves over the land, its state (in solution or solid) and on particle size if solid. To our knowledge, such a contribution to the soil has not been documented.

Some paddy fields in northern Thailand [9] and some grey soils in Senegal [69] are underlain by relatively permeable soil layers, which may conduct large quantities of water. Such shallow aquifers are capable of transporting measurable quantities of dissolved nitrogen leached from the soil surface. This contribution to the soil N pool will largely depend on both past and present use of the land from which the nitrogen originated. For northern Thailand, Brown [9] estimates a maximum contribution of less than 0.1 kg N ha<sup>-1</sup> yr<sup>-1</sup>.

*3.1.4. N<sub>2</sub> fixation.* This input to the soil can take place through phototrophs, mainly cyanobacteria [74], and heterotrophs. The former may play an important

role under flooded conditions such as prevail in a paddy field. Estimates [91] of their contribution to the soil vary from 1.5 to 50 kg N ha<sup>-1</sup> crop<sup>-1</sup>. However, when algae are in symbiosis with the water fern *Azolla*, their contribution may be much greater. Thus, 22 crops of the *Azolla-Anabaena* complex may accumulate up to 450 kg N ha<sup>-1</sup> over 330 days [80]. In China and Vietnam, this complex is used as a green manure for rice [81].

For heterotrophs not associated with the rhizosphere, the main limiting factor is available carbohydrate in the soil. Consequently, the return of plant materials such as straw tends to increase the amount of N fixed by heterotrophs [53]. In a rice bay the amount of N fixed by heterotrophs ranges from 6 to 25 kg ha<sup>-1</sup> depending on the amount of straw returned [91].

Evidence is accumulating to support the view that N<sub>2</sub> fixation in association with the roots of some Gramineae can contribute, though moderately, to the nitrogen economy of the host plant. In Australia, a fixation rate for *Sorghum plumosum* of 136 g N ha<sup>-1</sup> d<sup>-1</sup> was measured under laboratory conditions [82]. Nitrogenase activity in the rhizosphere of rice is about one-tenth of the activity of symbiotic systems [21, 22]. Assuming for the latter a rate of 100 kg N ha<sup>-1</sup> season<sup>-1</sup> [88], an associative N<sub>2</sub> fixation of about 10 kg N ha<sup>-1</sup> season<sup>-1</sup> can be expected. Based on integrated acetylene reduction values, Döbereiner and Boddey [19] estimated a maximum fixation rate for rice of 4.6 to 8.4 kg N ha<sup>-1</sup> season<sup>-1</sup>.

**3.1.5. Fertilizers.** In the tropics, organic fertilizers continue to play an important role in supplying the soil with nitrogen. An outstanding example of this occurs in China where two-thirds of the annual input of fertilizer N (ca 100 kg ha<sup>-1</sup>) is applied in organic form, mainly as animal and human wastes and plant residues [73]. However, in the tropics as a whole there is a trend towards increased use of industrially-produced nitrogen fertilizers, partly due to the need to supplement the 'natural' organic fertilizers, and partly because some tropical countries, especially in south-east Asia, have found major sources of natural gas that can support NH<sub>3</sub> production (P.J. Stangel, personal communication).

The amount of fertilizer N applied per crop ranges from 4 kg ha<sup>-1</sup> for rice in Burma to 300 kg ha<sup>-1</sup> for sugarcane in tropical Australia. In some rice growing areas such as Java in Indonesia, where nitrogen-responsive varieties are used, the recommended rate is 90 kg N ha<sup>-1</sup> crop<sup>-1</sup>, but on average the farmers apply only about half of this. For a perennial crop such as rubber a total of 1500 kg ha<sup>-1</sup> of fertilizer N is applied over the 30-year life of the tree in peninsular Malaysia, but the use of legumes reduces this to one-third [66].

In general, the amount of fertilizer N applied in the tropics is dependent on biological factors (e.g. land history, type of crop), physical factors (e.g. climate, access roads for fertilizer transport), and socio-economic factors (e.g. price ratio of grain to fertilizer [41], local customs).

**3.1.6. Return of plant residues, plant leaching and animal waste products.** These will be discussed in Sections 4.2.2. and 5.2.1.

### 3.2. Outputs

**3.2.1. Run-off, leaching and drainage.** When free water makes contact with the soil surface, certain fractions of the soil nitrogen may be dissolved. If the supply of water is greater than the rate of infiltration into the soil, this water will temporarily pond on the soil surface or run off. In the latter case, any soluble nitrogen in the water that originated from the soil is lost from the soil N pool. In addition, solid soil fractions can be removed as erosion products with the run-off water when the kinetic energy of the rain droplets at the time of impact on the soil surface is high enough to disperse soil aggregates. A dense plant cover over the soil surface absorbs much of the energy of the rain droplets and effectively reduces the loss of N through erosion (Table 2). The paucity of plant cover may lead to the removal of at least  $5 \text{ t ha}^{-1}$  during one season [11]. This is equivalent to a loss of  $3.5 \text{ kg N ha}^{-1}$ , assuming a soil N concentration of 0.07%.

Table 2. Estimate of nitrogen losses through erosion as a function of the plant cover, at the Séfa Agronomic Station, Senegal [11]

Plant cover	Erosion <sup>a</sup> (kg N ha <sup>-1</sup> )		
	Minimum	Maximum	Weighted mean
Forest	traces	< 1	< 1
Bush fallow	2	10	5
Crops	2	19	7
Bare soil	6	54	21

<sup>a</sup> A soil N content of 0.1% has been assumed.

Loss of N through run-off can be substantial in the wet tropics. Further, marginal land is continuously being opened for agriculture because of increasing population pressure, and such land is often steeply sloping. On land permanently under flooded rice conditions, overflow of excess rainfall or irrigation water can lead to a maximum loss of  $1 \text{ kg N ha}^{-1} \text{ crop}^{-1}$  in the absence of nitrogen fertilizers [91]. When a soluble fertilizer is broadcast into the floodwater, nearly all the applied N will be dissolved in the water in the first few days [98]. Substantial nitrogen losses can occur in that period should excess water lead to overflow of the paddy field.

The movement of water from one paddy field to another is a planned feature in many rice-growing areas, and under such conditions the loss of fertilizer N from one field due to overflow is the gain of this N to the adjacent area at a lower level. The total overflow loss of fertilizer N from the irrigation scheme as a whole will depend mainly on the flow rate of the water in relation to the total length of the slope, the type of fertilizer, and edaphic characteristics such as cation exchange capacity and pH.

Once water starts to infiltrate into the soil, only negatively charged soluble nitrogen fractions (principally nitrate and nitrite) will move down the soil profile

by convection (leaching), due to the mass flow of the soil solution and, to a much lesser extent, by diffusion due to concentration gradients. The movement of positively charged ions (principally ammonium) is restricted by the cation exchange capacity of the soil [86]. Leaching of the gaseous nitrogen fraction nitrous oxide has recently been shown to be of importance [23]. This fraction is a product of denitrification, a process of particular importance under wetland rice conditions.

In general, the rate of leaching is highly dependent on rainfall amount [85], and to some extent its intensity; therefore this loss pathway is of particular importance in the humid tropics. Once a leached nitrogen fraction has been moved permanently beyond the reach of plant roots, it may be regarded as lost. This is likely to occur sooner in a shallow soil profile than in a deep one. In the latter case, the nitrogen can be taken up at a later stage by deep-rooting crops such as pearl millet [95]. In general, soil depth can have a pronounced effect on the prevention of N losses.

Where artificial drainage systems have been installed at a shallow depth, any nitrogen contained in the drainage water will be a loss to the soil, i.e. a drainage loss is comparable to a leaching loss from a shallow soil profile. Under the artificially induced leaching conditions, zero or positive soil water potential is required for actual drainage to occur, i.e. anaerobic conditions conducive to denitrification may prevail under such circumstances. Indeed, Dowdell *et al.* [23] have shown that drainage water may contain the denitrification product nitrous oxide at concentrations that are one or two orders of magnitude higher than in rainwater.

The actual amount of nitrate moved down the soil profile is largely a function of the total amount of organic and fertilizer N in the topsoil and the rate at which they are nitrified. Under high temperature conditions, as in the low-altitude tropics, this nitrification can be rapid when soil moisture is adequate [54]. In addition, the mineralization rate of organic N is increased when a period wet enough for nitrification is preceded by a long dry period [6]. This means that in the monsoonal and semi-arid regions of the tropics nitrate concentration in the topsoil can increase rapidly at the beginning of the wet season. When there are no plant roots to take up nitrate, it can be leached into the sub-soil. Subsequent rains may move this nitrate permanently below the root zone. In northern Australia, one quarter of the N applied as ammonium sulphate to a sorghum crop was found below the root zone in a clay loam at the end of the growing season, after an excessive wet season with 1170 mm of rainfall [86]. In the sandy soils of the Sudan-Sahelian zone with a rainfall of only 400 to 550 mm yr<sup>-1</sup>, leaching losses have been estimated to vary between 15 and 50 kg N ha<sup>-1</sup> yr<sup>-1</sup> [63].

**3.2.2. Ammonia volatilization.** This process requires (i) presence of a source from which ammoniacal N can be formed, (ii) enhancement of the processes that lead to the formation and accumulation of ammoniacal N, and (iii) conditions for a low NH<sub>4</sub><sup>+</sup> to NH<sub>3</sub> ratio.

In the absence of nitrogen fertilizers or organic additives, the main N source in the soil is soil organic N. Under most dryland conditions, ammoniacal N formed



from this source does not accumulate in the soil, because the rate of nitrification of the ammoniacal N is almost invariably higher than the rate of ammonification [54]. Under anaerobic conditions, however, ammoniacal N can accumulate over time owing to the anaerobic mineralization of soil organic N and the absence of nitrification. In a flooded rice field, where such conditions prevail, Wetselaar *et al.* [98] found an ammonia volatilization loss of only 1.5 kg N ha<sup>-1</sup>, presumably because accumulation of ammoniacal N in the soil could not occur due to plant N uptake. In practice, significant accumulation only occurs with the application of high amounts of materials that contain or generate ammoniacal N, such as certain fertilizers, animal urine and large quantities of organic matter.

The dominant factor influencing the NH<sub>4</sub><sup>+</sup> to NH<sub>3</sub> ratio is the pH of the soil solution, because it affects the equilibrium represented by equation (4) [30]



The higher the pH, the lower is the ratio, and therefore the greater the potential for ammonia to be lost [30]. For example, at pH 6, 7, 8 and 9 the approximate ratios are 10, 1, 0.1 and 0.02 respectively.

Other factors that influence the relative proportions of NH<sub>4</sub><sup>+</sup> and NH<sub>3</sub> are titratable alkalinity, buffer capacity of the soil and the temperature of the soil solution [30, 79].

In practice, the pH of the floodwater in a paddy field can rise substantially, sometimes up to pH 10, during the middle of the day owing to the high CO<sub>2</sub> assimilation rate of algae [81]. In addition, the high temperatures of the low-altitude tropics increase the ratio of ammonia in the gaseous form to that in solution.

When other conditions are favourable for a high NH<sub>3</sub> to NH<sub>4</sub><sup>+</sup> ratio in the soil solution or floodwater, the flux of ammonia into the atmosphere is positively related to windspeed [18, 31].

When ammonium sulphate is applied to a flooded rice field in the tropics, the losses vary from 3 to 9% of the amount of N applied, depending on the mode of placement of the fertilizer [98]. Under dryland conditions, urea N losses through NH<sub>3</sub> volatilization of up to 40% have been recorded when applied to a crop of millet in Bambey, Senegal [32].

**3.2.3. Denitrification.** Nitrate and nitrite may be subject to dissimilatory reduction (denitrification) to the gaseous products NO, N<sub>2</sub>O and N<sub>2</sub> through the action of biochemically and taxonomically diverse types of bacteria [47]. Denitrification is a major loss pathway of nitrogen in an agrosystem and particularly in tropical agrosystems, for two reasons. First, the high and intensive rainfall induces temporary anaerobiosis in soils. Under such conditions, the strongly denitrification-inhibiting factor O<sub>2</sub> is removed, and when other conditions such as pH and supply of organic carbon are favourable, denitrification can take place. Second, the high temperature in the low-altitude tropics stimulates gaseous loss through denitrification, because the reaction is strongly temperature dependent (between 10 and 35 °C the reaction

has a  $Q_{10}$  of ca 2.0 [72] and the rate increases with higher temperature until a maximum is reached at 60 to 75 °C [47]).

Denitrification in an extreme form occurs in wetland rice agrosystems. In flooded soils, the layer immediately below the floodwater generally contains sufficient oxygen, obtained by diffusion through the floodwater or from the activity of photosynthetic organisms, for nitrification to take place. The nitrate so formed may diffuse or leach to deeper, anaerobic, layers where it may be denitrified. Consequently, when ammonium-type fertilizers are placed on or in the top few mm of a paddy field soil, low recoveries of the applied N are found. Since, in general, such losses can only occur if the fertilizer N has been nitrified, they can be reduced by deep-placement of these fertilizers in the anaerobic zone. In addition, such placement will reduce losses by ammonia volatilization, due to ammonium adsorption within the soil.

In general, periodic flooding alternating with aerobic conditions will stimulate losses through denitrification. Thus, Ponnampetuma [64] estimates a loss of about 26 kg N ha<sup>-1</sup> from wetland rice soils in the Philippines due to nitrate accumulation in the soil between harvesting and replanting of rice followed by flooding. On the other hand, when a soil is well draining, the absence of anaerobic macropores can preserve nitrate in the soil profile for at least four years [86].

Since most denitrifying bacteria are heterotrophs [47], the presence of organic compounds in the soil is important for their growth. Denitrification is stimulated by organic carbon that can be extracted from soil water [7, 10], and by root exudates and plant residues. Ganry *et al.* [33], in lysimeter studies in Bambey, Senegal, observed increasing N losses from <sup>15</sup>N-labelled urea applied to pearl millet due to the ploughing in of straw. Those losses were attributed to denitrification. When 90 kg ha<sup>-1</sup> of urea-N was applied, the losses ranged from 39% with no straw incorporated, to 55% with 30 t ha<sup>-1</sup> of straw incorporated; a similar loss increase was obtained from 150 kg ha<sup>-1</sup> of urea-N.

The main problem with the estimation of denitrification losses is the virtual impossibility of measuring the gaseous losses directly under representative field conditions. Denmead *et al.* [17] estimated that only a very small fraction (1.4%) of the nitrate N lost from a flooded soil was in the N<sub>2</sub>O form, the rest presumably being lost as N<sub>2</sub>. As the latter already constitutes about 80% of the atmosphere, the addition of a small amount of N<sub>2</sub> to this particular pool through denitrification is extremely difficult to estimate. Consequently, most assessments of denitrification losses are based on the difference method as given in equation (3). In this way, losses due to denitrification in an unfertilized paddy field are estimated to be between 3 and 34 kg N ha<sup>-1</sup> [91].

When using <sup>15</sup>N-labelled material, equation (3) can be replaced by

$$D_e = T - \sum (\text{known losses}) \quad (5)$$

In this case, all known losses are determined using the <sup>15</sup>N method, and it is assumed that the difference between these losses and the total loss ( $T$ ) is due to denitrification ( $D_e$ ).

Under field conditions, such fertilizer balances, as applied to an annual crop, are mostly determined at the end of a growing season when the crop has reached maturity. It is usually assumed that any nitrogen taken up by the plants remains there until maturity. Recently, Wetselaar and Farquhar [92] have pointed out that this is not necessarily the case. A reduction in nitrogen content of  $50 \text{ kg ha}^{-1} \text{ crop}^{-1}$  between flowering and maturity is not uncommon for annual crops such as rice, sorghum and wheat. The example given by Basinski and Airey [3] for rice (Fig. 3) suggests that the denitrification loss determined by the difference method (equation 5) could be much lower at anthesis than at maturity, i.e. any loss of N from plant tops could give an overestimate of denitrification loss. Further, losses from plant tops may occur continuously during the growth of a crop, but become only apparent when the rate of uptake is lower than the rate of loss [92].

In summary, denitrification losses could well have been overestimated, and there is an urgent need for techniques that can measure such losses directly under undisturbed field conditions.

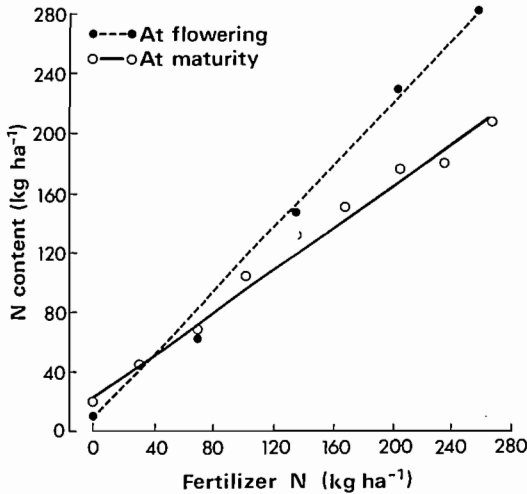


Fig. 3. N contents of rice at flowering (●) and at maturity (○), at different amounts of fertilizer N [3].

**3.2.4. Wind erosion.** The transfer of terrestrial material to the atmosphere through wind can cause substantial losses of N from an agrosystem. The removal of 1 mm of a topsoil containing 0.07% N would be equivalent to a loss of  $c 10 \text{ kg N ha}^{-1}$ . However, reliable assessments of N losses due to wind erosion are lacking, probably because of the problems associated with obtaining reliable results.

It can be assumed that all of the wind component N present in the atmosphere is returned to the earth surface through dry and wet deposition. The assessment of the total N content of these depositions may therefore give a measure of the

*maximum* N loss due to wind erosion. However, the deduction of the *actual* N loss due to wind erosion from this assessment remains a problem owing to (i) the presence in the depositions of N derived from processes other than wind erosion, and (ii) the difficulty of relating to its source any of this N in the depositions. The latter is due to the lateral transfer in the atmosphere of airborne particles of terrestrial origin caused by air movement. Possibly, the origin of the N from particular regions may be established by verification of ratios of certain elements or compounds that are specific to the region.

In conclusion, the assessment of the N contained in wet and dry deposition in a particular region is not likely to provide us with a proper assessment of N lost from that agrosystem through wind erosion. Possibly, flux measurements of airborne soil particles akin to those developed for ammonia by Denmead and various co-workers [14, 15, 16] could be considered.

## 4. The plant N pool: inputs and outputs

### 4.1. Inputs

*4.1.1. Soil and fertilizer N.* In most nitrogen balance studies, nitrogen in the soil and in plant roots is combined because of problems associated with separating them [92]. Consequently, when reference is made to nitrogen uptake by crops, this generally means the N content of the aboveground parts, or tops. For non-leguminous crops, uptake represents a transfer from the soil N pool to the plant N pool, and originates either from soil organic N that has been mineralized, or fertilizer N that has been placed on or in the soil or brought directly in contact with the plant.

The amount of soil N made available to plants in each growing season depends on soil type, land history and amount of rainfall, but is on average about 5.5% of the total organic N fraction in the soil for a semi-arid region such as northwest Australia [87]. In plant tops, the recovery of this N, together with that already available at the start of the growing season, can be as low as 20% and as high as 57% (Table 3). The high recovery by pearl millet and the low one by sorghum after a

*Table 3.* Plant nitrogen yields as percentage of total available soil nitrogen (nitrate in profile at start of season plus organic soil nitrogen mineralized during wet season) of non-leguminous crops following legumes [90]

After	Pearl millet	Grain sorghum	Sudan grass	Cotton	Weighted mean
Guar	42.7	43.1	56.8	43.1	46.4
Townsville stylo	37.9	47.4	42.6	42.6	42.6
Cowpea	54.0	47.3	56.0	48.7	51.3
Peanuts	35.4	41.9	50.2	38.6	41.4
<i>Weighted mean</i>	41.8	44.9	51.6	42.8	45.0
Bare fallow	46.2	19.9	25.3	25.6	

period of bare fallow is explained in terms of the differences in rooting depth between these species. During the bare fallow period, mineralized soil organic N accumulated as nitrate in the subsoil with a peak at about 1 to 1.5 m depth. Pearl millet can take up such nitrate from a much greater soil depth than sorghum [12, 95]. After five years of bare fallow in northwest Australia, one crop of millet recovered 203 kg N ha<sup>-1</sup> and sorghum only 105 kg N ha<sup>-1</sup> from the soil. However, when these two crops were sown in this same season (as for the previous measurements) on a 7-year old Townsville stylo (*Stylosanthes humilis*) pasture in which little or no nitrate had accumulated in the subsoil during the pasture phase, millet and sorghum took up 90 and 86 kg N ha<sup>-1</sup> respectively [95]. In other words, the capacity of these two crops to take up nitrogen made available in the topsoil during the growing season was the same.

Clearly, the mode and time of application, the type of nitrogen fertilizer, and edaphic and climatic conditions play a major role in determining the recovery of fertilizer N. In northwest Australia, the recovery of fertilizer N by sorghum ranges from 14 to 74% under rainfed conditions [55]. However, a low recovery by plant tops does not necessarily mean that the unrecovered part has been lost from the system. For instance, during an above-average wet season, about one quarter of the 100 kg N ha<sup>-1</sup> applied as ammonium sulphate to sorghum could be recovered as nitrate in the 60 to 120 cm soil layer at the end of the growing season [86]. This nitrate would still be available in the next wet season to a deep-rooting crop such as pearl millet. In this case, the low recovery of applied N by the sorghum crop was due to high amounts of rainfall leaching the nitrified applied ammonium. However, in the same region, a low recovery by a crop of sorghum due to lack of rain was also obtained when the application of 80 kg N ha<sup>-1</sup> as ammonium sulphate was followed by small and infrequent showers. After three months 44% of the applied N could still be found unnitrified in the surface soil, and out of reach of plant roots, due to the predominantly dry conditions in that soil layer [86].

Under wetland conditions, the recovery of applied N by the tops has been notoriously low, but deep placement of ammoniacal nitrogen fertilizers has substantially increased this recovery [13]. Enhanced recovery could be due to a reduction in ammonia volatilization [98], and/or a reduction in nitrification and therefore in denitrification. The reduction in nitrification may be achieved by placing the fertilizer in the anaerobic zone that is present several cm below the soil surface. Such placement inevitably increases the local fertilizer concentration, which *per se* has an inhibiting effect on nitrification [96]. In addition, local high fertilizer N concentrations in the soil tend to stimulate root proliferation to such an extent that any fertilizer N moving away from the point of placement may be intercepted by the roots before it can be leached or lost in other ways [62].

**4.1.2. N<sub>2</sub> fixation.** Leguminous crops can derive their nitrogen from the soil and from the atmosphere. When the soil N supply is low, the atmospheric contribution may be as high as 80% of the total amount of N taken up [36]. In a semi-arid tropical region, the fixation of N<sub>2</sub> can depend variously on the presence of effective

and specific *Rhizobium* strains, the amount of available N in the soil, and the soil water content. The results in Table 4 suggest that (i) where soybean was grown for the first time (in 1973), the effect of inoculation was dramatic, but no such effect was demonstrated with peanuts, (ii) fertilizer N had a depressing effect on N<sub>2</sub> fixation for both crops, and (iii) an inadequate supply of water reduces the grain yield of soybean, but not the proportion of N<sub>2</sub> fixed by the legume; for peanuts both were reduced (see also Fig. 4).

Table 4. The effect of three major environmental factors on the relative proportions of nitrogen coming from three sources (symbiotic fixation, soil and fertilizer) in aerial parts of two legumes and on their grain yield<sup>a</sup> [34]

Factors	Crop	Year	Treatment	Percentage of nitrogen in the aerial parts originating from			Grain yield (kg ha <sup>-1</sup> )
				N <sub>2</sub> fixation	Soil	Fertilizer	
Rhizobium	Soybean	1973	0	0	95	5	2020
	Soybean	1973	+	55	40	5	2320
	Peanuts	1974	0	44	54	2	1590
	Peanuts	1974	+	40	57	3	1620
	Peanuts	1975	0	66	32	2	1420
	Peanuts	1975	+	70	28	2	1500
N fertilization	Soybean	1979	s	58	38	4	840
	Soybean	1979	1	20	75	5	960
	Peanuts	1974	s	44	54	2	1590
	Peanuts	1974	1	20	68	12	1570
Precipitation	Soybean	1973	a	55	40	5	2320
	Soybean	1979	na	58	38	4	840
	Peanuts	1975	a	66	32	2	1420
	Peanuts	1974	i	44	54	2	1590
	Peanuts	1976	na	21	75	4	1130

<sup>a</sup> Work done within joint FAO/IAEA coordinated research program.

0, + = No inoculation or inoculation with effective rhizobium, respectively.

s, 1 = Small or large application of fertilizer, respectively.

na, i, a = Amount and distribution of precipitation is not adequate, intermediate or adequate, respectively.

There are many problems associated with the measurement of the *gross* amount of N<sub>2</sub> fixed by a legume over the whole period of its growth [48], and objections can be made to virtually all methods suggested [29]. The *net* contribution of legumes to the soil or to the soil-plant system can be measured slightly more accurately than the total amount fixed by determining (i) all N in the plant either remaining above the soil and/or being removed, plus (ii) all N in different soil layers before and after the introduction of the legume system. In this way, Henzell *et al.* [37] estimated that *Desmodium uncinatum* could make a net contribution of 112 kg N ha<sup>-1</sup> yr<sup>-1</sup>.

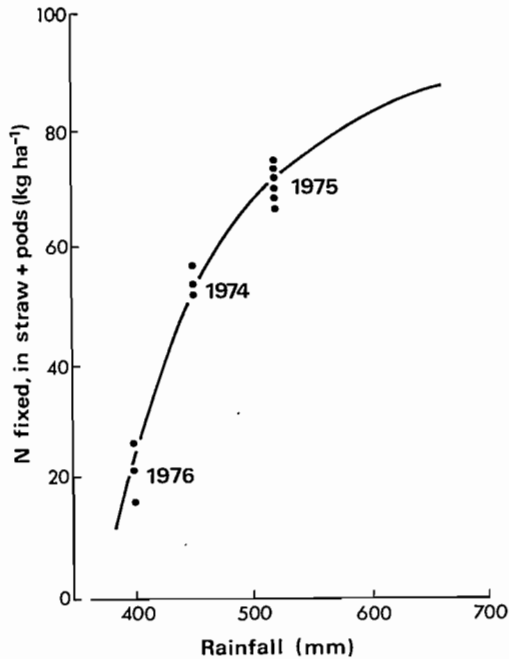


Fig. 4. Effect of rainfall on amount of  $N_2$  fixed by peanuts, for the years 1974–76. Each point represents one plot at the Experimental Station in Bambey, Senegal (Ganry, unpublished results).

Although there is considerable evidence to suggest that fixation of  $N_2$  takes place also in the phyllosphere of plants [67], such a contribution is small and probably not higher than about  $1 \text{ kg N ha}^{-1} \text{ crop}^{-1}$  for cultivated annuals.

**4.1.3. Ammonia absorption.** Leaves can take up and metabolize ammonia from their surrounding atmosphere [40, 65]. Such uptake has been demonstrated when high external pressures of ammonia (30 to 20,000 nbar) were imposed. Under such conditions, the contribution of gaseous ammonia to the N content of plants is likely to be substantial. However, in most areas, the external partial pressure of ammonia is generally only 1 to 8 nbar [43]. Because in leaves massive release and re-fixation of ammoniacal N takes place in the photorespiratory carbon cycle [44, 100], Farquhar *et al.* [24] inferred that there is a finite partial pressure of ammonia in the intercellular spaces of leaves. When this pressure is equal to or above the ambient air no ammonia uptake takes place. As this internal pressure is generally close to that prevailing in the air of unpolluted areas, uptake of ammonia by plants is likely to be restricted to regions downwind of areas with high industrial activity, or where a dense plant community covers soils from which ammonia can volatilize. For the latter case, it has been shown that pasture species can 'absorb'

virtually all ammonia released from decomposing plant material on the soil surface [14], and that rice plants take up some of the ammonia released from ammonium sulphate applied to the flood-water [98]. In both cases, the actual rate of ammonia absorption was higher than could be expected from assimilation through the stomata alone, and an additional uptake *via* a water film on the plant surface was suspected.

## 4.2. Outputs

Outputs or losses from the plant N pool take place through a removal from the field or a return to the soil. Both will be discussed below, but reference is made to Table 5, which summarizes the processes involved in these two loss pathways.

**4.2.1. Removal from the field.** Nitrogen in plant material may be removed from the field through harvesting, grazing, or through losses into the atmosphere. The amount removed through harvesting will depend on the total amount of N taken up by the plants and its distribution between harvested and non-harvested plant parts. In general, the grain is the main part removed from crops such as grain sorghum, pearl millet, and wheat, with the straw, stubble, or litter being either ploughed back into the soil or burnt. The ratio between the N in the grain and the total amount of N in the tops is reasonably constant and in the order of 0.68 for winter wheat [2] and 0.65 for rice [89], although for wheat, values as high as 0.85 have been obtained [1]. Thus, when only the grain is removed from these two crops, a plant N loss of 65 to 68% is incurred.

The nitrogen content of different plant parts for some crops in some tropical regions is given in Table 6. For grain crops like pearl millet, peanuts, grain sor-

Table 5. Nitrogen losses from the plant pool

I. REMOVAL FROM THE FIELD			
Harvest	Grazing		Into atmosphere
	Intentional	Unintentional	Solid
	*Cattle	*Birds	*Particulates
	*Sheep	*Insects	*Pollen
	*Goats	*Rats, etc	
		*Microorganisms	
			Gaseous
			*Amines
			*N <sub>2</sub>
			*N <sub>2</sub> O, NO <sub>x</sub>
II. RETURN TO THE SOIL			
Translocation	Leaching	Shedding	Return to soil
*to roots	*Rain	*Leaves	of non-harvested
*to soil	*Dew	*Flowers	part
	*Irrigation	*Fruits	
	*Spraying		



Table 6. Dry matter and nitrogen content of some tropical crops

Location	Crop	Treatment	Dry matter (kg ha <sup>-1</sup> )	N (%)	N (kg ha <sup>-1</sup> )	Reference
Senegal	Pearl millet grain straw	Rainfed, P & N	2560	1.3	33	Ganry (unpublished)
			6980	0.6	45	
Senegal	Peanuts kernels & straw shell & leaves	Rainfed P & starter N	4210	2.4	101	Ganry (unpublished)
			520	1.5	8	
Northwest Australia	Peanuts kernels shells trash	Rainfed & P	1120	5.0	56	Wetselaar and Norman [94]
			560	1.0	6	
			1680	1.0	17	
Northwest Australia	Grain sorghum grain stubble	Rainfed & P & N	2000	1.5	30	Wetselaar and Norman [94]
			6700	0.5	33	
Northwest Australia	Annual fodder crops cowpea guar Sudan grass sorghum bullrush millet	Rainfed & P & (N)	3920	2.0	78	Wetselaar and Norman [94]
			4480	2.0	90	
			7840	0.7	55	
			10640	0.75	80	
			13440	1.0	134	
Philippines	Rice grain stubble	Flooded, no N	4380	1.12	49	Khind and Ponnamperuma [45]
			–	–	19	
	grain stubble	Flooded, 150 N	6100	1.48	90	
			–	–	37	

ghum and rice, the amount of N lost on harvest will depend on whether the non-grain portion is used for other purposes such as fuel, cattle feed, etc., or whether it remains in the field. For fodder crops the total aboveground portion is lost from the plant N pool.

Losses through defoliation may be unintentional or intentional. Unintentional losses, such as occur when pests are in plague proportions, can induce substantial N removal, and  $\text{NH}_3$  volatilization losses have been postulated [92] as occurring when plants are 'diseased' (through microbial oxidation by microorganisms of amino acids obtained in aerial parts of plants).

The magnitude of intentional losses through grazing will depend on the type of animal, its age and the intensity of grazing imposed. In northwest Australia, grazing intensities of beef cattle can vary from 2 to 12 ha beast<sup>-1</sup> yr<sup>-1</sup> on native pasture to 0.4 ha beast<sup>-1</sup> yr<sup>-1</sup> for an introduced Townsville stylo-birdwood grass (*Cenchrus setigerus*) pasture [59].

Nitrogen can be lost from plant material to the atmosphere through the shedding of pollen, loss of minerals that accumulate on leaf surfaces due to mechanical agitation [46], burning, fragmentation, loss of wax rodlets during rapid leaf expansion or through the production of airborne salt crystals that are generated during rapid transpiration [4]. The magnitude of such losses into the atmosphere is not known, but is likely to be low and probably less than 1 kg ha<sup>-1</sup> crop<sup>-1</sup>. Norman and Wetselaar [61] have shown that at least 93% of the N contained in air-dry pasture material will be lost during aerobic combustion.

Mechanisms involved in gaseous losses of N from plant tops have been reviewed in detail elsewhere [92]. When the partial pressure of ammonia in the atmosphere is below a critical level there is a net release of ammonia from plant leaves [25]. This critical level, called the ammonia compensation point, influences the molar flux of ammonia into the leaf,  $J$ , according to

$$J = g(n_a - \gamma)/P \quad (6)$$

$g$  being the stomatal conductance to the diffusion of ammonia,  $n_a$  the ambient partial pressure of ammonia,  $\gamma$  the compensation point, and  $P$  the total atmospheric pressure.

Negative values for  $J$ , i.e. evolution of ammonia from the leaves, were observed during senescence of maize leaves [24]. This physiological period coincides with the flowering-to-maturity period during which the total N content of annual plant tops can decrease by as much as 75 kg ha<sup>-1</sup> [92]. The partial pressure of ammonia in unpolluted air, i.e. in most atmospheres in the rural tropics, is about 1 to 8 nbar, and compensation points are about 2 to 6 nbar [25]. Therefore, an unrealistically high  $\gamma$  value of at least 100 nbar above ambient would have to be assumed to explain such high plant N loss on the basis of ammonia evolution alone [92].

It follows that the lower the partial pressure of ammonia in the ambient atmosphere the greater the loss of ammonia from the plant will be. This might partly explain why Stutte and co-workers [76, 83, 84] found ammonia losses of up to 1.6 kg N ha<sup>-1</sup> d<sup>-1</sup> at a leaf area index (LAI) of 5, since they subjected leaves to near zero partial pressure of ammonia.

When both the reduced and oxidized forms of N emitted from plants are determined, the ammonia form appears to be by far the most important one [83, 84]. This suggests that the total gaseous loss of reduced plus oxidized N from plants is likely to be low, because losses in the  $\text{NH}_3$  form alone may already be assumed to be low and approximately of the order of  $0.05 \text{ kg N ha}^{-1} \text{ d}^{-1}$  at LAI 5 [24]. The possible loss of gaseous N in the form of  $\text{N}_2$  and HCN is discussed by Wetselaar and Farquhar [92], but this is likely to be small.

*4.2.2. Return to the soil.* The underground portion of most crop plants, excepting root crops and peanuts, remains in the soil after harvest and automatically becomes a part of the soil N pool. In principle, the N contained in plant tops can be returned to the soil through translocation into or *via* the roots, leaching out of plant parts by rain or irrigation water, shedding of plant material, and through decomposition of plant residues or litter not removed from the field after harvest.

The processes and amounts involved in a redistribution of plant N from the tops to the roots have been reviewed recently by Wetselaar and Farquhar [92], who indicate that for perennial plants such a translocation can definitely occur; there is no evidence for this process in annual plants. The authors conclude that the amount of N involved in root exudates is likely to be extremely small, but they caution that the lack of any soil N increase during the period when translocation of N from tops *via* the roots into the soil could be expected does not exclude the possibility of such a transfer followed by denitrification.

A return of N in tops to the soil *via* leaching is very likely to occur during rain, irrigation, spraying or dewfall in view of the evidence accumulated from throughfall measurements in forests [50]. For annual crops and pastures such evidence is sparse. When rice plants of high N content were sprayed each with 300 ml of distilled water per day for two days at ear initiation stage, the N content of the collected water was 46 ppm, equivalent to  $0.56 \text{ kg N ha}^{-1}$  per mm rainfall [77]. In addition, a nitrogen concentration of 102 ppm in dew was observed on the same rice plants [77]. In general, a transfer of N through leaching is therefore likely to be important in the tropics, where plants may experience intensive rainfall.

Other forms of plant N return to the soil are the spontaneous abortion of flowers and fruits, especially for a crop such as cotton, and the shedding of leaves. In pastures, all aboveground plant material that has not been consumed by herbivores is eventually returned to the soil surface. Legumes may be sown as green manure crops, converting  $\text{N}_2$  into plant N; incorporation of this plant N into the soil provides extra nitrogen to the soil N pool. However, when some parts of the tops of legumes are removed, the net result is not always an increase of N in the soil, as can be seen from Table 7. Likewise, Pieri [63] reported a decrease in soil N after the cultivation of some legumes in West Africa. However, a temporarily favorable effect can be obtained when a non-legume is preceded by a legume [42, 57]. A beneficial effect from peanut cropping is mainly due to an accumulation of nitrate formed during the period of early growth in the wide interspace between the peanut rows [63, 90].

Table 7. Topsoil organic nitrogen content and amount of plant nitrogen removed and returned to the soil after 3 years of legumes [90]

	Soil org. N (kg ha <sup>-1</sup> )	Plant N removed (kg ha <sup>-1</sup> )	Plant N returned (kg ha <sup>-1</sup> )
After 3 years			
Guar	1720	50	202
Peanuts	1580	168	56
Townsville stylo	1640	230	34
Cowpea	1510	364	0
At zero time	1700	—	—

The fate of plant N returned to the soil will depend on the chemical composition of the plant material, climatic and edaphic factors, the presence and activity of microorganisms and fauna, and the position of the plant material in relation to the soil surface. In general, a high N content will increase the weight-loss rate of the plant material, while a high lignin content will retard this process [5]. Three phases in the nitrogen dynamics of litter decomposition can be distinguished [5]: (i) a leaching phase, representing a rapid decline in absolute N content (kg ha<sup>-1</sup>) due to contact with water, (ii) an accumulation phase, when there is a net absolute increase in N content, and (iii) a release phase, consisting of a continuous net decrease in N content after the maximum N content has been reached. The rate and magnitude of these three phases will, no doubt, depend to a large extent on whether the plant material remains on the soil surface, or whether it is in close contact with the soil due to mixing of the litter material with the topsoil during cultivation. In the former case, losses due to ammonia volatilization into the atmosphere are possible [28] and are regarded by some authors [101] as a major source of loss of N in natural grasslands, when conditions for denitrification and leaching are not favourable. On the other hand, all litter N could be accounted for after two years of pasture growth, when <sup>15</sup>N-labelled pasture litter was incorporated into the top 0.5 cm of a clay loam [90, 97]. The actual release of this litter N for plant uptake depended on the C to N ratio of the litter, and varied from 6.5 to 17% during the first season.

Saprophytic grazers can consume microflora and excrete mineral forms of N, but their exact role in the turnover of litter N in different ecosystems is not known [101].

## 5. The animal N pool: inputs and outputs

In this section, we discuss vertebrate herbivores such as beef and dairy cattle and sheep that are introduced into the soil-plant system for the sole purpose of yielding animal products useful to mankind.

The animal N pool will be discussed in lesser detail than the other pools. This is certainly a reflection of the main interests of the authors. Nevertheless, an attempt

is being made to indicate the major gain and loss pathways and their likely magnitude. Problems arising from the social behaviour patterns of many domesticated herbivores in relation to the measurement of changes of the size of the different N pools will not be discussed.

## 5.1. Inputs

*5.1.1. Grazing.* The amount of N consumed by grazing animals per unit area of land depends on the amount of consumable plant material on offer, its N content, and the stocking rate. The utilization of the total dry matter production can be as low as 10 to 20% for extensive grazing systems and as high as about 80% in rotationally grazed high production systems [27]. Because animals tend to graze selectively, their N intake is difficult to estimate, but it can be roughly calculated from known liveweight gains (Table 8). For native pasture in northwest Australia, the total intake is not higher than  $6.7 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , which is close to the annual maximum N content of  $8.5 \text{ kg ha}^{-1}$  of the pasture. For introduced pastures in the same region, the intake is about  $60 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , which is appreciably less than the total N content of these pastures of about  $100 \text{ kg ha}^{-1}$  [59]. N intake as high as  $120 \text{ kg ha}^{-1} \text{ yr}^{-1}$  is possible on high quality pastures in tropical areas.

*5.1.2. N<sub>2</sub> fixation.* Increases of N content in the rumen over and above the amount of N brought in by feed has been suggested to be due to N<sub>2</sub> fixation, but such increases could possibly be due to endogenous additions [58]. Fixation of <sup>15</sup>N<sub>2</sub> in rumen contents *in vitro* indicates that the contribution of N<sub>2</sub> fixation, if it occurs, has no major effect on the total amount of N available to the microorganisms in the rumen [39].

## 5.2. Outputs

*5.2.1. Return to the soil.* Of the nitrogen taken in by animals such as beef cattle, only about 10% is retained, the rest being excreted mainly as faeces plus urine, or shed as surface cells plus hair. The latter group is dependent on the weight of the animal according to

$$N_s = 0.02 W^{0.75} \quad (7)$$

where  $N_s$  is the amount of N lost through the shedding of surface cells and hair ( $\text{g d}^{-1}$ ) and  $W$  is the liveweight (kg) [56]. With a liveweight of  $100 \text{ kg ha}^{-1}$ , this loss amounts to  $1.3 \text{ kg ha}^{-1} \text{ yr}^{-1}$ .

When high quality diets are ingested, i.e. diets with a protein-N concentration of 1.5 to 2%, the excess N is excreted in the urine rather than in the faeces, with the ratio between the two being as high as 7 or as low as 3. However, when animals are on a low quality diet, having a crude-protein-N concentration of about 0.5%, as for

Table 8. Calculation of N intake and N excreted for approx. 2-year old beef cattle, based on known liveweight gains (LWG)

System	LWG <sup>a</sup> (kg beast <sup>-1</sup> )	Stocking rate <sup>a</sup> (beast ha <sup>-1</sup> )	LWG (kg ha <sup>-1</sup> )	N gain <sup>c</sup> (kg ha <sup>-1</sup> )	N intake <sup>d</sup> (kg ha <sup>-1</sup> )	N excreted		
						Skin, etc. <sup>e</sup> (kg ha <sup>-1</sup> )	Faeces <sup>f</sup> (kg ha <sup>-1</sup> )	Urine <sup>f</sup> (kg ha <sup>-1</sup> )
<b>Native pasture<sup>a</sup></b>								
Wet season (6 months)	104	0.25	26	0.522	5.22	0.05	1.4	3.25
Dry season (6 months)	-54	0.25	-13.5	-0.27	1-2(?)	0.05	0.18	0.04
Total	50	0.25	12.5	0.252	6.7	0.1	1.6	3.3
<b>Introduced pasture<sup>a</sup></b>								
High qual. (6 months)	108	2.2	240	4.8	48	0.48	13	30.2
Low qual. (6 months)	30	2.2	66	1.32	13.2	0.13	3.5	8.3
Total	138	2.2	306	6.1	61.2	0.6	16.5	38.5
<b>Humid tropics<sup>b</sup></b>								
High qual. (12 months)	-	-	600	12	120	1.2	32	75

<sup>a</sup> In northwest Australia [59].

<sup>b</sup> Simpson and Stobbs [70].

<sup>c</sup> Assumes that the N concentration of the LWG is between 1.6 (J.B. Coombe, personal communication) and 2.4% [70], i.e. 2% average.

<sup>d</sup> Assumes that the N gain represents 10% of the total N intake.

<sup>e</sup> Represents N losses through shedding of skin and hair, belching of ammonia, and ammonia loss through sweating, estimated at 1% of total intake (J.B. Coombe, personal communication).

<sup>f</sup> For high quality feed 80% of N is excreted via faeces and 20% via urine; for low quality feed these are 80 and 20% respectively (J.B. Coombe, personal communication).

beef cattle on native pastures during the late dry season in northwest Australia, cattle lose weight and excrete more N than they take in; most of this excreted N (80%) is in the faeces.

Virtually all (90%) N in urine is in the urea or amino-N form, the rest occurring as ammonia, allantoin, creatine, creatinine and hippuric acid [70]. Its fate will depend on processes described under 3.2.2., but it must be kept in mind that the return of urine N to the soil is highly localized. With 2.5 cows ha<sup>-1</sup> only 15% of a pasture would be affected directly by urine per year [27] and one urine patch might therefore receive the equivalent of 300 to 500 kg N ha<sup>-1</sup> [70]. Because of such high concentrations and the high pH developed, losses through ammonia volatilization can be substantial. Nevertheless, because urine N has the highest proportion of the amount of N returned by large herbivores, it plays a dominant role in the conversion of plant N, often biologically fixed by legumes, into available N in the soil.

The N compounds in faeces are not well known. About 10 to 20% occur in undigested residues and 50 to 60% in bacterial matter [70]. Because most of this N is insoluble, it will only become available after incorporation into the soil and mineralization by microorganisms. Therefore, the role of dung-feeding insects, such as certain dung beetles in burying faecal material is an important factor in the rate of faecal N cycling.

*5.2.2. Removal from the field.* Nitrogen stored in the animal N pool can be removed from the field through milk, beef, wool, and loss of ammonia through belching and sweating.

In many tropical areas the nature of the herbage tends to be more fibrous than in temperate areas. Since lactation yield for dairy cattle is usually determined by the intake of digestible energy rather than of digestible protein, milk production per cow tends to be lower in the tropics than in temperate climates [70]. On the basis of Stobbs' [75] data on milk production, and assuming an N concentration of 0.57%, the N removed in milk can vary from 6 kg ha<sup>-1</sup> yr<sup>-1</sup> for unfertilized tropical pastures to 114 kg ha<sup>-1</sup> yr<sup>-1</sup> for irrigated tropical pastures with a high fertilizer input. This N represents between 10 and 30% of the total amount of N ingested [70].

The amount of N removed from the field as beef can be estimated for different types of tropical pastures from Table 8. For low quality, lightly-stocked native pasture, this would be about 0.25 kg N ha<sup>-1</sup> yr<sup>-1</sup>, but can be as high as 12 kg N ha<sup>-1</sup> yr<sup>-1</sup> for high quality pastures. The takeoff of 300 kg ha<sup>-1</sup> yr<sup>-1</sup> of lamb would reduce the animal N pool by 7.5 kg N ha<sup>-1</sup> yr<sup>-1</sup>.

Greasy wool consists of about 70% protein, containing 16.4% N, and the removal of each kg of wool represents an output of 0.11 kg of N [70]. On average, one sheep adds 1 g N d<sup>-1</sup> to its wool (J.B. Coombe, personal communication). With stocking rates varying from 0.2 to 30 head ha<sup>-1</sup>, the annual takeoff of wool N would range from 0.07 to 11 kg ha<sup>-1</sup>.

The amount of N removed *via* belching and sweating is not well known. The loss

through belching is only likely to occur with high intakes of urea, e.g. from a urea lick, which would act as an ammonia source and also increase the pH in the rumen, which is normally between 6 and 7 (H. Dove, personal communication). The amount of N lost through sweating is generally regarded to be less than 1% of the total amount of N intake.

## 6. Examples of N balances

In the following, we shall give some examples of nitrogen balances made for different cropping systems in different parts of the tropics, to illustrate the type of measurements that have been made of inputs and outputs, and to indicate the changes that normally occur in the different pools. Although it is recognized that domesticated herbivores can play an important role in the cycling of nitrogen and in the maintenance of soil fertility, no N balances that include the animal N pool are presented, because of the lack of relevant data for the tropics.

In some cases, only changes in the size of the soil N pool have been determined, so that equation (1) applies. In other cases, the measurement of such changes are combined with measurements of *some* inputs and outputs. Based on equation (3) we can write

$$N_t = N_0 + \text{inputs} - \text{outputs} \quad (8)$$

or

$$N_t = N_0 + (I_k + I_u) - (O_k + O_u) \quad (9)$$

where  $I_k$  and  $I_u$  are known and unknown inputs, respectively and  $O_k$  and  $O_u$  are known and unknown outputs, respectively. Therefore,

$$I_u - O_u = N_t - N_0 - I_k + O_k \quad (10)$$

$I_u - O_u$  can be regarded as the *net* contribution of N to the soil-plant system, and represents in most cases a measure of the net amount of N added via  $N_2$  fixation. Let  $I_u - O_u = \text{Net } I_u$ , then equation (10) becomes

$$\text{Net } I_u = N_t - N_0 - I_k + O_k \quad (11)$$

### 6.1. *Casuarina* (equation (1))

In the tropical arid climate of the northern coast of Cape Vert peninsula in West Africa, sand dunes have been planted to *Casuarina equisetifolia* for stabilization. After 13 years,  $\Delta N$  for the soil and plant N pools were 229 and 531 kg ha<sup>-1</sup>, respectively [20]. Thus, the total annual addition of N to the soil-plant system was 58.5 kg ha<sup>-1</sup>, of which about 6 kg ha<sup>-1</sup> originated from wet deposition. This suggests that on average 52.5 kg ha<sup>-1</sup> yr<sup>-1</sup> was contributed through biological  $N_2$  fixation.



### 6.2. Peanuts and millet (equation (2))

For a 2-year cropping period of one season peanuts followed by one season millet in Senegal (Ganry, unpublished results), it is assumed that all inputs to and outputs from the soil N pool are known, in which case equation (2) will apply. The balance sheet (Table 9) suggests a total loss of 71 kg N ha<sup>-1</sup> from the soil-plant system, on the assumption that inputs due to wet plus dry deposition and non-symbiotic N<sub>2</sub> fixation were negligible, which was not necessarily the case.

Table 9. N inputs and outputs, and soil N changes, for a 2-year period of peanuts-millet cropping in the semi-arid tropics of Senegal (Ganry, unpublished)

	N (kg ha <sup>-1</sup> 2 yr <sup>-1</sup> )	
<b>Inputs (<math>I_k</math>)</b>		
Precipitation	Negligible	
Non-symbiotic N <sub>2</sub> fixation	Negligible	
Fertilizer	95	
Symbiotic N <sub>2</sub> fixation	82	
$\Sigma_o^t$ inputs		177
<b>Outputs (<math>O_k</math>)</b>		
Removed through millet	33	
Removed through peanuts	109	
Leaching	20	
Denitrification and volatilization from soil N	50	
Denitrification and volatilization from plant residues	8	
Denitrification and volatilization from fertilizer N	28	
$\Sigma_o^t$ outputs		248
Change of soil N pool ( $\Delta N$ , equation (2))		-71

### 6.3. Different legumes (equations (11))

In the semi-arid tropics of northwest Australia, one bare fallow area and four different legumes were maintained in parallel for three consecutive years. The balance sheet is represented by Fig. 5. It assumes that, in relation to equation (11): (i) N = organic N in the topsoil + nitrate N in the whole soil profile, (ii) N<sub>0</sub> = N value for bare fallow and N<sub>t</sub> = N value after three years of a legume, and (iii)  $I_k$  is ignored, representing only the N input *via* sowing of the legume, while the input *via* wet + dry deposition is zero, since N<sub>0</sub> and N<sub>t</sub> received the same amount through this input, or (N<sub>0</sub> + N in deposition) - (N<sub>t</sub> + N in deposition) = N<sub>0</sub> - N<sub>t</sub>.

By making a N balance after the first year, actual values were found for Net  $I_u$  of 93, 90, 67, and 26 kg ha<sup>-1</sup> yr<sup>-1</sup> for the mean of the 2nd and 3rd year for Townsville stylo, guar (*Cyamopsis tetragonoloba*), cowpea, and peanuts, respectively [88]. These values are likely to represent the net contribution of the legume, *via* symbiotic N<sub>2</sub> fixation, to the soil-plant system.

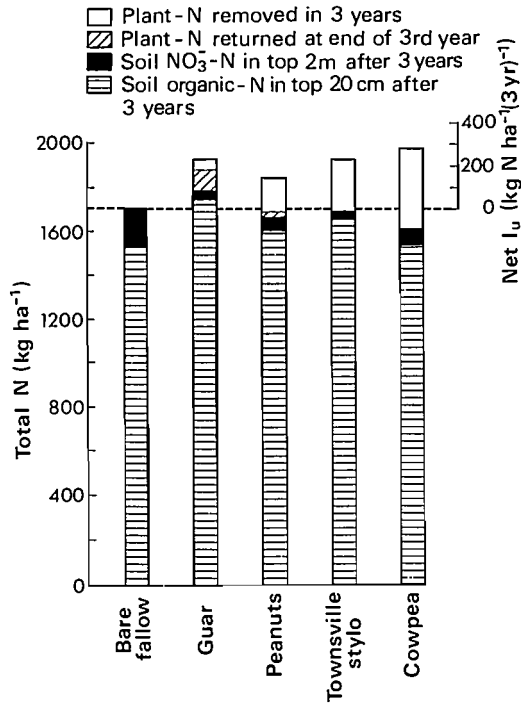


Fig. 5. Nitrogen balance after 3 years of legumes or bare fallow [88]; for  $Net I_u$  see equation (11), Section 6.

#### 6.4. Rice (Equation (11))

In southern Senegal, rice was grown for nine consecutive years, without any application of nitrogen fertilizer, on a grey soil characterized by a temporary shallow groundwater table at the end of the wet season [69]. Over this cropping period there was no significant change in soil N content, i.e.  $N_t - N_0 = 0$ . The total known input was through wet deposition ( $I_r = 10$ ), while the total amount of N removed in grain + straw was  $460 \text{ kg N ha}^{-1}$ . Thus, according to equation (11),  $Net I_u = 450$ . This represents a net average gain of  $50 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , perhaps through groundwater and  $N_2$  fixation. A similar net gain ( $40 \text{ kg N ha}^{-1} \text{ crop}^{-1}$ ) was found for unfertilized rice in central Thailand [26].

At the International Rice Research Institute at Los Baños, Philippines, 24 crops of three varieties were grown in 12 years without any nitrogen fertilizer [49]. The following values were found:

$$N_0 = 4130 \text{ kg N ha}^{-1}$$

$$N_t = 4440 \text{ kg N ha}^{-1} \text{ (mean of three varieties)}$$

$$I_k = 72 \text{ (rainwater)} + 120 \text{ (irrigation water)} \text{ kg N ha}^{-1}$$

$$O_k = 1024 \text{ (grain)} + 368 \text{ (straw)} \text{ kg N ha}^{-1}$$

Thus, according to equation (11), Net  $J_u = 1510 \text{ kg N ha}^{-1}$ , which is equivalent to a net input of  $126 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  or  $63 \text{ kg N ha}^{-1} \text{ crop}^{-1}$ .

All three balance sheets suggest that under wetland rice conditions, in the absence of fertilizer N, there is a net N gain for the soil-plant system. In the Senegal and Thailand experiments, the total nitrogen content in the soil did not change significantly, but in the Philippines there was a net increase of  $13 \text{ kg N ha}^{-1} \text{ crop}^{-1}$ . All three examples indicate that the traditional method of wetland rice growing is a very stable one so far as nitrogen is concerned.

In addition, data given by Koyama and App [49] suggest that different varieties can have a significantly different effect on the changes in total soil N content. In the Thailand case [26], the rotation of rice with the legume mung bean indicates that this legume contributes between  $58$  and  $107 \text{ kg N ha}^{-1} \text{ crop}^{-1}$  to the soil-plant system, but it has no positive effect on the soil N status, presumably because most of the N in the aboveground part of the legume is removed.

### 6.5. Rice (equation (5), $^{15}\text{N}$ )

In the central Plain of Thailand,  $^{15}\text{N}$ -labelled ammonium sulphate was applied to an irrigated dry-season crop of rice, either on the surface or at depth, split or non-split, and at  $50$  or  $100 \text{ kg N ha}^{-1}$ . At 2, 4, 7 and 12 weeks after transplanting sub-plots were destructively sampled and the amount of  $^{15}\text{N}$  was determined in different pools and sub-pools (Shaw, Oupathum, Thitipoca and Wetselaar, unpublished results). In addition, the  $\text{NH}_3$  originating from the fertilizer, that had been volatilized was also determined [98]. The results are given in Table 10.

In this case, the unaccounted-for applied N could represent (i) denitrification losses, (ii) losses via plant tops, and (iii) losses through unknown pathways. Leaching losses to the subsoil were unlikely, because deep sampling did not indicate the presence of any  $^{15}\text{N}$  compounds. Losses due to overflow or run-off were excluded, since for each subplot the fertilizer was applied within a frame, where the water level was strictly controlled.

The balance sheet suggests that at least some fertilizer N was lost through denitrification. In addition, there are strong indications that  $^{15}\text{N}$  was lost from the plant tops between 7 and 12 weeks where  $100 \text{ kg N ha}^{-1}$  had been applied; this loss represents between 70 and 75% of the increase in unaccounted-for N during that period. At the same time, the total amount of  $^{15}\text{N}$  in the soil (including roots) also decreased. It is therefore unlikely that the decrease in N content of the tops was due to a transfer of plant N into the roots or soil.

Table 10. Fate of fertilizer N ( $\text{kg ha}^{-1}$ ) based on  $^{15}\text{N}$ -labelled ammonium sulphate applied to transplanted rice, in the field, in the central plain of Thailand (Shaw, Oupathum, Thitipoca and Wetselaar, unpublished results). For experimental details see Wetselaar *et al.* [98]

Treatment <sup>a</sup>	Weeks after	Fertilizer N ( $\text{kg ha}^{-1}$ )				
		Tops	Soil		$\text{NH}_3$ volatilized	Unaccounted for
			Mineral N	Org. N + root N		
$S_{50}$	2	2.7	10.5	11.7	4.4	20.7
	4	6.8	1.1	15.4	4.4	22.3
	7	7.3	0.2	16.7	4.4	21.4
	12	9.3	0.3	16.3	4.4	19.7
$S_{50+50}$	2	2.1 <sup>b</sup>	9.8 <sup>b</sup>	9.6 <sup>b</sup>	3 <sup>b</sup>	25.5 <sup>b</sup>
	4	9.7 <sup>b</sup>	1.2 <sup>b</sup>	15.3 <sup>b</sup>	3 <sup>b</sup>	20.8 <sup>b</sup>
	7	36.7	0.8	26.8	3	32.7
	12	20.1	0.5	21.2	3	55.2
$S_{100}$	2	3.5	56.4	13.1	4.3	22.7
	4	25.3	10.3	21.4	4.3	38.7
	7	24.6	0.4	23.8	4.3	46.9
	12	19.1	0.5	21.4	4.3	54.7
$D_{100}$	2	3.3	56.3	15.7	0.7	24.0
	4	25.6	17.3	18.9	0.7	37.5
	7	38.1	0.7	26.5	0.7	34.0
	12	30.2	1.1	23.4	0.7	44.6

<sup>a</sup>  $S_{50}$  = 50  $\text{kg N ha}^{-1}$  on surface at transplanting time.

$S_{100}$  = 100  $\text{kg N ha}^{-1}$  on surface at transplanting time.

$S_{50+50}$  = 50  $\text{kg N ha}^{-1}$  on surface at transplanting time plus 50  $\text{kg N ha}^{-1}$  on surface at panicle initiation.

$D_{100}$  = 100  $\text{kg N ha}^{-1}$  in mudball, at 10 cm depth, one ball per plant.

<sup>b</sup> For first 50 N application only.

## 6.6. Regional (equation (2))

For the Suchow district of the Jiangsu province of China, Zhu [102] drew up an N balance sheet for an average cropping system. In this district, the cropping systems are one winter crop (barley, rape, or wheat) plus one or two crops of irrigated wet-land rice per annum. Apart from chemical N fertilizers, organic ones such as farm-yard manure, compost, *Azolla* and milk vetch (*Astragalus* spp.) are also used extensively.

Table 11. Nitrogen balance sheet, averaged over all agricultural fields of the Suchow district, for 1978 [102]

Input		Output (kg N ha <sup>-1</sup> yr <sup>-1</sup> )	
Chemical fertilizers	246	Harvesting	204
Symbiotic fixation, milk vetch	12	Leaching + run-off	2
azolla	2	Estimated loss from chemical fertilizers	123
Non-symbiotic fixation	?	Organic manures losses	8
Aquatic plants	1		
Rice straw	11		
Night soil	10		
Pig manure	28		
Seeds	7		
Irrigation water	3		
Precipitation	23		
Total	343 + ?		337

Applying equation (2) to the results given in Table 11,  $\Delta N = 6 + ? \text{ kg N ha}^{-1} \text{ yr}^{-1}$ . This suggests that the agricultural systems in the district are on average reasonably stable as far as N is concerned. This could be due in part to the relatively high input of organic nitrogen.

## 7. Significance and conclusions

The management of an agrosystem should aim to, at least, maintain the N status of a soil by keeping all N losses to a minimum and bringing all N gains to a maximum, provided that the gains have no detrimental effects on the environment [99]. This aim cannot be achieved using only empirical procedures. For instance, although legumes may add N to the soil-plant system in the tropics (see 6.3.), a nitrogen balance study indicates that only under certain management conditions where legumes are employed is the N content of the soil maintained (Table 7). Monitoring of the soil N content will indicate the magnitude and direction of the net changes, but this cannot give the information required to correct the changes. Such information can be obtained through detailed N balance studies, involving measure-

ment of as many inputs and outputs as possible. These studies will indicate (i) whether the soil-plant system as a whole gains or loses N over time, (ii) in which pool or sub-pool these positive or negative accumulations occur, and (iii) what the causes are for such accumulation.

In general, nitrogen balances are important means of determining which N loss and gain pathways are important and what their magnitudes are. They are therefore a useful tool in identifying research priorities, in testing potential improvements, and in assessing the net gains or losses due to certain management strategies such as the introduction of N<sub>2</sub> fixing species or associations. They are also likely to be a useful tool in testing of certain nitrogen simulation models.

The more the important inputs and outputs can be determined at the same time for the same agrosystem the higher the research efficiency becomes, since such results may verify the links between the different transfers and their interactions [91]. However, as has been shown in this chapter, such research could be improved by the development of appropriate methodology for certain gain or loss pathways; specifically these are denitrification, gross N<sub>2</sub> fixation, wind erosion, and gaseous losses from plant tops. In addition, realistic N assessments are required for wet and dry deposition and for leaching from plants.

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