Managing seasonal soil N-dynamics in rice wheat-rotation systems of Nepal

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Summary

The rice-wheat annual double cropping system occupies an estimated 0.5 million hectares in Nepal where it provides food for about 23 million people. The production systems are similar with regards to the prevailing soil types and the agronomic management but differ in terms of the climatic environment, stretching from the hot tropical lowlands to cold temperate mountain areas. Current production levels of both rice and wheat are far below their reported potential with N-deficiency being the major production constraint. Because of mainly subsistence-oriented smallholder agriculture, mineral fertilizer use is negligible and crops have to rely largely on native soil supply for their N nutrition. Between the harvest of winter season wheat and the transplanting of monsoon season rice lies a transition season of variable length (>10 weeks in the lowlands to <5 weeks in the mountains), where the land is typically under bare fallow. During this dry-to-wet season transition period (DWT), the soil aeration status changes from aerobic to anaerobic, resulting in an initial peak of soil N mineralization and its subsequent disappearance upon soil flooding. Protecting this native soil N from being lost is seen to contribute to improve the N nutrition and the currently negative N balances with impact on yield and productivity. Possible options may include the temporary immobilization of soil N in the biomass of soil micro-organisms and/or of transition season crops. Pot and field experiments were conducted in the greenhouse and under field conditions at various sites in Nepal between 2001 and 2003 to assess the potential of wheat straw management (short DWT in cool mountainous areas), grain and green manure legumes (long DWT in the lowland areas) and combinations of those on soil N dynamics, crop yields and systems' N balances.

When the land was left bare during the transition season (farmers practice), N_{min} was initially building up (50-80 kg of nitrate-N) and subsequently lost by nitrate leaching and denitrification, resulting in low N uptake and yield of both rice and wheat. The application of wheat straw during DWT significantly reduced soil N_{min} at the same rate as soil microbial biomass-N increased and resulted in <1 kg ha^{-1} of nitrate leaching and minimal nitrous oxide emissions from the soil. Increased grain yields were limited to the rice crop and increased with straw application rate and the duration of DWT. A crop cover with legumes reduced leaching losses by half and nitrous oxide emissions by two thirds of those in the bare fallow control, and BNF-N additions by legumes ranged from 27 to 56 kg ha^{-1}. Depending on the type of legume, this resulted in direct (rice) and residual (wheat) increases of 24-42 kg N ha^{-1} yr^{-1} in crop N uptake and of 1.2-2.1 Mg ha^{-1} yr^{-1} in grain yield, while improving the overall N balance of the systems. The lower benefits were associated with the grain legume, (50% of the N assimilation removed by grain harvest), while the high benefits were obtained with green manures. About one third of these legume-induced productivity gains could be ascribed directly to the conservation of soil N. We conclude that in environments where the time span between wheat harvest and rice transplanting (DWT) is too short to grow an even short-cycled crop (mid-hills and mountain areas), the incorporation of wheat straw can save native soil N from losses and improve the systems' nitrogen N balance. Where the DWT is sufficiently long, the cultivation of legumes appears economically and ecologically beneficial and should be encouraged. Combinations of straw amendment and green manure use during DWT provide the largest benefits in terms of grain yield, and N balance with possible longer-term benefits for system's productivity.

Zusammenfassung

Das Anbausystem der Reis-Weizen-Rotation nimmt in Nepal etwa 0,5 Millionen Hektar ein und stellt die Ernährung von ca. 23 Millionen Menschen sicher. Die Produktionssysteme in Nepal ähneln sich hinsichtlich der vorherrschenden Bodentypen und der Bewirtschaftungsweise, unterscheiden sich aber im Hinblick auf die klimatischen Bedingungen, die vom heißen tropischen Tiefland bis zu den kalt gemäßigten Bergregionen reichen. Sowohl bei Reis als auch bei Weizen werden die potentiell erzielbaren Erträge bei weitem nicht erreicht, wobei N-Mangel die wichtigste Ursache für die Mindererträge ist. Wegen der hauptsächlich Subsistenz-orientierten kleinbäuerlichen Landwirtschaft wird kaum mineralischer Dünger eingesetzt. Bodenbürtiger N bildet daher die Hauptgrundlage für die pflanzliche Produktion. Zwischen der Weizenernte der Wintersaison und der Auspflanzung von Reis in der Monsunzeit gibt es eine Übergangsphase von unterschiedlicher Länge (> 10 Wochen im Tiefland, < 5 Wochen in den Bergen), in der die Felder üblicherweise brachliegen (Nacktbrache). Während dieser Trocken-Nass-Übergangsphase (DWT: dry-to-wet transition period) wechselt der Bodenbelüftungszustand von aerob zu anaerob, was zu einem anfänglichen N-Mineralisierungs-Peak führt, der bei der Überstauung des Bodens wieder verschwindet.

Die Konservierung dieses natürlichen Bodenstickstoffs wird als Maßnahme angesehen, die N-Ernährung der Pflanzen und die gegenwärtig negative N-Bilanzen der Böden zu verbessern, was den Ertrag und die Produktivität erhöhen könnte. Mögliche Maßnahmen beinhalten die vorübergehende Festlegung von Boden-N in mikrobieller Biomasse und/oder in Zwischenfrüchten. Zwischen 2001 und 2003 wurden Topf- und Freilandexperimente im Gewächshaus und an verschiedenen Standorten in Nepal durchgeführt, um das Potential von Weizenstroh-Management (bei kurzer DWT in kühlen Bergregionen) und von Mais, Gründüngung und Körnerleguminosen (lange DWT im Tiefland) und ihrer Kombination auf die N-Dynamik im Boden, die Erträge und die N-Bilanz der Systeme zu untersuchen.

Bei einer Nacktbrache während der Übergangsphase (übliche landwirtschaftliche Praxis) kam es zu einem anfänglichen Anstieg von N_{min} (50-80 kg ha^{-1} Nitrat-N), der anschließend durch Nitrat-Auswaschung und Denitrifizierung verloren ging. Das führte zu einer geringen N-Aufnahme und zu geringen Erträgen von Reis und Weizen. Die Applikation von Weizenstroh während der DWT reduzierte signifikant die N_{min}-Gehalte und führte gleichzeitig zu einem entsprechenden Anstieg des mikrobiell

gebundenen N. Darüber hinaus sank die Nitratauswaschung auf <1 kg ha^{-1} bei minimalen N_2O-Emissionen aus dem Boden. Steigende Kornerträge wurden nur bei Reis verzeichnet. Diese nahmen mit steigender Applikationsrate und mit zunehmender Länge der DWT zu. Ein Zwischenfruchtanbau von Leguminosen reduzierte die N-Auswaschungsverluste im Verglich zur Nacktbrache um die Hälfte und die N_2O-Emissionen um zwei Drittel. Die N-Akkumulation durch biologische N-Fixierung der Leguminosen betrug zwischen 27 und 56 kg ha^{-1}. Je nach Leguminosenart führte dies zu einem direkten (Reis) und residualen (Weizen) Anstieg der N-Aufnahme der Folgekulturen um 24 bis 42 kg N ha^{-1} a^{-1} und zu einer Steigerung der Kornerträge von 1,2 bis 2,1 Mg ha^{-1} a^{-1} sowie zu einer Verbesserung der N-Bilanzen der Systeme. Körnerleguminosen führten zu einem weniger starken Effekt als eine reine Gründüngung, da 50% der N-Assimilation durch die Ernte der Körner aus dem System entfernt wurde. Etwa ein Drittel des durch Leguminosen hervorgerufenen Anstiegs der Produktivität konnte direkt der Konservierung des Boden-N zugeschrieben werden. Aus diesen Ergebnissen wird gefolgert, dass in den Regionen, in denen die Zeitdauer zwischen der Weizenernte und dem Reisanbau (DWT) zu kurz für einen Zwischenfruchtanbau ist, durch eine Einarbeitung von Weizenstroh N-Verluste aus dem Boden vermieden und die N-Bilanzen der Systeme verbessert werden können. Bei einer ausreichend langen DWT scheint der Leguminosenanbau ökonomisch und ökologisch am sinnvollsten und sollte gefördert werden. Die Kombination von Stroh und Gründüngung während der DWT erzielt den größten Nutzen hinsichtlich Kornertrag und der N-Bilanz und erhöht längerfristig sehr wahrscheinlich die Produktivität der Anbausysteme.

Erklärung

Ich versichere, daß ich diese Arbeit selbständig verfaßt habe, keine anderen Quellen und Hilfsmaterialien als die angegebenen benutzt und die Stellen der Arbeit, die anderen Werken dem Wortlaut oder dem Sinn nach entnommen sind, kenntlich gemacht habe.

Die Arbeit hat in gleicher oder ähnlicher Form keiner anderen Prüfungsbehörde vorgelegen.

Keshab Raj Pande
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Dedication

to my father **Shree Ganga Nath Pande** and mother **Dibya Kumari Pande.**

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Abbreviations

BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung
BNF	Biological Nitrogen Fixation
C:N	Carbon to Nitrogen Ratio
CBS	Central Bureau of Statistics
DAAD	Deutscher Akademischer Austauschdienst (German Academic Exchange Service)
DFG	Deutsche Forschungsgemeinschaft
DMRT	Duncan Multiple Range Test
DWT	Dry-to-wet season transition period
ECD	Electron capture detector
IAAS	Institute of Agriculture and Animal Science
IGP	Indo Gangetic Plain
KCl	Potassium Chloride
Kg ha^{-1}	Kilogram per hectar
L:N	Lignin to Nitrogen Ratio
M	Molar, Mol
Mg ha^{-1}	Megagram per hectar
NGLIP	National Grain Legumes Improvement Program
NMDP	National Maize Development Program
RCBD	Complete Randomized Block Design
TDR	Time Domain Reflectometry
NHI	Nitrogen Harvest Index
NFE	Nitrogen Fertilizer Equivalence

1. Introduction

1.1. Background

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) provide food for about 400 million people in South Asia (Swaminathan, 1984) and for 23 million people in Nepal alone (Ladha *et al.,* 2000). These two crops are often grown in the same field in an annual rotation. The rice-wheat annual double cropping system covers about 13.5 million hectares in the Indo-Gangetic Plain (IGP) and about 0.5 million hectares in Nepal (Hobbs and Morris, 1996).

The reported maximum grain yield of rice was 8 Mg ha^{-1} in mid hills research station at Khumaltar (Pandey *et al*., 1999) and 5 Mg ha^{-1} in the Terai experimental station at Bhairahawa (Gami and Shah., 1998, Regmi *et al.,* 2002). Long-term monitoring on experimental stations and farmers' field, indicates that at constant inputs, the grain yield of both crops are declining (Giri, 1994). Currently, the mean yields in this most important production system of the country are low and rarely exceed 2 Mg ha^{-1} in rice and 1.3 Mg ha^{-1} in wheat (Pandey *et al.,* 1999). However, to provide food for a rapidly growing population, Nepal needs to increase the production of rice by 1 Mg ha^{-1} and that of wheat by 0,6 Mg ha^{-1} by the end of 2020 (Hobbs and Adhikari, 1997, Adhikari *et al*., 1999, Gami *et al.,* 2001). The gap between the maximum observed and national average yield as well as the declining yield trend in long-term experiments require urgent research attention.

In this production system, rice is grown during the warm and wet summer season in flooded soil while wheat is grown during the cold and dry winter season under upland condition, using the residual moisture of the summer season rice. Besides these seasonal changes in soil aeration status, the rice-wheat systems in Nepal are characterized by a wide adaptability to different agro-ecological situations ranging from the subtropical lowlands of the Terai (150-500 m) to the temperate mid-hills (up to 2800 m a.s.l.). While the temperature environment and the resulting crop growth duration vary substantially along the altitude gradient, soil types and agronomic management practices are similar across the country, and so are the low yield levels.

1.2. Production constraints

A number of factors have been associated with the current low and even declining productivity of the system. A diagnostic field survey conducted in the Terai area of Nepal identified both short-term and long-term key problems associated with low production and declining productivity in the rice-wheat system (Harrington *et al.,* 1993). Short-term problems are those arising during the production period and include nutrient deficiencies, especially N, early season water logging, and late season drought. The long-term production problems comprise the declining soil fertility (mainly associated with declining soil organic matter and soil N supplying capacity) and the build up of insect pest problems. Dominating both the long and short-term problems are soil fertility issues, primarily those associated with N deficiency.

From long-term field experiments it has been concluded that N is the most limiting factor for the production of both rice and wheat in Nepal (Regmi *et al,* 2002, Gami *et al.,* 2001). However, the average N uses (both mineral and animal manure) by rice-wheat farmers in 2000 was less than 30 kg ha^{-1} yr^{-1} (Pandey and Joshy, 2000), while the recommendation from national extension services for both rice and wheat amounts to more than 100 kg N ha^{-1}. The reason for this discrepancy is found in the fact that the majority of Nepalese farmers have fragmented, small land holdings with less than 0,5 hectares (CBS, 2000) and about 40% of them live below the poverty line with less than 244 US$ per capita of annual income (CBS, 2001). Hence, external inputs (i.e. mineral fertilizers) are generally not affordable. In addition, because of the inadequate transportation network and poor fertilizer storage condition, mineral fertilizers are frequently available neither in the amounts and quality required nor at the right time. Consequently, the N nutrition of both rice and wheat is largely based on the supply from the native soil N pool and, to a lesser extent, on animal manure. Under such circumstances, the efficient use of systems' internal resources such as the recycling of crop residues and manures, minimization of nutrient losses, and the addition of N by biological nitrogen fixation (BNF) must be exploited to a much larger extent than currently.

Maximization of the benefits from these internal resources and provision of site-specifically adapted and adoptable technology options, is seen to require an improved understanding of (1) the seasonal dynamics of native soil N and its underlying processes as well as the extent and mechanisms of N losses (leaching, denitrification and ammonia volatilization), (2) the potential, the benefits, and the target environments of inter-season legume crops and (3) the development and spatial targeting of possible technical options to improve N use efficiency at systems level.

1.3. N transformation processes in the rice-wheat system

In the rice-wheat systems of Nepal, rice is grown during monsoon season and wheat is grown during cold and dry winter season. Between the harvest of wheat and the transplanting of rice, there is a transition season fallow period of variable length, which is determined by the temperature environment and the resulting growth duration of the rice and wheat crops. While this dry-to-wet season transition (DWT) can extend for over 12 weeks in the hot tropical climate of the Terai lowlands, it gradually shortens as one moves up the altitude gradient into the Himalayan mid-hills, until reaching less than 5 weeks at the high altitude sites. This DWT is seen to be crucial in determining native soil N dynamics and N losses. After the onset of the spring rains, several cycles of soil drying re-wetting may occur, stimulating soil N mineralization (Schreven, 1968). As the land is bare of vegetation during DWT, the accumulated N_{min} is potentially prone to loss mechanisms. Particularly where the N_{min} peak (Birch effect) is dominated by the oxidized N form (nitrate), soil saturation or submergence with the onset of the monsoon rains and before the fields are transplanted to rice is likely to entail N losses by leaching and denitrification.

All these N transformation processes (ammonification, nitrification and denitrification), are linked to soil aeration status (Redox) and water availability and are therefore showing a strong seasonality. Before the onset of rain, the soil contains mostly organic and little mineral N (Aulakh *et al.,* 2000). With the re-wetting of the soil at the onset of rains, soil organic N is subject to intense chemical and microbiological transformation processes (hydrolysis, oxidations, reduction, assimilation) and is therefore a very mobile element in the soil–plant–atmosphere continuum (De Datta and Buresh, 1989). The share of plant-available native soil N_{min} is determined by the soil organic matter content and the ecological conditions favouring N mineralization, transformation and movement (Hynes, 1986). The hydrolysis of organic N results first in the formation of ammonium-N, which may be sorbed onto clay particles (Veen *et al.,* 1985). In the presence of molecular oxygen, ammonium can be oxidized to nitrite by specialized aerobic microorganisms belonging to the Nitroso-group (e.g. *Nitrosomonas, Nitrosococcus, Nitrosolobus*, etc.) and in a further step, nitrite can be oxidised to nitrate by organisms belonging to the nitro group (e.g. *Nitrosobactors, Nitrocystis*, etc). The amount of mineralized N is increased at higher soil organic N levels (Broadbent, 1979). Soil water fluctuation generally results in a large production of NO_3-N (Birch, 1960, Herlihy et al., 1979, Nunan, 2000).

Contrarily to NH_4-N, NO_3-N, being an anion, is not sorbed onto clay minerals and can easily move with the water flow (leaching). Flooding of aerated soil has generally been accepted as a major factor of NO_3-N loss that can reach up to 90% from rice soils (Bacon *et al.,* 1986, Buresh *et al.,* 1989). Soil flooding can promote leaching losses of NO_3-N particularly from sandy textured soils. Downward water flow carries NO_3-N to lower soil layers. Two direct determinants of NO_3-N leaching are the net downward flux of water and the concentration of NO_3-N in the soil or the leaching water. Large NO_3-N losses by leaching generally occur from aggregated soils by and from soils which are under bare fallow during the aerobic phase before puddling for rice cultivation.

Soil saturation results in a depletion of molecular oxygen, thus creating favourable conditions for denitrifying organisms. When nitrate encounters anoxic conditions (redox potential of less than 500 mV), e.g. in saturated soils, it may be used as an alternative electron acceptor by 0.1-1% of the microbial population in the soil. In this process of anaerobic respiration of nitrate, N_2 and N_2O gasses are formed (denitrification) and N is thus lost from the soil (Vor, 2003, Haynes, 1986). The rate of N_2, and N_2O evolution from soils will be higher under conditions of fluctuating redox potentials (wetting and drying cycles) than the constant redox potential (Hütsch *et al.,* 1999, Reddy and Patrick, 1975). Nitrate N losses during the initial period of soil flooding have been attributed primarily to denitrification (Bacon *et al*, 1986, Goreau *et al*., 1980, Bollmann and Conrad, 1998).

Before the onset of the spring rains (after wheat harvest), most lowland soils in Nepal are dry and contain little mineral N. However, after the onset of sporadic spring rains, the alternate drying and wetting of the soil occurs and large amounts of N mineralization and nitrate accumulation in the fallow land during this transition period is expected.

At the end of the dry-to-wet season transition period soil saturation coincides with the onset of the monsoon rains and Nitrate-N losses reported from Chitwan province in Nepal reached >40 kg ha^{-1} (Pande and Becker, 2003). However, the mechanism of loss is not still clear. The extent of the prevailing loss mechanism will depend on the amount of nitrate present in the soil solution, the quantity of easily mineralizable carbon sources, the intensity of the rain and the flow of water in the soil profile (Wulf *et al.,* 1999, Bognonkpe and Becker, 2000). Such losses are likely to be dominated by leaching in well-draining sandy soils (e.g. the Ultisols of the upper Terai) and by denitrification in saturated heavy-textured soils (e.g. the Aqults of the lower Terai). Avoidance of that loss may improve N nutrition of the succeeding crop rice. With wide spread rural poverty and mineral fertilizer scarcity in Nepal, native soil N management is essential to sustain and enhance soil productivity and crop yields. The quantification of native soil N dynamics and the understanding of the underlying processes and their driving forces may help to develop low-cost soil and crop management options.

1.4. Management options

Options that are acceptable to farmers must be based on available (non-purchased internal rather than capital-intensive external) resources and must be adoptable by smallholder farmers without offsetting the existing cropping calendar or the labour allocation patterns. Locally available resources comprise crop residues, animal manure and some commonly known green manure and grain legumes.

In the rice-wheat rotations of Nepal, the crop residues (cereal stubble and straw) are generally removed from the field. *In-situ* wheat straw burning is common and it contributes to the emission of large amounts of climate relevant trace gases such as CO_2, NH_4, CO and N_2O. The residue removal exacerbates the decline in soil organic matter (Hobbs and Pasuquin, 1999, Regmi *et al.,* 2000) and can substantially contribute to K imbalances (Mussgnug *et al*., 2003). Residue removal has also been shown in other tropical cereal-based cropping systems to largely explain a declining N supplying capacity of the soil (Becker and Johnson, 2001). A very low external input use combined with residue removal has reportedly increased the nutrient imbalances in a range of rice-based production systems (Dobermann *et al.,* 2003), but most particularly that of N deficiency in rice-wheat rotations (Ladha *et al,* 2003). One option may be to return the wheat straw to the plots, which is normally removed or burnt, either in the field (*in situ*) or on the threshing floor. Returning straw to the field will not only return substantial quantities of carbon and potassium to the soil, it may also reduce N losses by temporary immobilization of N_{min} in the soil microbial biomass.

Another option may be to grow short-cycled crops (<90 days) during DWT and recycle the green biomass and/or crop residues and the nutrients they contain. Such crops assimilate soil nitrate and may thus protect it from possible leaching and denitrification losses. Growing nitrogen-fixing crops, particularly green manures or grain legumes with a low N harvest index, may additionally contribute N from the atmosphere to the system. A combination of straw cycling together with legume cultivation during DWT may further increase above mentioned benefits. The choice of the option will depend on the length of DTW (temperature environment along the altitude gradient) and farmers' needs or alternative use options for residues (i.e. wheat straw used as bedding for animals or as fuel and legume stover needed as animal feed) and such options need hence to be site- and system-specifically targeted.

Several field studies conducted in West Africa and The Philippines could show that simply maintaining a weedy fallow vegetation in the field during DWT (in contrast to the commonly practiced bare fallow), was sufficient to increases the yield of a subsequent crop of lowland rice by 0.4 to 1.1 Mg ha^{-1}, probably as a result of reduced soil N losses during DWT (Becker and Bognonkpe, 2000, Kondo *et al.,* 2000). The decomposition patterns and N mineralization dynamics of a wide range of organic residues and the biomass of green manures grown during DWT as well as their determining factors were determined by Becker *et a*l. (1994a) and Ladha *et al*., (1996). Applying low-quality residues (e.g. straw from the preceding cereal crop) has been shown to result in a temporary net-N immobilization for 2-7 weeks. The speed of green biomass mineralization is largely determined by the lignin: N-ratio, which can be manipulated by plant species, plant age and mixing low-quality crop residues such as straw (Becker and Ladha 1996). Using appropriate mixes of residues and green manure biomass can thus be used to synchronize the N supply from organic matter mineralization with the N demand of the growing rice crop, thus minimizing N losses while increasing N uptake and the yield of subsequent crops (Becker *et al.,* 1994b).

Above results highlight (1) the importance of DWT for native soil N dynamics, (2) the role of low quality crop residue on temporary N immobilization and thus N conservation, and (3) the possible effects of pre-rice nitrate catch crops on N conservation and BNF-N addition. To date, no published study has looked at N dynamics and their management in rice-wheat rotations and the response of both the wet season rice and wheat in a holistic way. Further, factors determining the microbial N immobilization in aerobic soils and the N re-mineralization in the flooded soil during the wet season are still unclear. This study attempts to fill these knowledge gaps by addressing the subject of diagnosis and management of seasonal soil N dynamics at systems level.

2. Hypothesis and Objectives

Previous research could show that N is the main limiting factor and responsible for the reported yield decline of both rice and wheat. Particularly in the low input system of South Asia in general and of Nepal specifically, the management of native soil N appears essential to sustain the productivity of rice-wheat system in Nepal. Based on previous studies, it is reasonable to assume that, large amounts of nitrate-N accumulate during DWT. With soil saturation, at the end of DWT, most NO_3^--N is lost by either denitrification and/or leaching processes. During DWT, the incorporation of low quality residues with a wide C/N- or lignin/N-ratio (wheat straw) will result in a temporary immobilization of N_{min} in the soil microbial biomass thus preventing the build-up of NO_3^--N and reduce N losses to occur. A growing vegetation green manure or short-duration grain legumes during DWT can absorb nitrate and immobilizes it in the biomass (nitrate catch crops). Growing legumes with a low N harvest index will not only cycle soil N but also add N by biological N_2 fixation (BNF). The N conserved and returned in the form of plant biomass to the saturated/flooded soil will become gradually available and improve the synchrony of soil N supply and crop N uptake. Grain yields of both rice and wheat will benefit from native soil N conservation and BNF N addition and improve the currently very negative N balance of the traditional rice-wheat rotation systems.

We further hypothesize that an improved understanding of N mineralization, immobilization and loss mechanisms will help in the development and spatial/temporal targeting of soil and crop management systems that sustain soil N supply, increase N use efficiency of both rice and wheat and enhance the productivity of small-holder rice-wheat systems in the short term with possible long-term benefits. A series of experiments were conducted in a greenhouse in Germany and at various field sites in Nepal (on-station experiment at Rampur and on-farm experiments at three representative field sites in Chitwan and one field site in Kaski province) with the following objectives:

(1) Quantify the effect of management options on N dynamics during the transition season, involving

- soil N mineralization, nitrate-N leaching and N_2O emissions,
- N immobilization in microbial biomass and growing crops,
- atmospheric N_2 fixation by legumes.

2. Evaluate the effect of management options on N dynamics during the wet season, involving

- soil and residue N mineralization and nitrate-N leaching,
- N uptake by rice.

3. Evaluate the effect of management options on N dynamics during the dry season, involving

- soil and residue N mineralization, and nitrate-N leaching,
- N uptake by wheat.

4. Establish N balances of the various rice-wheat production systems.

5. Validate the observed effects of N management options in farmers' field.

3. Materials and Methods

A series of experiments was conducted both in a greenhouse under climate-controlled conditions in Germany and at different rice-wheat growing field sites in Nepal to study the seasonal soil N dynamics, the extent and mechanism of N losses and the possibilities to improve the N use efficiency and the yield of lowland rice and wheat. Different crops and straw management options were evaluated during the dry-to-wet season transition period under both improved and traditional management systems. The study was divided into three components:

(1) Pot experiments in the greenhouse, University of Bonn, Germany,

(2) On-station experiments at the experimental farm of the Institute of Agriculture and Animal Science (IAAS), Rampur, Chitwan province, Nepal,

(3) On-farm experiments at field sites in Chitwan and Kaski province, Nepal.

3.1. Experimental sites and climatic conditions

3.1.1. Greenhouse

Experiments were conducted under climate-controlled conditions in potted soil in 2001 and 2003. The temperature and day length conditions prevailing during DWT in Nepal were simulated in a tropical greenhouse of the Rheinische Friedrich-Wilhelms-Universität Bonn, Germany. The maximum and minimum temperatures during the experimental period were 28-32°C and 19-21°C, respectively. The day length was adjusted 14 hours using Sodium vapour lights with a light intensity of 650-900 µmol m^{-2} s^{-1}. The relative humidity in the green house ranged between 65% and 85%, corresponding to a vapour pressure deficit of 1.0-0.4 k Pa.

Soil moisture was gradually increased from 25% to 50%, 75%, 100% of field capacity (FC) and soil flooding in two weeks intervals during the 10 weeks experimental period 2001 (Fig.1) and from 50% to 75%, 100% FC and soil flooding in two weeks interval during the 8 weeks experimental period of 2003.

3.1.2. Field sites

The locations of the experimental field sites in Nepal at different altitude are presented in plate 1.

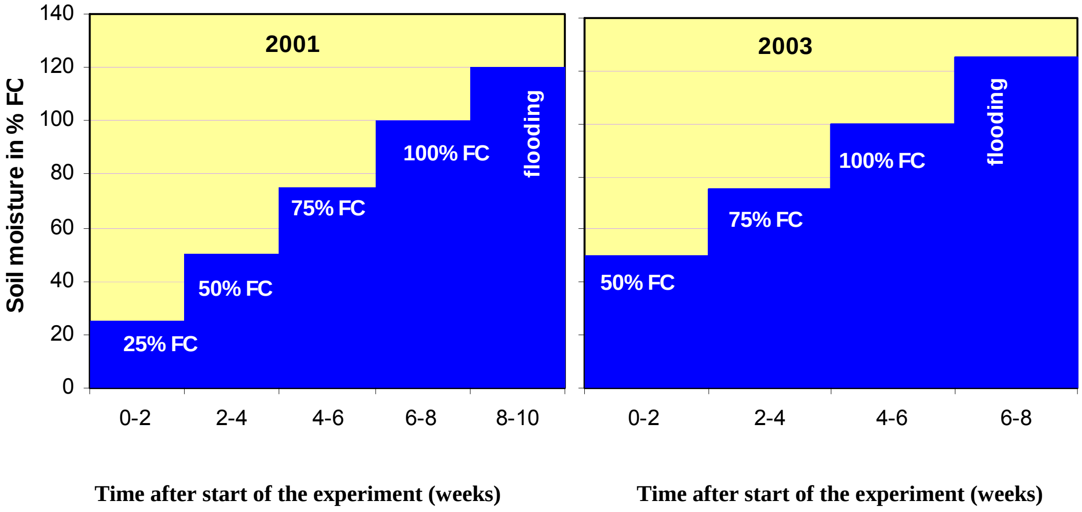

Figure 1. Soil moisture levels of potted soil applied in the greenhouse experiments under climate-controlled conditions (pot experiments, Bonn, Germany, 2001 and 2003).

a).High altitude site

The field study sites in Nepal comprised an experimental farm and three representative farmers' field in Chitwan province and one farmer's field at Lumle, Maramche in Kaski province (plate 1). The site in Lumle was located close to the village of Maramche and is representative of rice-wheat cropping system at high altitudes of the Himalayan mid-hills. It is located at 28° 18`N latitude and 83° 28`E longitude at 1740 m above the sea level. The climate is cold subtropical with cold and dry winter and a monsoon influenced warm and humid summer season. The annual rainfall of 5500 mm is concentrated in the period between May and October. The temperature ranges from 20-28°C in summer and 2-12°C in winter with a mean annual temperature of 19.8°C (Fig. 2). The relative humidity exceeds 85% in summer and drops to less than 50% during the winter season. The site was under continuous rice-wheat rotation since 10 years. The cultivation period for lowland rice is between June and October that of wheat is between November and April. Between the harvest of wheat and transplanting of lowland rice lies a relatively short dry-to-wet season transition period of 6-8 weeks during which the land lies fallow (tilled bare fallow in the traditional rice-wheat production system of the region).

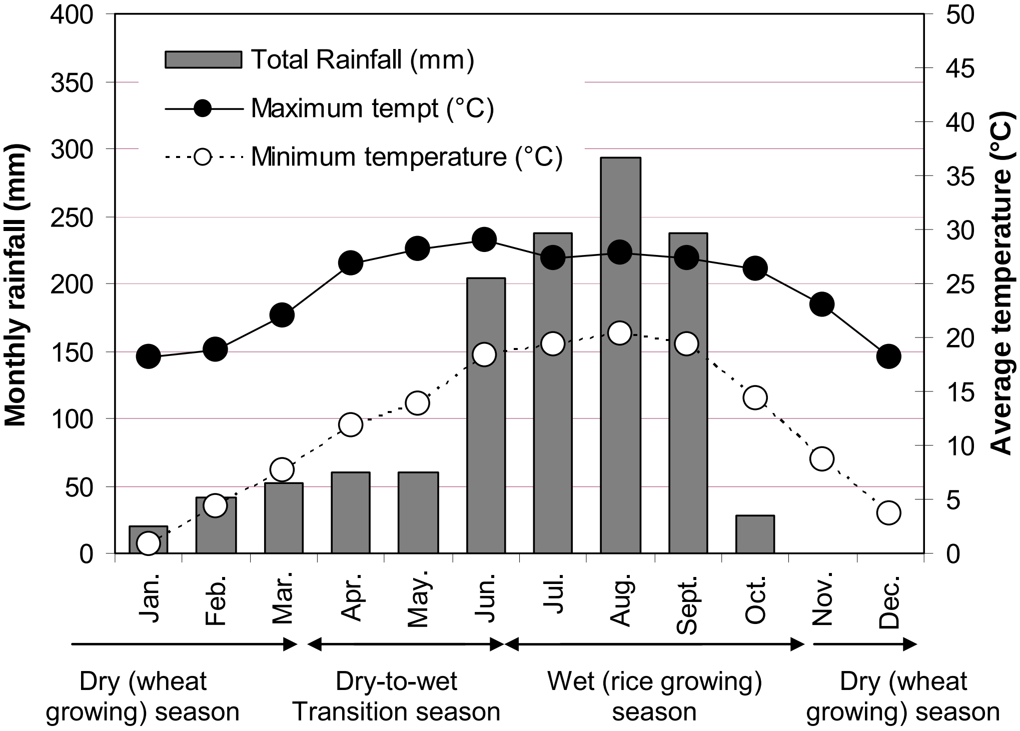

Figure 2. Monthly rainfall and mean maximum-minimum temperatures at the high altitude field site in Nepal (field experiment, Maramche, Kaski province, Nepal, 2003).

b). Low altitude site

The field study sites, representative of the tropical and subtropical lowland area of the Terai were selected in Chitwan province. The four field sites were located at 27°37' N latitude and 84°25' E longitude with an elevation of 240-260 meter above sea level. The climate is warm subtropical with dry winter and a monsoon-influenced warm and humid summer season. The monthly rainfall gradually increased from 101 mm in April to 930 mm in July. The total annual rainfall of 2600 mm is concentrated in the period between May and October. The temperature ranges from 33.7-35.5°C in summer and 19.7-25.4°C in winter with a mean annual temperature of 28.6°C. The relative humidity exceeds 85% in summer and drops to 51% during the winter season. The site was under continuous rice-wheat rotation more than 10 years. The cultivation period for lowland rice is between July and November and that of wheat is between December and April. Between the harvest of wheat and transplanting of lowland rice lies a relatively long DWT of 10-12 weeks during which the land lies fallow in the traditional rice-wheat production system of the region. The average monthly temperatures and rainfall of the experimental site are presented in Figure 3.

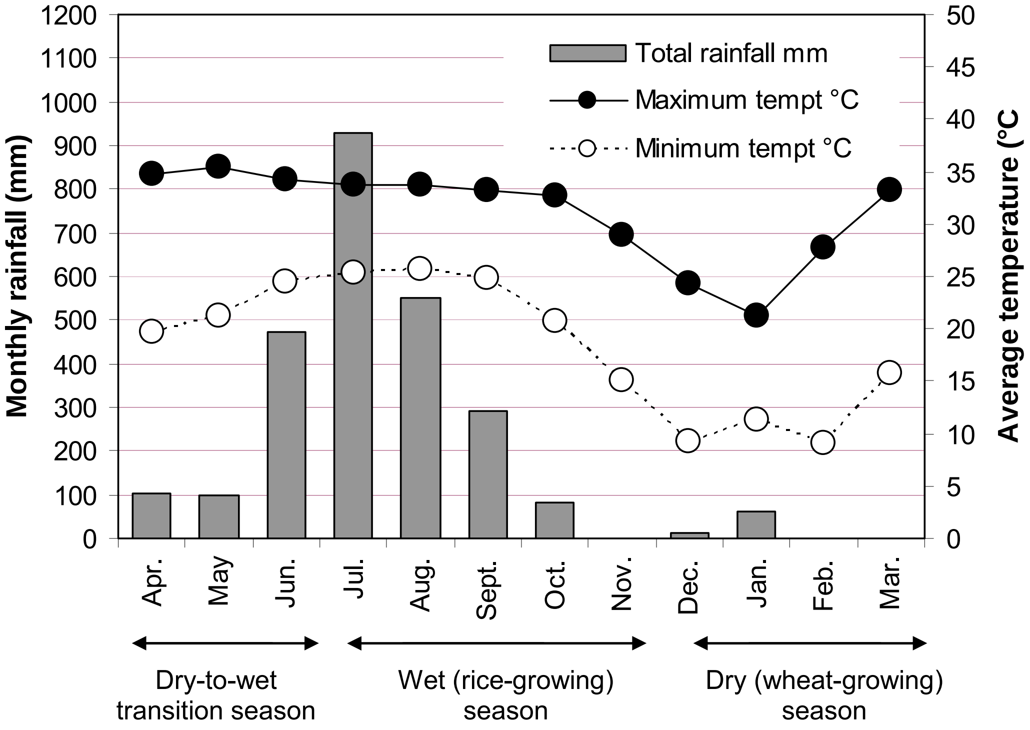

Figure 3. Monthly rainfall and mean maximum-minimum temperatures at the lowland field site in Nepal (field experiment, Rampur, Chitwan province, Nepal, 2003).

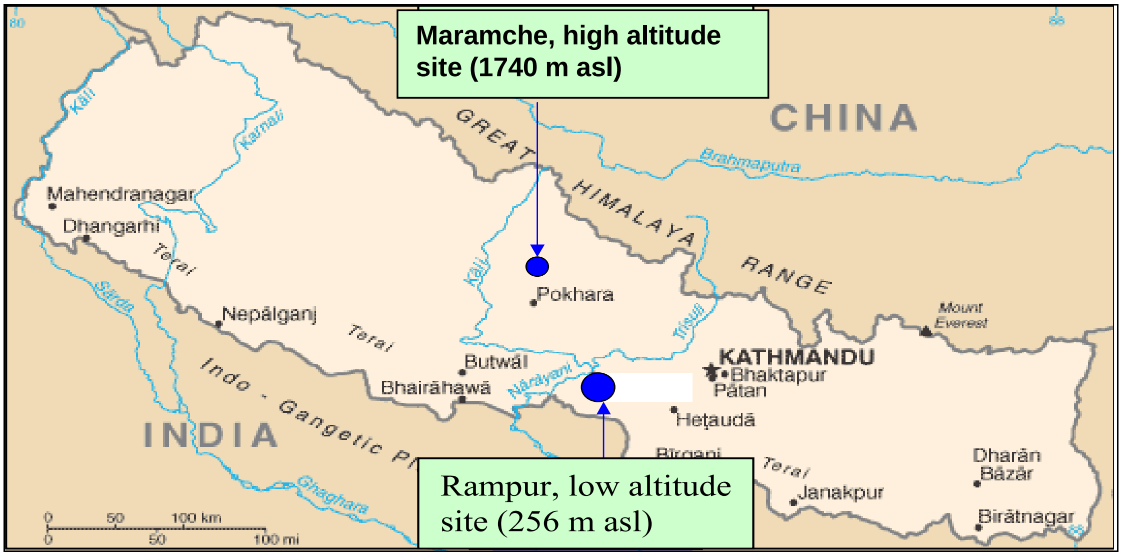

Plate 1. Location of the experimental field sites in Nepal.

3.2. Experimental soils

Soils at the experimental field sites of Kaski, high altitude as well as Rampur-IAAS and the three farmers fields of Rameshwor, Hari and Kopila (Chitwan, lowaltitude) are classified as sandy loam Ultisols (Tropaquult) with similar textural class (sandy loam soil). The pH is more acidic at the high altitude (pH 4.4) than at low altitude sites (pH 6.1-6.8). The soils of the low altitude sites contained less organic carbon (1.1-1.5%) and N (0.1%) than of the high altitude site, where soil organic carbon exceeded 3% and N content was 0.43%. The soil used in the greenhouse experiment was collected from the unfertilized control plots (0-20 cm) of Meckenheim, Germany. It contained 6.9% sand, 77.1% silt and 16% clay and with 1.29% of organic matter. The soil was shade dried ground and sieved to 2 mm to use for pot experiment in the greenhouse. The characteristics of the experimental soils used for the pot experiment in the greenhouse at Bonn and field experiments at different rice-wheat growing field sites of Nepal are presented in Table 1.

Table. 1. Physical and chemical characteristics of experimental soils.

Soil parameters	----------------------On-farm--------------------			On-station	Greenhouse
	Rameshwor (Terai)	Hari/Kopila (Terai)	Lumle (Mid-hills)	Rampur* (Terai)	Meckenheim (Germany)
Soil class (USDA)	---------------------------Ultisol (typical Tropaquult)----------------------------				Inceptisol
Soil texture	Sandy loam	Sandy loam	Sandy loam	Sandy loam	Silt loam
Sand (%)	77.4	69.4	50.9	70.4	6.9
Silt (%)	9.0	14.0	39.5	14.0	77.1
Clay (%)	13.6	16.6	9.6	15.6	16.0
pH	6.1	6.1	4.4	6.8	6.2
Total N (%)	0.1	0.1	0.4	0.1	0.1
Organic C (%)	1.3	1.1	3.8	1.5	0.7
Bulk density (g cm^{-3})	1.35	1.48	1.45	1.38	1.08

Khakural et al., 1984.

3.3. Plant material

3.3.1. Lowland rice (*Oryza sativa* L.)

The lowland rice variety Masuli was selected for both on-station and on-farm experiments. It was a semi-dwarf, medium duration (145 days), improved rice variety commonly grown by farmers in Nepal. Seeds were obtained from the agronomy farm of the Institute of Agriculture and Animal Science (IAAS) Rampur. Seeds were pre-soaked for 24 hours in water before seeding in a nursery seedbed. Freshly uprooted, 21-day-old seedlings were transplanted at 20x20 cm spacing with three seedlings per hill in the puddled, flooded soil.

3.3.2. Wheat (*Triticum aestivum* L.)

The improved wheat variety BL 1724 was row-seeded immediately after harvesting of rice in November at a rate of 120 kg ha^{-1}. It is commonly recommended for use in lowland fields (rice-wheat rotation) in Nepal. Seeds were obtained from IAAS, Rampur. The straw was cut at ground level and after threshing the grain was stored for analysis and further use.

3.3.3. Dry-to-wet season transition period crops

a).Mucuna (*Mucuna puriens* var *utilis* L)

The green manure *Mucuna puriens* var *utilis* L. is one of the legumes grown during the DWT. Mucuna is a broad-leaved, fast-growing green manure that was traditionally used as a minor vegetable in Nepal and Northern India. Because of its fast growth and rapid canopy development, it was introduced in Africa as a weed suppression crop. Seeds were obtained from CIEPA germplasm exchange program IITA, Benin and multiplied in Nepal. Mucuna was seeded at a spacing of 40x30 cm spacing.

b). Mungbean (*Vigna radiata* L.)

Another legume selected to grow during DWT was a green-seeded local mungbean variety. It is a grain legume commonly grown in Nepal. Seeds were obtained from the National Grain Legume Development Program (NGLIP), Rampur and seeded at a 40x5 cm spacing at 3 seeds per hill.

c).Maize (*Zea mays*)

The yellow seeded 90 days composite variety Arun-2 was selected as a non-N_2 fixing plant to grow during DWT and to serve as a reference to determine atmospheric N_2 fixation by the legumes ($\delta^{15}N$ dilution method). Seed was obtained from the National Maize Development Programme (NMDP), Rampur and seeded at 40X20 cm spacing at two seeds per hill.

3.4. Soil and plant analyses

3.4.1. Plant analysis

The above ground plant biomass was cut at the ground level and dry matter was determined based on 1 m^2 harvest areas of each field plot at the end of DWT. Sub-samples of 100g fresh matter were oven dried at 70°C for 48 hrs until constant weight. Dried material was rough ground (<2 mm) and a sub-sample of one gram was fine ground (<0.1 mm) for further chemical analysis. The total N was determined by micro-Kjeldahl procedure and ^{15}N was analysed using mass spectrometry (ANCA SL coupled to 20-20 stable isotope analyser IRMS, Europa scientific/ PDZ now Sercon Ltd., UK). The natural abundance of the staple isotope ^{15}N was determined in fine ground plant samples using the method described by Shearer and Kohl (1980) with

$$\text{o/oo } \delta 15 \text{ N excess} = \frac{\text{atom } \%\delta^{15}\text{N sample} - \text{atom } \%\delta^{15}\text{N atmosphere}}{\text{atom } \%\delta^{15}\text{N atmosphere}}$$

The share of biological nitrogen fixation was calculated as,

$$\text{Ndfa } \% = 1 - \frac{\delta^{15}\text{N excess in the sample}}{\delta^{15}\text{N excess in the reference plant } + \beta} \text{ X } 100$$

The β-values for natural discrimination against ^{15}N were taken from Becker and Johnson (1998).

3.4.2. Soil chemical analysis

Soil samples of about 40 g (dry weight) were extracted with 100 ml of 2M KCl after shaking for two hours at 100 r.p.m. The extraction solution was filtered and the filtrate was stored at 4°C for further analysis. Ammonium and nitrate in soil extracts were determined colorimetrically using an EC standard Autoanalyser III, Bran+Luebbe, Norderstedt, Germany. A fresh soil sample of about 20 g was oven-dried to determine the soil moisture content.

a).Resin analysis

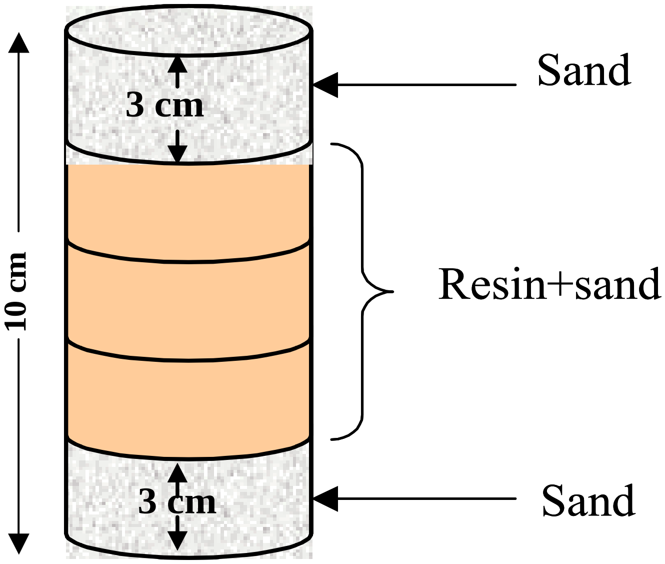

Figure 4. Schemaitic presentation of the ion exchange resin cores used to dertermine cummulative nitrate leaching from soil (field experiments, Nepal, 2003).

The amount of NO_3-N leached from the topsoil during a given season (DWT, wet and dry season) was determined in mixed ion-exchange resin cores containing three resin bags in each core and placed at 30 cm depth. The core was a cylindrical PVC tube of 6 cm diameter and 10 cm height, closed by a nylon mesh on one side. It was filled with 60 g of ion exchange resin mixed with 60 g of the washed sand and sandwiched between layers of 3.0 cm of washed sand. Industrial grade mixed-bed anion and cation exchange resin (Rohm and Haas, France, SAS) with a density of 0,8 $g.cm^3$, was used for the experiment. Sand was obtained from the nearest river Narayani and was washed with water to remove the clay portion, dried, sieved (5 mm) and finally washed in 0.5 M HCl and dried before use. The sand-resin mixture divided into three parts and filled in nylon bags and inserted in the PVC cores (Fig. 4). Both ends of the core was filled by cleaned sand and closed by nylon clothes. Three cores per plot were buried in the soil at equidistance from the centre at a depth of 30 cm. Each core was placed vertically 15 cm far from the inner wall of the hole made in the soil to install the resin cores.

At the end of each cropping season, one core from each plot was taken out from the soil. The cores taken from each plots were well labelled and dried. To reduce the experimental error, resins from the upper two bags of each core were combined and the resin was separated from the sand by sieving. Ten-gram resin was sub-sampled from each composite sample and extracted for N_{min}. Twenty millilitres of 0.05N sulphuric acid was added to 10g of resin and shaken for 30 minutes. After 10 minutes of decantation, the supernatant was collected and another 20 ml H_2SO_4 was added and shaken again for 30 minutes. The process was repeated three times to obtain a total volume of 60 ml. The nitrate content in the supernatant was analysed colorimetrically by auto analyzer (Autoanalyser III, Bran+Luebbe, Norderstedt, Germany). Analyses were done in the Institute of Plant Nutrition at the University of Bonn.

b). Microbial biomass analysis

The effect of straw amendment on temporary immobilization of soil N_{min} (NO_3-N +NH_4-N) in the microbial biomass was quantified using the chloroform fumigation technique (Jenkinson and Powlson, 1976). Two soil samples of 10 g dry weight were taken from each treatment and initial N_{min} was removed by extracting with 50ml of 0,05M K_2SO_4. Thereafter, one sample was extracted with 50ml of 0,05M K_2SO_4 and the remaining sample was fumigated in chloroform for 24 hours and subsequently extracted with 50ml of 0,05M K_2SO_4 after shaking for 45 minutes at 100-110 r.p.m. The N_{min} content in the extracts of both fumigated and unfumigated (control) samples were determined colorimetrically by using Autoanalyser. The difference in N_{min} of fumigated and non-fumigated samples was assumed to be microbial N.

3.5. Gas analysis

Nitrous oxide emitted from soils during the DWT was measured in three times replicates. Nine polythene chambers with 19 cm diameter and 24 cm height were installed for gas collection in the field plots. Two small holes were made at the bottom of each chamber. A soft rubber stopper was fitted in one hole and the other hole remained open until 2 minutes after the installation of the chamber in the plot. This hole served to equalize the initial air pressure differences between inside the chamber and the atmosphere. In each plot, one chamber was installed (Plate 2).

Plate 2. Installation of gas collection chambers in the field plots (on/station field experiments, Rampur, Chitwan province, Nepal, 2003).

Both at regular bi-weekly intervals as well as after each rainfall event, gas collection chambers were installed and two gas samples were taken in each sampling. The initial sample was taken just after installation of the chamber and next after 2 hours. A syringe of 50 ml volume was used to take the gas from the chamber and to fill in the glass vials of 20 ml volume. The sampled gas was filled in the glass vials using double displacement method. The gas filled vials were properly labelled and stored at room temperature before analysis. The same procedure was used in the pot experiments in the greenhouse. Here, the gas collection chambers covered the whole space of the pot. The gas was collected in pre-evacuated glass vials of 20 ml volume and stored at room temperature before analysis.

Sub-samples collected from each chamber in 20ml vials were brought to Germany and analyzed for N_2O by gas chromatography (SRI [Torrance, CA] 8610C) with a back flush system to eliminate water vapour and on an electron capture detector (ECD) for N_2O. The gas chromatograph was operated at a column temperature of 40°C, an ECD temperature of 320°C, and gas flow rates (nitrogen 5.0) were adjusted to 35 ml min^{-1} for the carrier gas and 6 mL min^{-1} for the ECD makeup gas. N_2O emission was expressed as µg m^{-2} h^{-1}.

3.6. Soil moisture determination

The soil moisture was measured at regular bi-weekly interval during both DWT and wheat growing dry period by using Time Domain Refractometer (TDR). The TDR used was a Trime FM 2 (IMCO GmbH, Ettlingen, Germany). TDR probe was inserted at a depth of 10 cm and soil moisture of 0-10 cm was determined by taking average of 5 reading in each plot.

3.7. Treatment application

The treatments applied during the dry-to-wet season transition period in the greenhouse and in the field (on-farm at high altitude site, on-station at low-altitude site and on-farm at low altitude site) are described separately.

3.7.1. Greenhouse experiment

The management treatments applied during the dry-to-wet season transition period to the potted soil in a climate controlled greenhouse included four types of crops and four types of wheat straw management. Crop management options comprised the bare fallow control and three different transition season crops, namely mucuna, mungbean and maize. Wheat straw management comprised 3 levels of straw application (0, 1.5 and 3.0 Mg ha^{-1}) at two application strategies (incorporation, surface mulching). The crop management options were evaluated in 2001 and while straw management options were compared in 2003.

a).Crop management

To study soil N dynamics and the atmospheric N_2 fixation by legumes grown during the dry-to-wet season transition period in the potted soil in the greenhouse under controlled temperature and moisture conditions, bare fallow (control), mucuna, mungbean and maize were arranged in a Complete Randomized Block Design (RCBD) in four replications.

Sixteen experimental pots of 10 litre volume and 22 cm diameter were connected with leachate collection tubes and filled each with 8 kg of Meckenheim topsoil (0-

20cm). The leachate collecting pipes were opened while the soil was initially flushed with de-ionized water for 36 hrs to remove nitrate before the beginning of the experiment. After water soaking for 6 hrs, four seeds each of mucuna, mungbean and maize were placed in each drained pot (12 hrs after flushing). Gap filling was done after 7 days using seedlings of the same age. Seven days after seeding, legume seedlings were inoculated with one millilitre of rhizobium inoculums solution prepared from about 10 g of fresh nodules crushed in 100 ml of distilled water. Soil samples were taken before seeding of the transition season crops (initial sample) and at 15-days intervals thereafter composites of three small auger samples of about 25-40 g of fresh soil, which were stored at 4 °C until further analysis.

b). Straw management

To study the dynamics of the native soil N, N_2O emission and to quantify the role of a temporary N immobilization in the soil microbial biomass after application of a crop residue with a high C:N ratio (wheat straw), a pot experiment was conducted in the tropical greenhouse of the Institute of Plant Nutrition, University of Bonn, Germany in 2003. Treatments included the unamended control and the use of wheat straw at 1.5 and 3.0 Mg ha^{-1} using two methods of application, surface mulching and incorporation. As in the crop management experiment, the soil was flushed to remove NO_3-N before filling 20 experimental pots of 5-litre volume and 12 cm diameter with 3 kg of soil. Wheat straw was chopped into 2 cm segments and applied at 1.5 or 3.0 Mg ha^{-1} either as surface mulch or incorporated into the soil. Soil moisture was gradually increased as described in chapter 3.1. Soil samples were taken at bi-weekly intervals for N_{min} and soil microbial biomass N.

3.7.2. Field experiment

a).Straw management at the high altitude site

The findings of the greenhouse experiment on straw management were validated in farmer’s fields at the high altitude research site at Maramche. Treatments included three levels of straw with two application methods as follows:

- bare fallow control
- 1.5 Mg ha^{-1} wheat straw incorporated
- 1.5 Mg ha^{-1} wheat straw mulched

- 3 Mg ha^{-1} wheat straw incorporated
- 3 Mg ha^{-1} wheat straw mulched.

All treatments were replicated 4 times in a completely randomized block design (RCBD). Well-dried and chopped (2 cm in size) wheat straw was applied in the field at the beginning of the DWT on 2nd week of April. Soil samples were taken at 15-days intervals during the DWT of 2003 and stored at 4°C for N_{min} analysis. After soil saturation at the onset of the monsoon rains, 21-day-old rice seedlings were transplanted in the puddle field plots of 5x4 m in the 1st week of June at the rate of 3 seedlings per hill. Individual irrigation and drainage facilities were provided for each plot. Plots were hand weeded 6 and 12 weeks after rice transplanting and rice was harvested at full maturity stage in the 2nd week of November.

Treatment effects on the N nutrition of the succeeding crops of rice and wheat were evaluated by total N uptake at harvest and the grain yield of rice and wheat.

b). Crop and straw management at the low altitude site

A series of field experiments was conducted in 2001 and 2003 on the experimental farm of the Institute of the Agriculture and Animal Science of the Tribhuvan University as well as in three farmers' fields (2003) in Chitwan province, Nepal. Eight treatment combinations were applied during the DWT and evaluated during the rice-growing and the wheat-growing seasons of 2001 and 2003. Field experiments had to be discontinued in 2002 due to the political situation in the country. Hence, comprehensive data sets are limited to DWT and the rice-growing season of 2001 and to the DWT, the rice and the wheat-growing seasons of 2003.

Treatments applied during DWT included the bare fallow control, fallow+straw, maize, maize+straw, mungbean, mungbean+straw, mucuna and mucuna+straw. They comparatively evaluated the use of a non-fixing cereal and of N_2-fixing grain and green manure legumes, solely or in combination with the application of wheat straw at a rate of 2 Mg ha^{-1}. Treatments were randomized (CRBD) in four replications. The plot size was 5mx4m. Each plot was provided with individual irrigation and drainage facilities. All plots received a basal dose of P and K at a rate of 20 kg ha^{-1} as Triple Super Phosphate and Muriate of Potash (KCl) respectively. The DWT crops were seeded in the respective plots on 22nd March in 2001 and 1st April in 2003. One day before seeding the DWT crops, three resin cores were installed at a depth of 30 cm to determine the amount of nitrate leached from the topsoil. Plants germinated within 10 days and gap filling was performed at 15 days after seeding. At 15-day intervals, soil samples were taken from alternate inter-plant spaces as composites of 8 sub-samples. Each freshly sampled soil samples were extracted with 2M KCl and stored in a refrigerator until further use. On June 18, 2001 and June 27, 2003 (90 days after seeding), the transition season crops were harvested.

Fresh biomass was determined from a 1 m^2 area at the centre of each plot and dry matter was determined after oven drying sub-sample of 100 g fresh matter at 70°C for 48 hrs. Twenty grams of dry biomass were ground for total N and ^{15}N analysis.

At the end of the transition season maize cobs and grain legume pods were harvested and the stover produced during the 90-day long DWT was incorporated in the respective plots. As in the pot experiment, after *in situ* recycling of the DWT crop residues, 21-day-old rice seedlings were transplanted in the puddle field plots on 1st week of July at the rate of 3 seedlings per hill. Soil samples were taken at 15-day intervals to evaluate the mineralization of the recycled crop residues. Composite soil samples of 25-40 g were taken from each plot using aluminium tubes and stored at 4°C for soil N_{min} (NH_4-N and NO_3^--N) analyses (Chapter 3.4.2.). Plots were hand weeded 6 and 12 weeks after rice transplanting and rice was harvested at full maturity stage on 10th November 2003. Grain and straw yield were determined from a central 2 m x 3 m harvest area and reported at 14% grain moisture. The N uptake by rice grain and straw was determined at harvest. Treatment effects on the N nutrition of the succeeding crop of rice were evaluated by the N uptake at harvest and the grain yield.

Winter season wheat was sown after harvesting summer season rice on 10th November in 2003. At full maturity, wheat was harvested on 14th March 2003. Grain and straw yields were determined from a central 2mx3m harvest area. The grain weight was reported at 14% moisture and the N uptake by wheat grain and straw were determined analysing respective dried and ground samples.

Treatments included for the on-farm at the low altitude sites were the same as described for the on-station experiment. The DWT crops were seeded in first week of April (April 1-6, 2003) and harvested in the last week of June (June 25-29, 2003).

The atmospheric N_2 fixation by legumes and the total N uptake at harvest were determined at a plant age of 90 days. Mungbean pods and maize cobs were removed and the remaining crop residues were incorporated into the respective plots. Nitrate leaching from the topsoil (0-10 cm) was determined by ion-exchange resins placed at 30 cm depth. After *in situ* recycling of the DWT crop residues, rice was transplanted at 3 seedlings per hill at a 20x20 cm spacing in the 1st week of July in the puddled soil. Rice was harvested at full maturity stage in the 2nd week of November. Treatment effects on the succeeding crop of rice were evaluated N uptake and grain yield at harvest.

3.8. Data analysis

Data were subjected to analysis of variance. Mean separation was done by Duncans Multiple Range Test (DMRT), using SPSS 10.0 for Windows. Microsoft Excel and Sigma Plot were used to prepare graphs.

4. Results

This chapter describes the outcome of the experiments that were conducted under controlled conditions at the University of Bonn and under field conditions in Nepal with the objective to study the soil N dynamics under traditional and “improved” land management. Series of pot experiments were conducted in the tropical greenhouse of the University of Bonn, Germany and field experiments were conducted at various rice-wheat growing field sites in Nepal. On-station experiments were conducted at the experimental farm of the Institute of Agriculture and Animal Science in Chitwan province and on-farm experiments were conducted in four farmers’ field at a high altitude site in Maramche, Kaski province and three farmers’ fields at low altitude field sites in Chitwan province, Nepal.

4.1. Management of soil N-dynamics in the greenhouse

The climatic conditions (temperature, soil moisture and day length) of the dry-to-wet season transition period (DWT) encountered in subtropical rice-wheat sites of Nepal were simulated in a greenhouse, where pot experiments in the native soil N dynamics under different levels of straw and crop management options were studied.

4.1.1. Effects of straw management during the transition season

a).Soil N dynamics during DWT

The gradual increase of soil moisture from 50% field capacity to full water saturation of the pore space affected differently on the amount of NO_3-N and NH_4-N in the soil.

The NH_4-N content in the bare soil initially decreased from 94 to 0.01 mg kg^{-1} soil with gradual increase of soil moisture up to 75% field capacity (FC) possibly a result of the oxidation of ammonium to nitrate during the aerobic soil phase. As soil moisture exceeded 75% field capacity (FC), the exchangeable ammonium (NH_4-N) increased again and reached to a maximum of 14.7 mg kg^{-1} soil at soil flooding. A reverse pattern was observed in the case of nitrate (NO_3-N). The soil NO_3-N gradually increased with increasing in soil moisture. It reached a peak of 47.5 mg kg^{-1} soil at 75% field capacity (FC) and rapidly declined to 0.1 mg kg^{-1} soil upon soil flooding (Table 2).

Table. 2. Soil N_{min} (mg kg^{-1} soil) during the dry-to-wet season transition period as affected by straw management treatments applied in the potted soil in the tropical green house of the University of Bonn, Germany, 2003.

Soil moisture	Straw management treatments				
	No straw	1,5* Mg ha^{-1} Mulch	1,5 Mg ha^{-1} Incorporation	3,0 Mg ha^{-1} Mulch	3,0* Mg ha^{-1} Incorporation
---NO_3-N (mg kg^{-1} soil)---					
Initial	3.7a***	3.1a	3.0a	3.8a	3.8a
50%FC**	43.4a	27.4b	30.2b	26.1b	19.9b
75%FC	47.5a	40.5a	32.6b	32.5b	25.2c
Flooding	0.1a	0.1a	0.1a	0.1a	0.1a
---N (mg kg^{-1} soil)---					
Initial	94.4a	75.2a	95.8a	74.1a	69.9a
50%FC	53.2a	52.1a	61.8a	53.3a	58.6a
75%FC	0.1a	0.1a	0.1a	0.1a	0.1a
Flooding	14.0b	14.7b	22.3ab	19.8b	34.6a

*1.5 and 3.0 Mg ha^{-1} were the amount of straw applied in the potted soil.
**FC indicates field capacity
***Values follow by the same letter within one row do not differ significantly by DMRT (0.05).

The rapid decline in NO_3-N at soil flooding could be the result of anaerobic microbial respiration (denitrification). The application of coarsely ground wheat straw in the potted soil reduced the build up of NO_3-N in the soil. The extent of this effect increased with straw application rate (nitrate peak of only 25 mg kg^{-1} soil) and tended to be more when straw was incorporated than when same straw was applied as surface mulch (on average 8 ppm less nitrate kg^{-1} soil when straw was incorporated than when straw was surface mulched). Possible implications of a reduced amount of availed soil mineral nitrogen (N_{min}) may involve in increased N mineralization in the soil microbial biomass pool and a reduced potential for N losses to occur.

b). N_2O emission

In potted soil in the greenhouse, a step-wise increase in soil moisture content resulted in a first step in the build-up of a soil nitrate-N peak of 48 mg N kg^{-1} soil (75% field capacity) and the subsequent near complete disappearance of nitrate upon soil flooding. This nitrate-N disappearance was associated with a peak in nitrous oxide emissions (denitrification) of up to 11 µmol N_2O m^{-2}. The application of the straw from a preceding crop of wheat significantly reduced the soil nitrate-N peak by 30-50% compared to the unamended control (bare fallow). The reduction in available soil N_{min} increased with straw application rate (higher the amount of straw applied more was the immobilization) and was more with straw incorporation than when the straw was applied as surface mulch. This reduction was associated with a parallel increase in the amount of soil microbial biomass N (Fig. 6) and a 20-35% reduction in the emission of nitrous oxide (Fig. 5), both from the processes of nitrification (at around 75% field capacity) and denitrification (at the onset of soil flooding). Straw-induced soil N_{min} immobilization in the microbial biomass and reduction in N losses (denitrification) increased with the duration of the transition season from 4 to 8 weeks and benefited a subsequent crop of lowland rice. The dry biomass and the N accumulation by 10 week-old rice tended to be more with straw amendment than in the unamended control (bare fallow). This effect was not significant when straw was incorporated as N immobilization may have persisted when larger amounts of straw were applied. It may be concluded that the use of wheat straw presents a feasible option to reduce native soil N losses during the dry-to-wet season transition period in rice-wheat rotation systems. The effectiveness of straw management in conserving native soil N increases with application rate and the length of the transition season and is more with straw incorporation than with straw mulching.

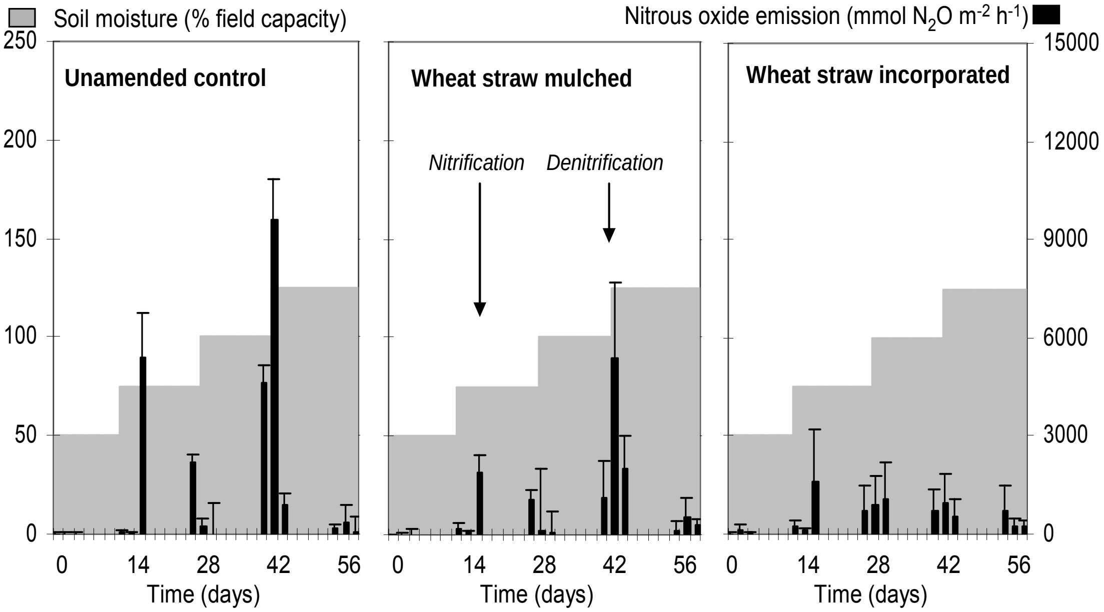

Figure 5. Effects of straw management (bare soil control, 3 Mg ha^{-1} applied as surface mulch and 3 Mg ha^{-1} incorporated) on the nitrous oxide emissions from potted soil during a simulated 8 weeks long dry-to-wet season transition period (step-wise increase of soil moisture from 50, 75 and 100% field capacity to water saturation). Pot experiment, Bonn, Germany, 2003. Bars represent standard errors of the mean (n=3).

c).Soil microbial biomass

The soil microbial biomass N in the bare soil ranged from 0.4 to 2.4 mg kg^{-1} soil. The largest amount of soil microbial biomass N (4.8 mg N kg^{-1} soil) was observed with incorporation of 3.0 M g ha^{-1} wheat straw and was significantly (P=0.05) more than with surface mulching (3.2 mg N kg^{-1} soil). The largest microbial biomass N of 2.4 mg N kg^{-1} soil was observed in the bare fallow control of at 75% FC. Soil incorporation of wheat straw may provide more energy substrates and larger surface area to microbial population to access to the substrates for decomposition. Both at soil flooding and at less than 50% soil moisture, the observed microbial biomass N was lower. Both moisture conditions would not be favourable for the microbial growth (Fig. 6). The effectiveness of straw management in conserving native soil N increased with application rate and was more in incorporation than surface mulching. Straw-induced soil N_{min} immobilization in the microbial biomass may explain the observed reduced N losses.

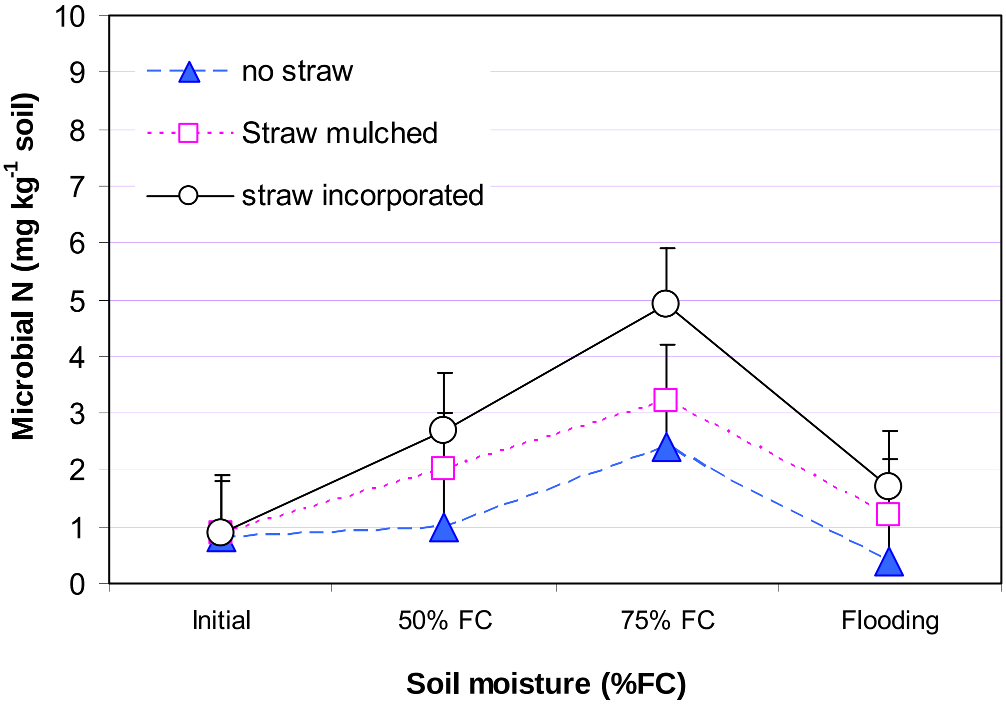

Figure 6. Soil microbial biomass N as affected by wheat straw application (3 mg ha^{-1}) to potted soil in the greenhouse (pot experiment, Bonn, Germany, 2003). Bars present the standard error of the mean (n=4).

d). Rice N uptake under flooded condition

Application of wheat straw during DWT affected the N uptake of the succeeding crop of rice. Straw induced soil N_{min} immobilization in the microbial biomass and reduced N losses by which may benefit lowland rice. In the bare fallow control plots, the observed biomass and N accumulation by 10 week-old rice plants were 13.1 g pot^{-1} and 333 mg pot^{-1} respectively. In the plots where straw was incorporated, the dry biomass of rice ranged from 12.5 to 12.8 mg pot^{-1} with the total N uptake of 314 to 321 mg pot^{-1}. The highest dry biomass (13.2 mg pot^{-1}) and N accumulation (341 mg pot^{-1}) was observed when straw was mulched at a rate of 3 Mg ha^{-1} (Fig.7). However, the effect of straw application on dry biomass and N uptake by rice did not differ significantly.

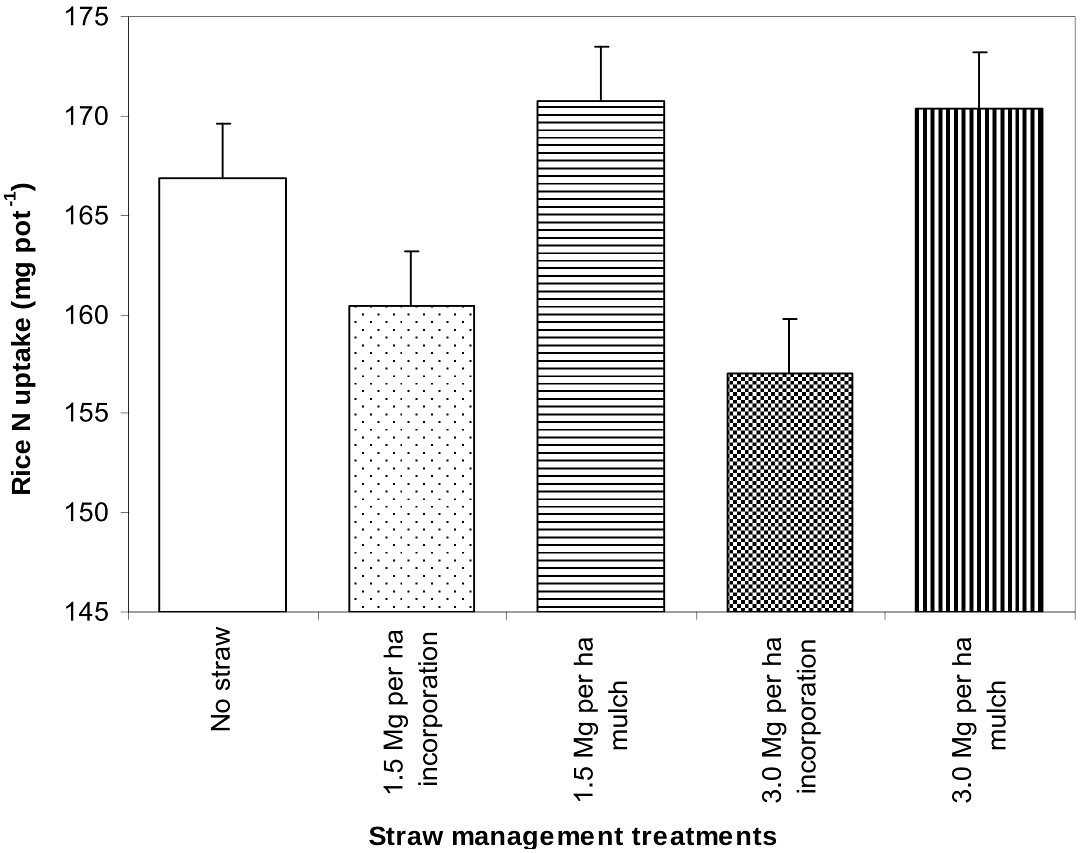

Figure 7. Soil N uptake by 8 week-old transplanted rice as affected by different rates and methods of straw application in the greenhouse (pot experiment, Bonn, Germany, 2003). Bars present the standard error of the mean (n=4).

4.1.2. Effect of crop management during the transition season

a).Soil N dynamics under different crop management options

An increase in soil moisture from 25% FC to complete soil submergence differently affected the amount of N_{min} in potted soil. The NH_4-N content in bare soil initially decreased from 7.4 to 0.7 mg kg^{-1} soil at 75% FC, possibly the result of microbial oxidation of NH_4-N to NO_3-N. Upon soil submergence, NH_4-N increased to 9.0 mg kg-1 soil possibly the result of enhanced mineralization of organic residues present in the soil. Six weeks after seeding, the amount of NH_4-N gradually decreased from 5.5 to 0.8 in mucuna, from 6.5 to 0.9 in mungbean and from 5.3 to 0.6 mg kg^{-1} soil in maize. This decline in N_{min} was associated with N uptake by the growing crops and its immobilization in the plant biomass. Thereafter, NH_4-N gradually increased in all treatments, possibly as the result of the mineralization of dead tissues and leaf litters.

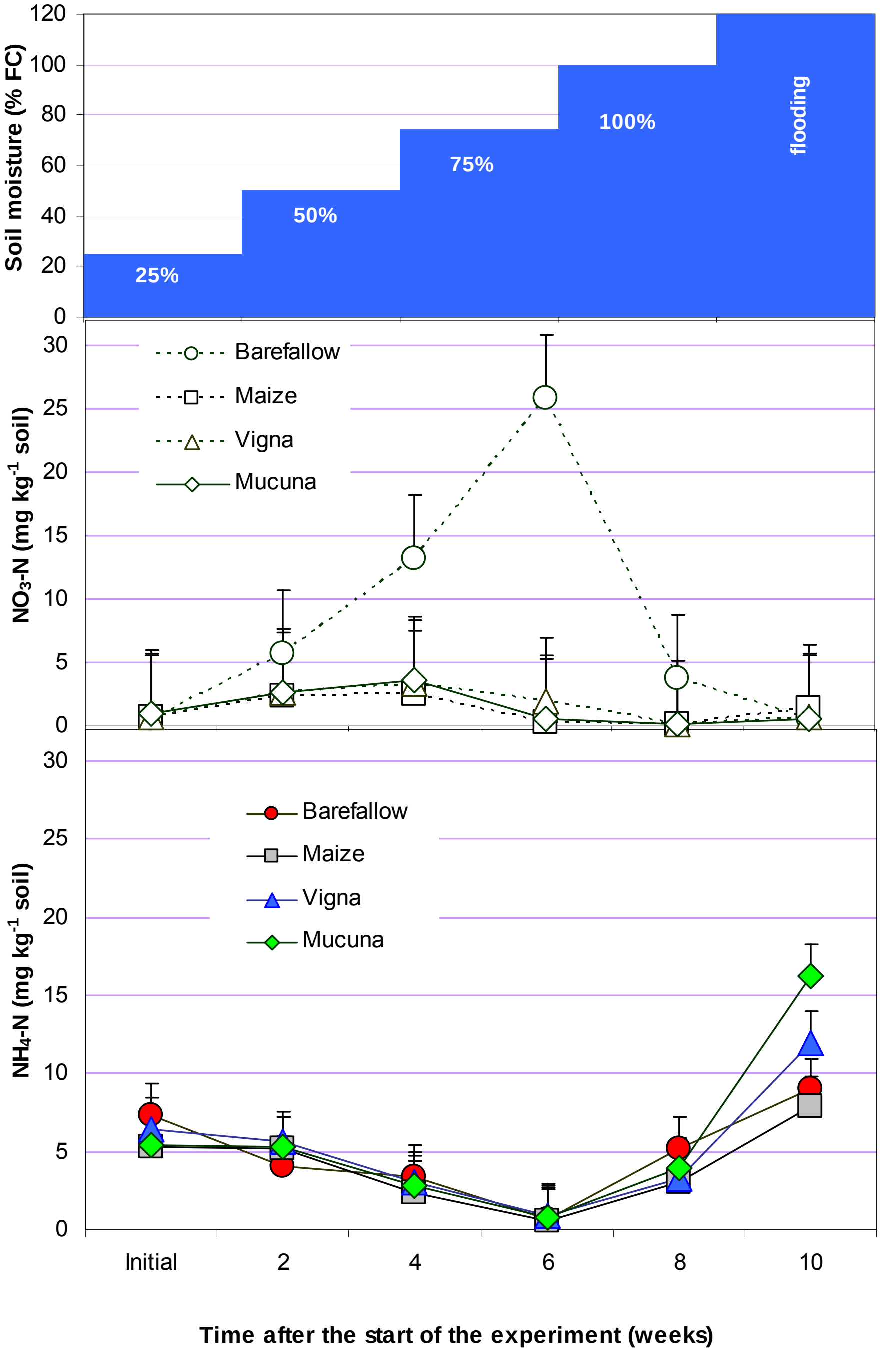

Figure 8. Dynamics of exchangeable soil nitrate and ammonium during the simulated dry-to-wet season transition period as affected by soil moisture and different crop options applied in the potted soil (greenhouse experiment, Bonn, Germany, 2001). Bars present standard error of means (n=4).

A reverse pattern was observed in the case of NO_3-N which gradually increased and reached a peak of 25.8 mg kg^{-1} soil at about 75% FC and rapidly declined thereafter, probably as the result of microbial respiration (denitrification). This trend of initial increase and subsequent rapid decline of extractable nitrate was generally observed but it’s extent varied by treatments. Growing crops (mungbean, mucuna and maize) during DWT reduced the NO_3-N peak to 3.0 mg kg^{-1} soil. Upon soil submergence, all NO_3-N disappeared, possibly the result denitrification caused by microbial respiration (Fig. 8).

b). Nitrogen assimilation by transition season cops

Crops grown during DWT in Nepal can typically be differentiated into non-N_2-fixing crops (exemplified by maize), N_2-fixing grain legumes (exemplified by mungbean) and green manures (exemplified by mucuna). The crop N uptake during the 10 weeks DWT can thus be ascribed to the assimilation of soil N_{min} (all crops) and the assimilation of N derived by the process of biological N_2 fixation from the atmosphere (mucuna and mungbean). Depending on the crops, the N accumulation varied between 700 and 1800 mg N pot^{-1}.

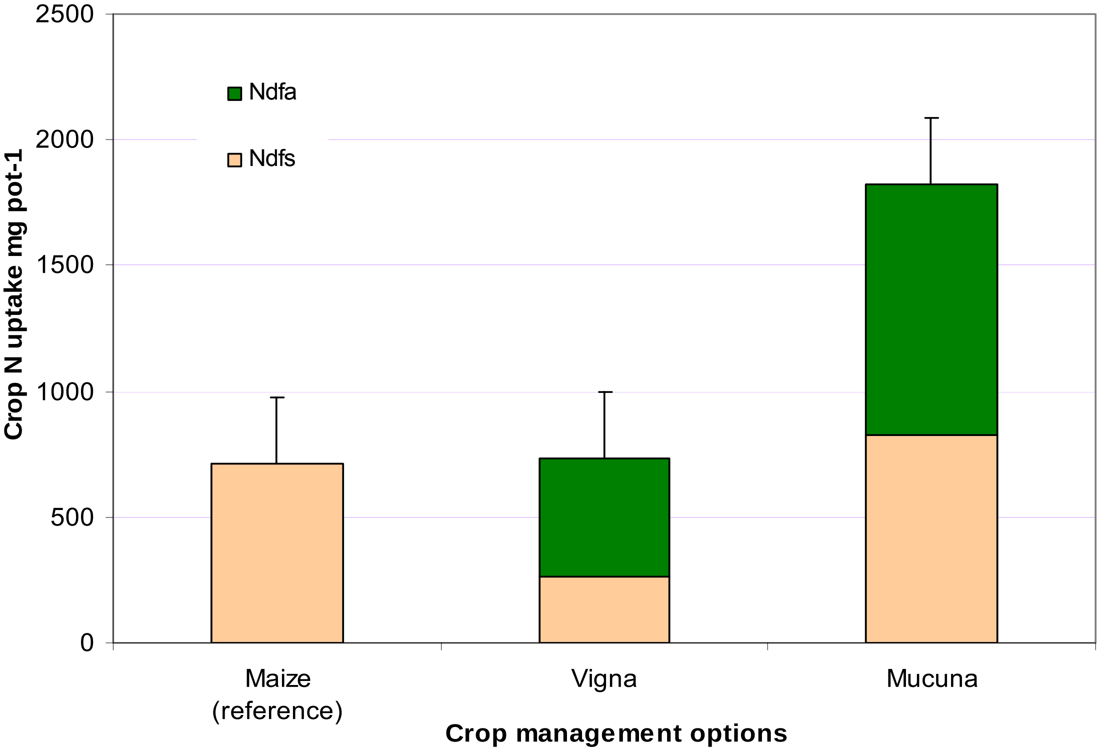

Figure 9. Total N uptake and share of N derived from the soil (Ndfs) and biological N_2 fixation (Ndfa) by dry-to-wet transition season crops in the greenhouse (pot experiment, Bonn, Germany, 2001). Bars present standard errors of the mean (n=4).

The N accumulation by maize can be ascribed exclusively to N uptake from the soil and hence, linked to the soil NO_3-N depletion. On the other hand, mungbean and mucuna derived the in their biomass from both soil N_{min} and from the atmosphere (Ndfa) via biological nitrogen fixation. The highest amount of 1820 mg N pot^{-1} in the above-round biomass was observed with mucuna and was significantly (P=0.05) higher than the N accumulation by mungbean (731 mg pot^{-1}). However, the share of atmospheric N by mungbean was 9% higher (64% of total N accumulation) than that of mucuna (55% of total N accumulation). Most of the soil N accumulation by mucuna was likely to be from the nitrate fraction, which was continuously depleted with mucuna growth. Growing mucuna during DWT may be a promising option to recycle soil NO_3-N which may otherwise be loosed, while adding substantial amounts of biologically fixed N (Fig. 9).

c).Soil N dynamics under flooded conditions and N uptake by rice

The biomass of the crops grown during DWT was incorporated into the potted soil and the N_{min} dynamics (NH_4-N only) were studied during a 10 week-long anaerobic soil phase in the presence of transplanted lowland rice.

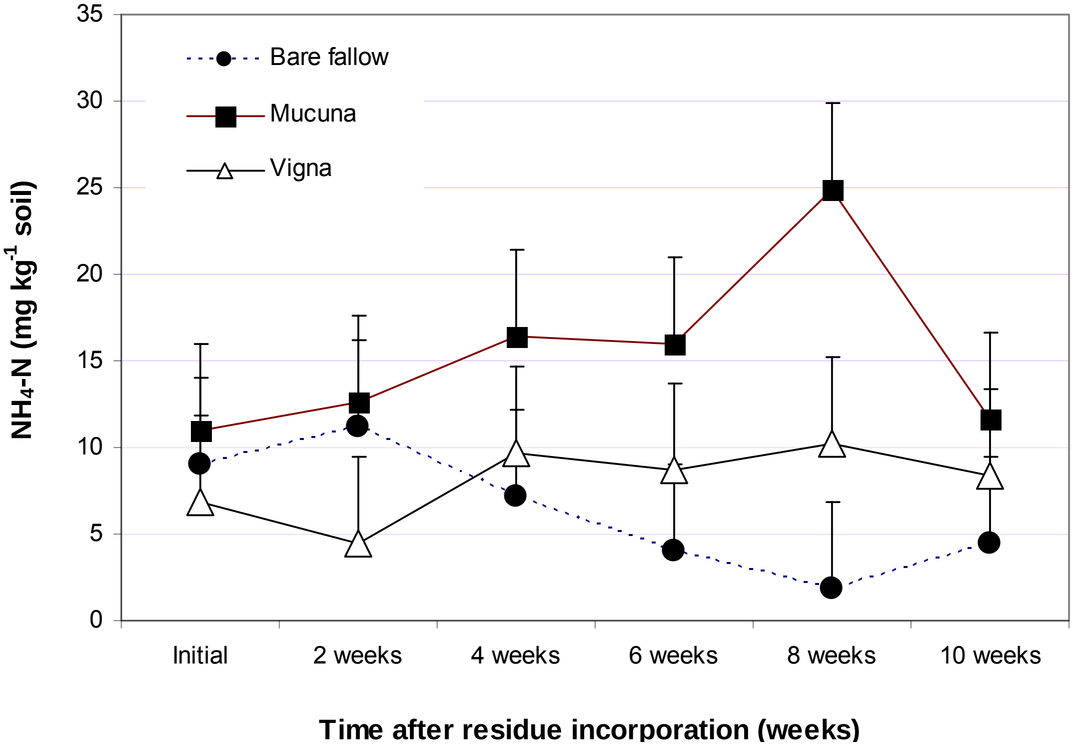

Figure 10. Exchangeable NH_4-N (mg kg^{-1} soil) in flooded soil after incorporation of dry-to-wet season transition period crops in the greenhouse (pot experiment, Bonn, Germany, 2003). Bars present standard errors of the mean (n=4).

Large differences in soil extractable NH_4-N was observed among DWT pre-treatments. During the initial two weeks, the NH_4-N content in the bare soil treatment gradually decreased as rice seedlings grew and is reached a minimum of 1.9 mg kg^{-1}

soil at 8 weeks after rice transplanting. The incorporation of crop residues resulted in a large NH_4-N mineralization with a maximum of 24.8 mg kg^{-1} soil at 8 weeks after incorporation of mucuna residues. The incorporation of mungbean residues resulted in an intermediate N mineralization with a maximum of 10 mg kg^{-1} soil after 8 weeks (Fig. 10). These extractable soil NH_4-N mineralization rates were also reflected in the rice N uptake. Large differences in N uptake by transplanted rice were observed among treatments after incorporation of DWT crop residues.

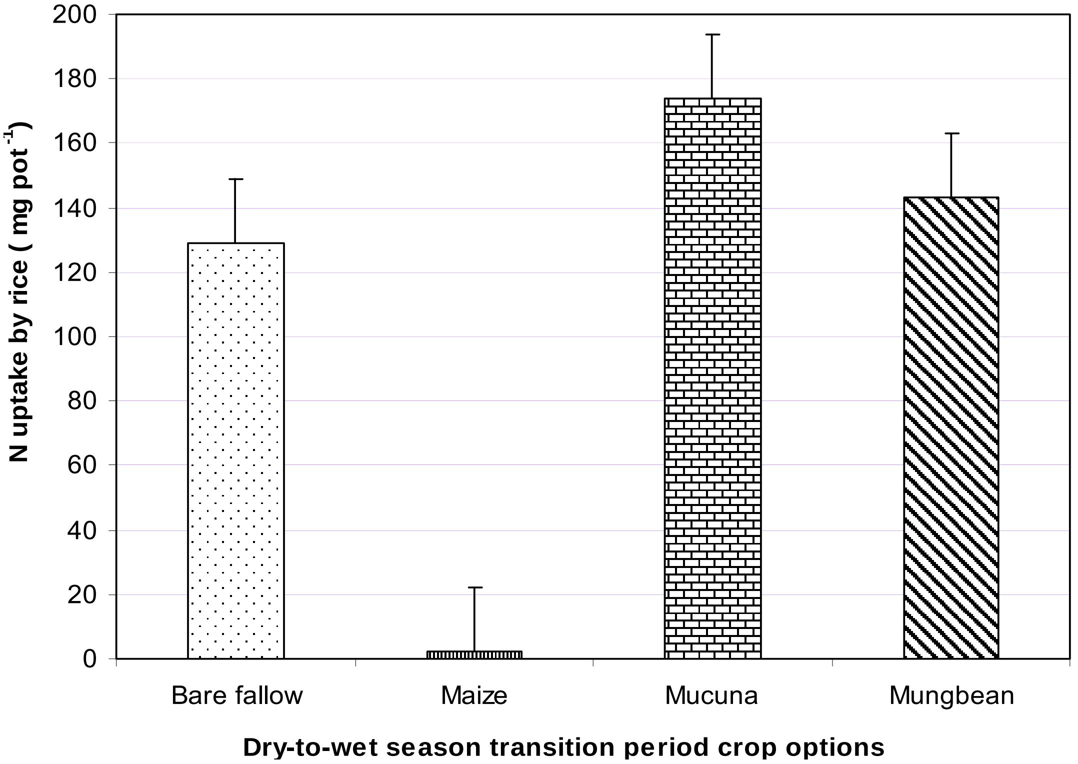

Figure 11. N uptake by 8 week-old transplanted rice as affected by different crop options applied in the potted soil during the simulated dry-to-wet transition season (greenhouse experiment, Bonn, Germany, 2003). Bars present the standard errors of the means (n=4).

The highest N uptake of 174 mg pot^{-1} was determined where mucuna crop residue with 1820 mg N had been incorporated, while the lowest N uptake of 129 mg pot^{-1} was determined in the bare soil control treatment. The biomass of maize was relatively large (131 g pot^{-1}), and transplanted rice seedlings did not survive under the conditions created by the anaerobic decomposition of these low quality residues (Fig. 11).

4.2. Management and dynamics of N in the field

4.2.1. Straw management

a).Soil N dynamics during the dry-to-wet season transition period

The effects of the application of various methods and rates of wheat straw in the potted soil in the greenhouse were validated at the high altitude field site at Maramche, Kaski, Nepal. It is a field site with relatively shorter dry-to wet season fallow period (50 days) where only the wheat straw management options are applicable.

In contrast to the pot experiment, there was no significant change in the soil NH_4-N content with straw management treatments. However, the NO_3-N content significantly differed among treatments. A NO_3-N peak of 28.kg ha^{-1} was observed in the bare fallow treatment at 30% volumetric soil moisture 4 weeks after the start of the experiment. A significantly lower nitrate peak was observed with wheat straw application and a positive relation was observed between the NO_3-N peak and straw application rates. The lowest NO_3-N peak (12 kg ha^{-1}) was determined at the highest rate (3 Mg ha^{-1}) of wheat straw incorporation. Straw incorporation in the surface soil of 0-15 cm was more effective than surface mulching to immobilize soil N. Similar to the pot experiment almost all NO_3-N was disappeared at soil flooding. At soil saturation by rain, a sharp decline in soil NO_3-N was observed and it could be linked to the use of NO_3-N by the microbial population for respiration under anaerobic soil condition (Fig. 12).

The application of wheat straw by different methods in different rates during DWT showed large differences in nitrate accumulation in the ion-exchange resin that were placed at 30 cm soil depth to determine NO_3-N leaching losses. The highest amount of 6.1 kg ha^{-1} of nitrate leaching was observed in the bare fallow treatment. Compared to surface mulching, wheat straw incorporation in the top 0-15 cm of the soil of significantly reduced nitrate leaching and the lowest amount of 0.82 kg ha^{-1} of NO_3-N was observed in the treatments in which wheat straw was incorporated at a rate of 3.0 Mg ha^{-1} of. As with the soil N mineralization dynamics, nitrate leaching was inversely related to the rate of wheat straw application and was positively related to the build up of NO_3-N in the top soil (Fig. 13).

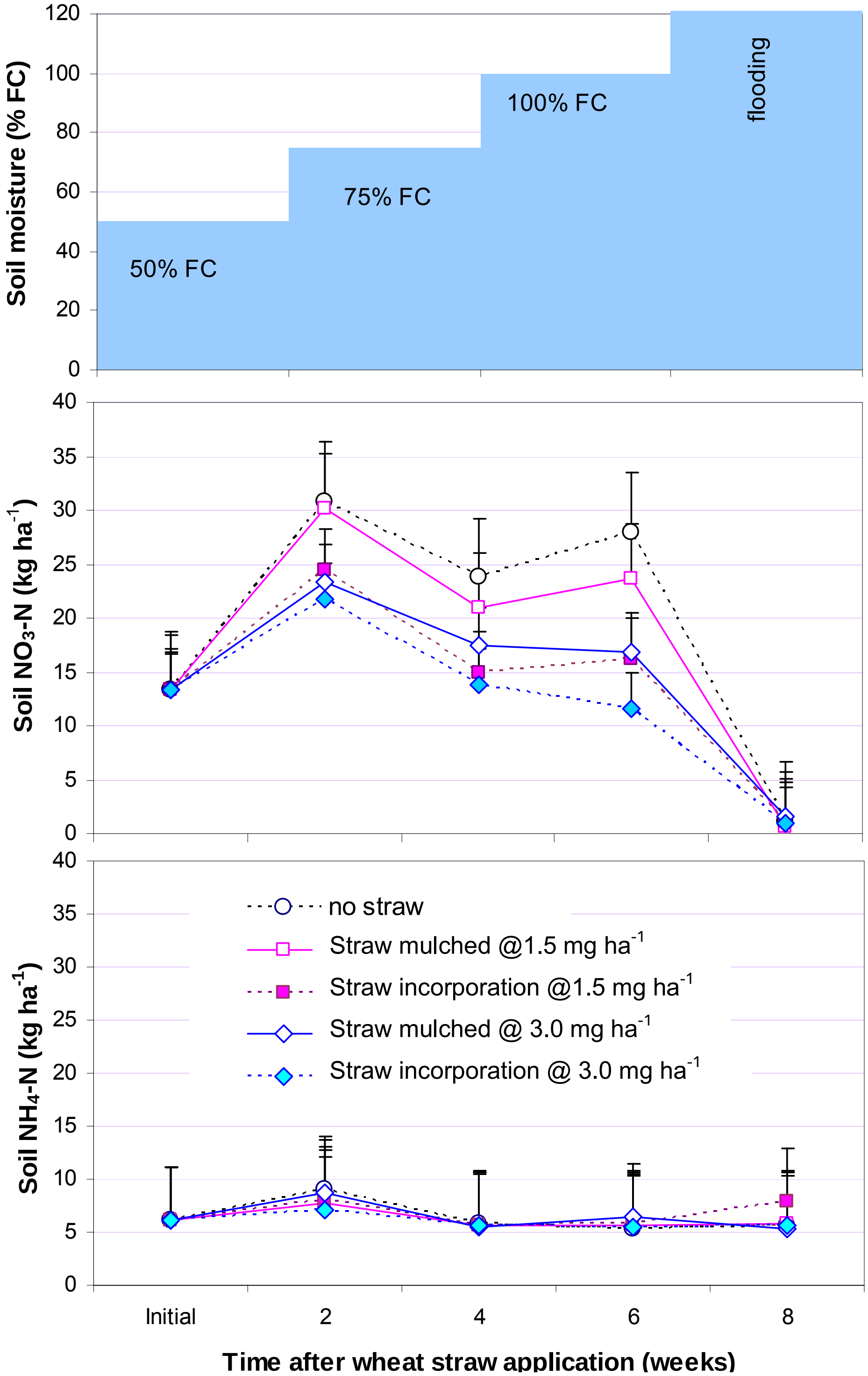

Figure 12. Soil N_{min} dynamics observed in the farmers field as affected by the application of different rates of wheat straw by different methods during 8 week-long dry-to-wet season transition period at the high altitude field site in Maramche (field experiment, Kaski province, Nepal, 2003). Bars present standard errors of mean (n=4).

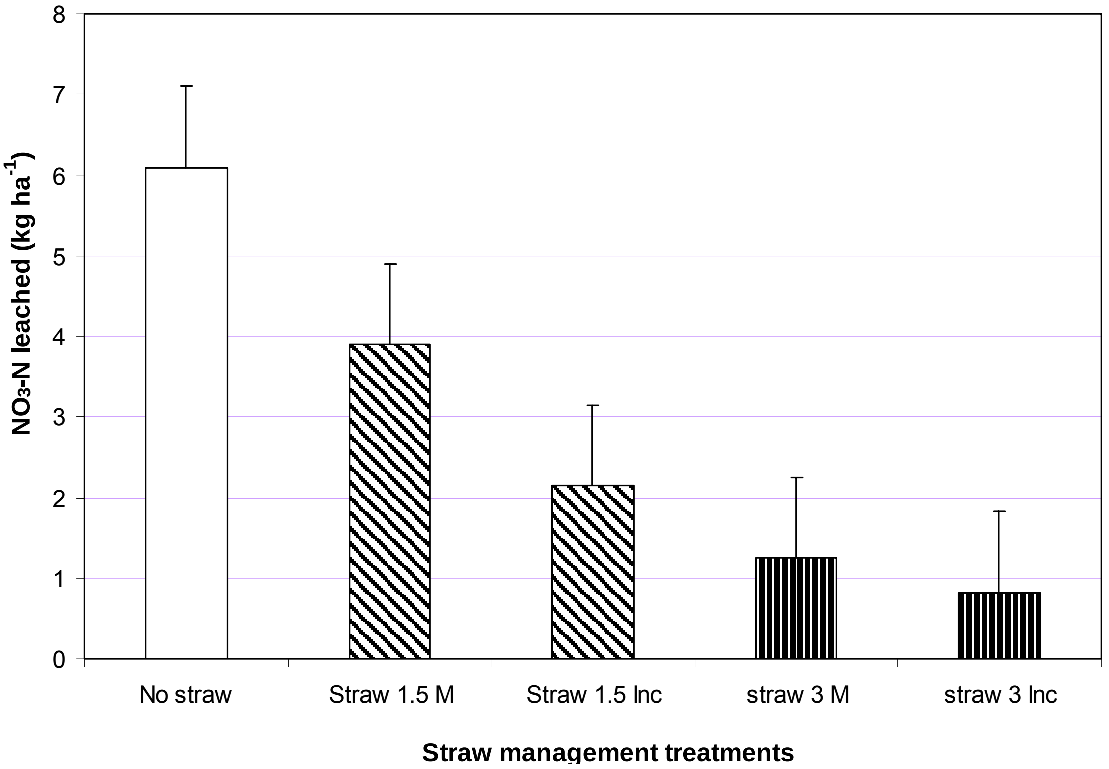

Figure 13. Nitrate leaching from the surface soil (0-15 cm) as affected by different rates and methods of straw application at the high altitude field site (field experiment, Maramche, Kaski province, Nepal, 2003). Figure in the X-axis represents amounts of wheat straw applied in Mg ha^{-1}, M indicates mulching and Inc indicates incorporation. Bars present standard errors of the mean (n=4).

b). Rice yield and N uptake

Significant (P = 0.05) differences were observed in grain yield and N uptake of a succeeding crop of rice that owed different straw management options during DWT. The highest grain yield of 2.5 Mg ha^{-1} and the highest total N uptake of 71.2 kg ha^{-1} were observed from plots which were managed by incorporation of 3.0 Mg ha^{-1} of wheat straw. The lowest grain yield of 1.5 Mg ha^{-1} with a corresponding crop N uptake of 47.2 kg ha^{-1} was observed in plots kept under bare fallow during DWT. The heavy losses of NO_3-N at the end of DWT by denitrification and NO_3-N leaching limited rice growth and resulted in reduced grain yield and N uptake in the bare fallow pre-treatment (Table 3). It may be concluded that in areas where large amounts of wheat straw are produced and where this straw is not used as a commercial commodity, its incorporation into the soil after wheat harvest can significantly contribute to reduce native soil N losses and possibly increase the yield of wet of wet season rice.

Table. 3. Biomass yield (Mg ha^{-1}) and N uptake (kg ha^{-1}) of summer season rice as affected by the straw management during the dry-to-wet season transition period (Maramche, Kaski province, Nepal, 2003).

Straw application	Crop yield (Mg ha^{-1})			N uptake (kg ha^{-1})
	Grain	Straw	Biomass	
no straw	1.47c	4.35b	5.8c	47,2c
1.5 Mg ha^{-1}M*	1.85bc	5.18ab	7.1bc	57,3bc
1.5 Mg ha^{-1}Inc**	1.95b	4.88b	6.8bc	55,9bc
3 Mg ha^{-1}M	2.40a	5.25ab	7.7ab	63,7ab
3 Mg ha^{-1}Inc	2.53a***	6.18a	8.7a	71,2a

*M indicates surface mulch

**Inc indicates straw incorporation in the surface soil of 0-15 cm depth

***Values follows by the same letter within one column do not differ significantly by DMRT (P=0.05).

4.2.2. Crop management during the dry-to -wet transition season

a).N dynamics during the dry-to-wet transition season

The occurrence of relatively long DWT in the Terai and Inner-Terai than in the midhills allowed for the cultivation of transition season crops as additional option beside wheat straw application to manage seasonal soil N dynamics during DWT in major rice-wheat fields in Rampur, Chitwan, Nepal. Similar to the pot experiment, a gradual increment in soil moisture resulted changes in the available forms of N_{min} in the soil. The initial NH_4-N content in the bare soil decreased from 21.2 to 5.9 kg ha^{-1} and from 12.3 to 9.3 kg ha^{-1} at 6 weeks after wheat harvesting in the years 2001 and 2003, respectively. At soil saturation by the monsoon rains, the NH_4-N content gradually increased to 26.4 and 28.8 kg ha^{-1} 14 weeks after wheat harvesting in the years 2001 and 2003, respectively. A reverse pattern was observed in the case of NO_3-N in both years. Nitrate peak of 51 kg ha^{-1} and 75.3 kg ha^{-1} were observed in the bare fallow soil in the years 2001 and 2003, respectively: With the onset of monsoon rain, the soil was saturated by water and almost all NO_3-N disappeared from the soil. The initial increment in NO_3-N in the bare fallow soil during the aerobic phase was possibly associated with the oxidation of NH_4-N to NO_3-N, while the sharp decline in NO_3-N at the end of DWT at soil saturation by monsoon rain was associated with N losses by denitrification and leaching. The NH_4-N and NO_3-N content in the bare soil showed an inverse relation in both years 2001 and 2003 (Fig. 14).

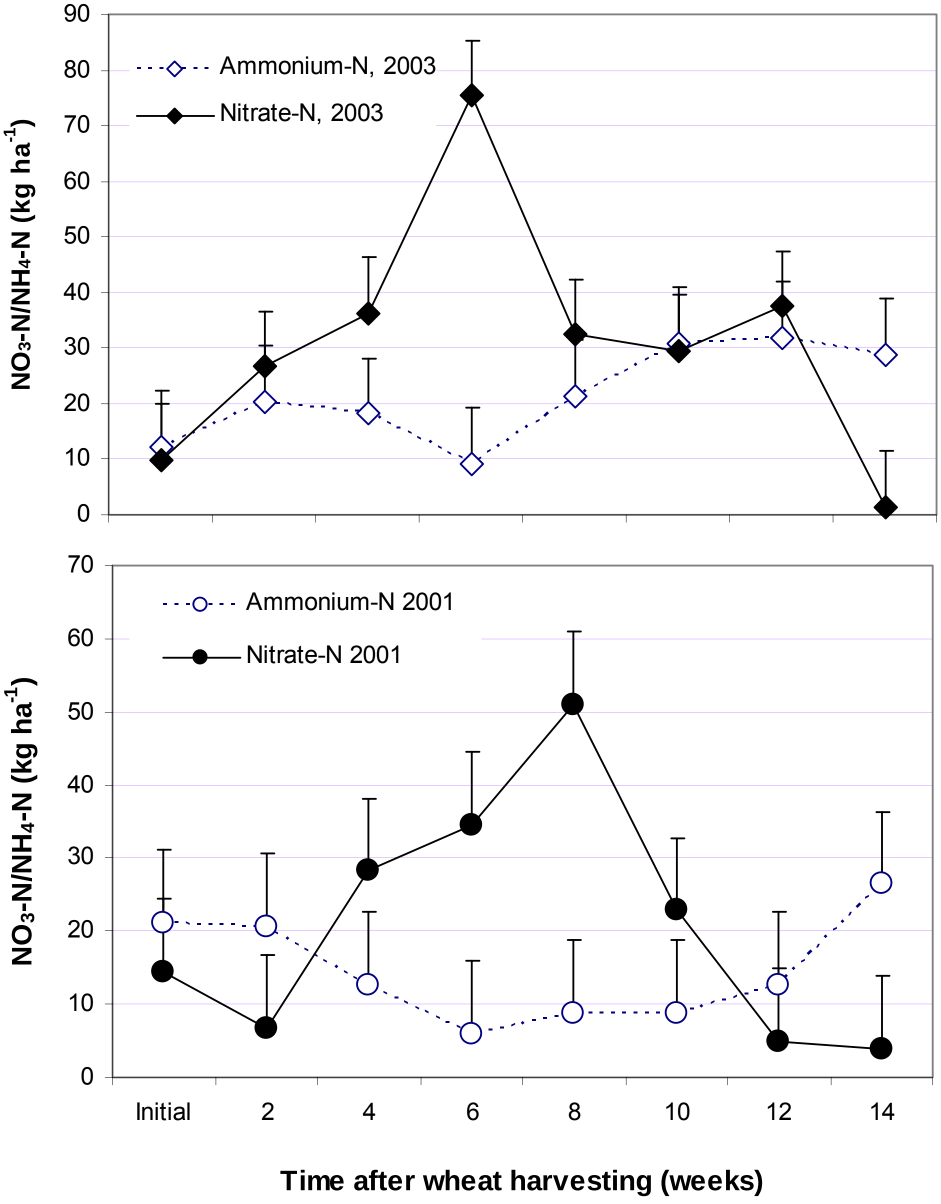

Figure 14. Soil N_{min} dynamics in the bare fallow soil during the dry-to-wet season transition period at the lowland field sites (field experiment, Rampur, Chitwan province, Nepal, 2001 and 2003). Bars present standard errors of the mean (n=4).

As in the greenhouse, the incorporation of wheat straw reduced the build up of soil N_{min}. The change in NO_3-N was more pronounced than the changes in NH_4-N content. The incorporation of wheat straw at the rate of 2 Mg ha^{-1} reduced the build up of soil NO_3-N from 51 kg ha^{-1} in the bare fallow to 12.8 kg ha^{-1}. After soil saturation, the NH_4-N was increased from 26 kg ha^{-1} to 32.1 kg ha^{-1} in the straw amended bare fallow plots (Table 4). Similar results were observed in the year 2003 (Table 5).

The growth of the transition season crops reduced the soil NO_3-N peak from 51 (2001) and 75 kg ha^{-1} in the bare fallow to 25, 27 and 32 kg ha^{-1} in 2001 and to 34.9, 36.6 and 29.4 kg ha^{-1} in 2003 in the treatments with maize, mungbean and mucuna respectively. A combination of wheat straw amendment and the growth of transition season crops further reduced the build up of NO_3-N in the soil. Peak levels of 7 and 25 kg NO_3-N ha^{-1} were observed in the straw amended mucuna treatment in 2001 and 2003, respectively. The low NO_3-N content observed in the straw amended mucuna treatment is likely to be associated with the immobilization of soil N_{min} both in the plants and in the microbial biomass. Soil NO_3-N leaching during DWT was determined by ion-exchange resin capsules placed at 30 cm soil depth. Large differences in NO_3-N leaching from the top soil were observed among DWT treatments. The highest amount of 12 kg NO_3-N ha^{-1} leached from the topsoil was observed in the bare fallow control treatment, followed by the straw amended fallow with 3.02 kg NO_3-N ha^{-1}. Thus, wheat straw amendment significantly ($P=0.05$) reduced the nitrate N leaching (table 9). The lowest amount of 0.57 kg ha^{-1} of NO_3-N leaching was observed in the wheat straw amended mucuna treatment and was associated with the immobilization of soil N_{min} in both microbial and plant biomass.

Gas collected by the closed chamber method during the DWT of 2003 was analysed using gas chromatography to determine the effect of straw and crop management during DWT on N_2O emission from the soil. With the onset of sporadic spring rains, several cycles of soil drying and wetting occurred. The change in soil moisture status resulted in an increase in N_2O emission from the soil. With a further increase in soil moisture to >43% FC, N_2O emission was increased. However, both prolonged drying and prolonged wetting periods decreased the emission. A first peak of N_2O emission of 27 µg N m^{-2} h^{-1} was observed at 63 % FC soil moisture in the bare fallow treatment. This N_2O emission peak was related with the maximum of NO_3-N in the soil and was possibly associated with the oxidation of NH_4-N (nitrification).

Table. 4. Dynamics of soil N_{min} (ammonium and nitrate) in kg ha^{-1} during the 90 days transition period between the harvest of wheat and the transplanting of wetland rice as affected by crops and wheat straw management (on-station experiment, Rampur, Chitwan province, Nepal, 2001).

Transition season treatments	Time after wheat harvest (weeks)							
	Initial	2	4	6	8	10	12	14
NH_4-N (kg ha^{-1})								
Bare fallow 'control'	21.2a**	20.5ab	12.7cd	5.9bc	8.7a	8.8b	12.7e	26.4e
Fallow+straw*	16.2b	22.0ab	18.4a	7.4ab	10.0a	13.3ab	16.1cde	32.1de
Maize	16.9b	21.4ab	12.4cd	6.9abc	10.7a	12.8ab	15.1de	31.9de
Maize+straw*	14.6b	18.7b	15.0abc	6.3bc	10.3a	12.2ab	15.7de	36.2cde
Mungbean	15.7b	25.3a	10.8d	5.4c	10.6a	14.3a	18.6bcd	39.2bcd
Mungbean+straw *	18.7b	21.4ab	16.2ab	6.7abc	10.0a	12.9ab	23.9a	47.3ab
Mucuna	16.3b	21.2ab	12.9bcd	5.8c	11.1a	15.9a	20.6abc	44.8abc
Mucuna+straw*	17.5b	19.6ab	16.9a	7.8a	9.5a	16.6a	21.7ab	51.7a
NO_3-N (kg ha^{-1})								
Bare fallow 'control'	14.5ab	6.6a	28.2a	34.5a	51.0a	22.8ab	4.8ab	3.8ab
Fallow+straw*	10.4c	5.6a	7.8c	5.2c	12.8cd	12.4bcd	4.9ab	3.6ab
Maize	15.3a	7.5a	17.7b	25.2b	23.9bc	12.5bcd	3.1bc	3.1b
Maize+straw*	11.5c	4.9a	9.9c	3.7c	7.7d	6.0d	2.5c	3.0b
Mungbean	15.3a	5.9a	26.0a	26.8b	32.2b	20.1abc	5.4a	3.4ab
Mungbean+straw *	12.2bc	7.3a	9.6c	8.1c	6.6d	9.8dc	3.8abc	4.1a
Mucuna	15.2ab	6.5a	23.7a	28.1ab	31.8b	26.9a	4.3abc	3.7ab
Mucuna+straw*	13.4abc	6.6a	9.8c	10.4c	9.9d	7.3d	4.7ab	3.6ab

* 2 Mg ha^{-1} of wheat straw incorporated at 0-20 cm depth

**Values followed by the same letter within one column do not differ significantly by DMRT (0.05)

Table. 5. Dynamics of soil N_{min} (ammonium and nitrate) in kg ha^{-1} during the 90 days transition period between the harvest of wheat and the transplanting of wetland rice as affected by crops and wheat straw management (on-station experiment, Rampur, Chitwan province, Nepal, 2003).

Transition season treatments	---Time after wheat harvest (weeks).---							
	Initial	2	4	6	8	10	12	14
---.NH_4-N (kg ha^{-1}) ---								
Bare fallow control'	12.3a**	20.4a	18.2d	9.3c	21.3c	30.8bc	31.8bcd	28.8d
Fallow+straw*	13.4a	22.1a	20.6bcd	9.6c	22.4bc	35.3a	35.1ab	34.5bc
Maize	13.3a	19.9a	19.1cd	9.7c	26.1ab	28.6c	29.6d	32.4cd
Maize+straw*	13.9a	23.8a	20.8bcd	11.0bc	27.5a	27.7c	30.8cd	33.4bc
Mungbean	12.6a	22.4a	18.6cd	12.3bc	26.6a	33.9abc	32.8bcd	37.0ab
Mungbean+straw*	12.9a	21.7a	22.0ab	14.3ab	29.4a	38.7a	34.0abc	36.5abc
Mucuna	12.2a	21.8a	21.1bc	14.1ab	25.6ab	38.3a	36.9a	36.0abc
Mucuna+straw*	11.6a	22.9a	24.2a	16.9a	28.7a	29.0c	36.9a	38.9a
---.NO_3-N (kg ha^{-1}) ---								
Bare fallow control'	9.8bc	26.7a	36.3a	75.3a	32.4a	29.6a	37.4a	1.5a
Fallow+straw*	10.1bc	17.5cd	23.5d	38.8b	25.6b	21.7b	31.4b	2.4a
Maize	8.7c	17.0cde	27.9bc	34.9b	10.1d	7.0c	18.2cd	1.8a
Maize+straw*	10.8ab	14.0ef	19.6e	25.5c	11.9d	6.4c	22.8c	2.3a
Mungbean	12.0a	22.3b	30.5b	36.6b	17.0c	7.6c	14.2de	2.0a
Mungbean+straw*	9.8bc	15.0def	19.5e	25.9c	12.5d	5.1c	12.0e	2.2a
Mucuna	10.2abc	18.2c	26.5cd	29.4c	9.6d	7.2c	11.8e	2.3a
Mucuna+straw*	6.0d	13.0f	16.7e	24.8c	10.9d	5.2c	11.8e	3.0a

* 2 Mg ha^{-1} of wheat straw incorporated at 0-20 cm depth.

**Values followed by the same letter within one column do not differ significantly by DMRT (0.05).

After the onset of monsoon the soil got saturated and the highest amount of N_2O emission of 48 µg N m^{-2} h^{-1} was observed in the bare fallow treatment. This second peak was associated with a rapid reduction in the NO_3-N content in the soil was possibly associated with microbial reduction of NO_3-N under anaerobic soil moisture condition (denitrification). The application of wheat straw significantly reduced the emissions and was further reduced by a combination of DWT crop with wheat straw application, possibly the result of the combined effects of N immobilization in the soil microbial biomass with wheat straw application and N uptake by growing crops (Fig. 15).

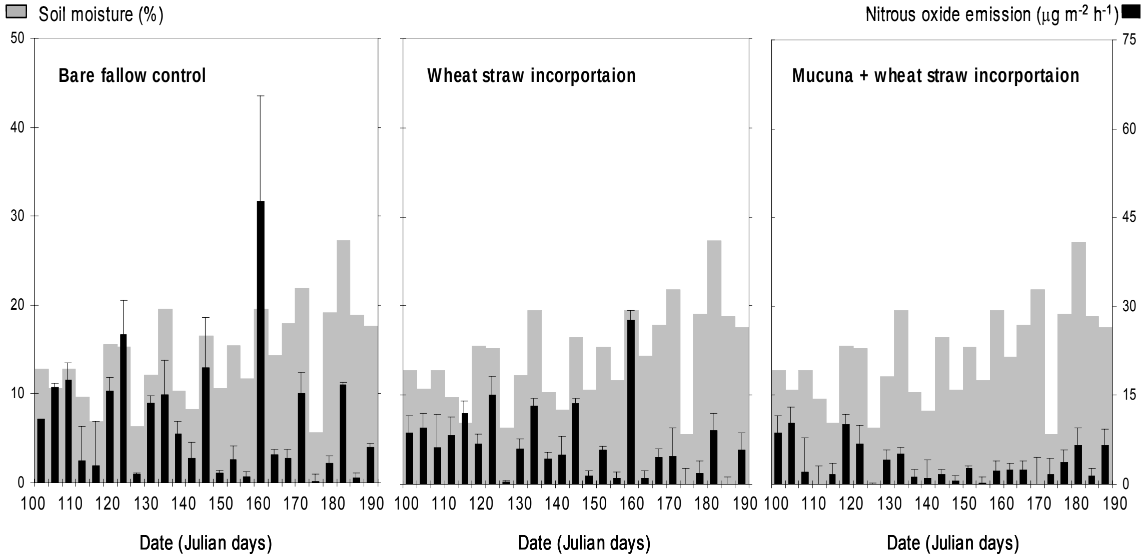

Figure 15. Effects of straw (bare fallow control, 2 Mg ha^{-1} applied as soil incorporation) and crop management (mucuna +straw) on the N_2O emissions from the lowland fields during the dry-to-wet season transition period (field experiments, Rampur, Chitwan province, Nepal, 2003). Bars present standard errors of the mean (n=4).

b). Nitrogen assimilation by transition season crops

Crops grown during DWT showed large differences in N accumulation. Total N accumulation by maize was 86 kg N ha^{-1} in 2001 and was significantly (P=0.05) reduced to 74 kg N ha^{-1} by wheat straw application. The grain legume mungbean and the green manure legume mucuna accumulated 53 and 80 kg N $ha^{-1,}$ respectively in the absence of wheat straw and 66 and 92 kg ha^{-1}, respectively with wheat straw amendment. Hence, application of wheat straw resulted significantly (P=0.05) higher N accumulation by legumes while the reverse trend was observed in the pot experiment. Nitrogen-15 analysis indicated that the major portion of this N was derived from biological nitrogen fixation (Fig. 16).

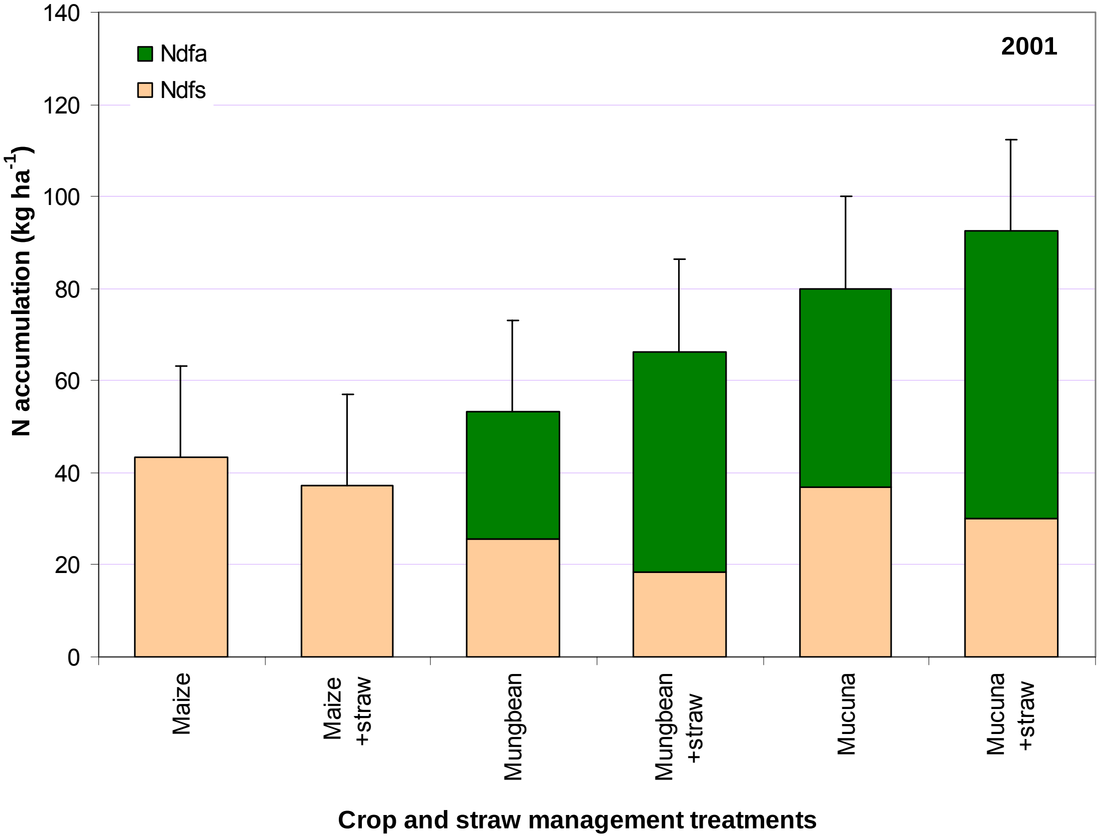

Figure 16. Nitrogen accumulation and N_2 fixation ($\delta^{15}N$ dilution method) in the biomass of 10 weeks-old crops grown in Chitwan, Nepal during the dry-to-wet transition season (field experiments, Rampur, Chitwan province, Nepal, 2001). Bars represent standard errors of the means (n = 4).

Determination of the N accumulation by DWT crops in 2003 also showed significantly large differences in plant N uptake as in 2001. The total N accumulation by mucuna, mungbean and maize were 108, 80 and 54 kg ha^{-1}, respectively. Wheat straw application reduced the N uptake by maize from 54 kg ha^{-1} to 48 kg ha^{-1}, however, that further enhanced the total N accumulation by both legumes (mucuna and mungbean). The highest amount of 116 kg N ha^{-1} of N was accumulated by the straw amended mucuna. The increased N accumulation by legumes was due to the increased atmospheric N fixation under wheat straw application (Fig. 17).

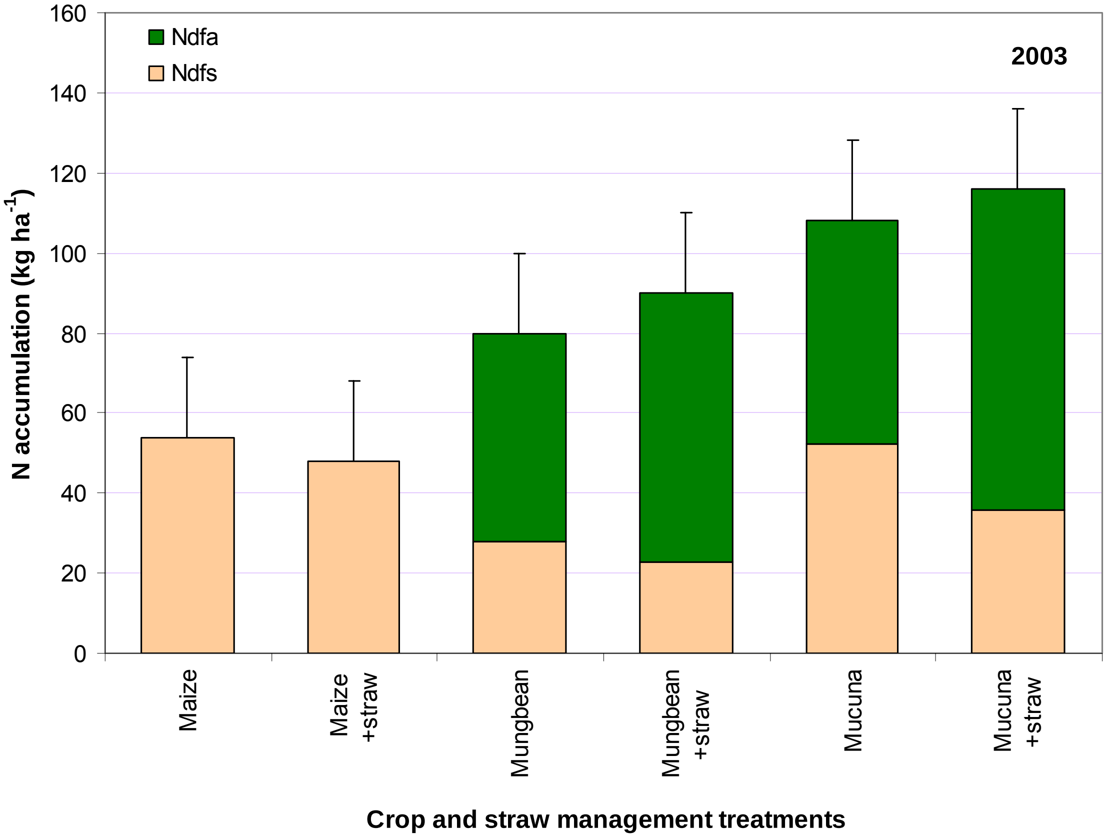

Figure 17. Nitrogen accumulation and N_2 fixation ($\delta^{15}N$ dilution method) in the biomass of 10 weeks-old crops grown in Chitwan, Nepal during the dry-to-wet season transition periods (field experiments , Rampur, Chitwan province, Nepal, 2003). Bars represent standard errors of the means (n = 4).

4.2.3. Wet (rice-growing) season

a).Soil N dynamics

Large differences in K_2SO_4 exchangeable soil NH_4-N were observed among DWT pre-treatments in flooded soil after rice transplantation. The highest amount of 51.2 kg ha^{-1} of NH_4-N occurred in case of the straw-amended mucuna treatment followed by the straw amended mungbean treatment (49 kg ha^{-1}). The lowest soil NH_4-N of 22 kg ha^{-1} of was observed in the bare fallow treatment during the initial two weeks after soil flooding and it rapidly declined afterwards. There was sharp decline in the soil NH_4-N content 4 weeks after rice transplanting in all treatments that was possibly associated with N uptake by the growing rice crop. Nitrate-N was hardly detectable in the flooded soil and there were no significant treatment effects (Table 6). Also no significant nitrate leaching losses occurred during the wet season (Table 9).

Table. 6. Dynamics of soil N_{min} (kg ha^{-1}) during the rice-growing season under anaerobic soil condition as affected by crop and wheat straw management treatments applied during the dry-to-wet season transition period (on-station field experiment, Rampur, Nepal, 2003).

Soil management	---Time after rice transplanting (weeks)---					
	Initial	2	4	6	8	10
	---NH_4-N (kg ha^{-1})---					
Bare fallow 'control'	22.2c	22.8e	19.1d	16.0d	08.6d	5.0e
Fallow+straw*	29.6bc	35.5d	41.9bc	19.4cd	14.9c	8.2d
Maize	30.9bc	36.8cd	40.8bc	19.9cd	15.0c	8.3d
Maize+straw*	34.2b	38.9bcd	43.7abc	19.7cd	14.3c	08.5d
Mungbean	31.3bc	39.5bc	38.6c	22.3c	16.1c	11.7c
Mungbean+straw*	38.5ab	41.9b	49.4ab	30.8b	21.2b	18.0b
Mucuna	35.3b	37.4cd	39.4c	27.9b	16.1c	17.2b
Mucuna+straw*	46.4a	48.4a	51.2a	35.4a	25.0a	22.5a
	---NO_3-N (kg ha^{-1})---					
Bare fallow 'control'	1.0a	0.4ab	0.6a	4.4ab	5.0a	02.3c
Fallow+straw*	0.4a	0.7a	0.4a	5.5ab	5.8a	06.8a
Maize	0.2a	0.4ab	0.8a	4.2ab	4.7a	02.4c
Maize+straw*	0.5a	0.4ab	0.6a	4.1ab	5.7a	01.8c
Mungbean	1.3a	0.3b	0.5a	5.9a	5.0a	02.2c
Mungbean+straw*	2.1a	0.3b	0.8a	5.1ab	5.6a	06.7a
Mucuna	1.8a	0.3b	0.4a	4.4ab	5.0a	04.8b
Mucuna+straw*	1.5a	0.3b	0.7a	3.9b	4.4a	04.8b

2 Mg ha^{-1} of wheat straw incorporated at 0-20 cm depth.

**Values followed by the same letter within one column do not differ significantly by DMRT (P = 0.05).

b). Rice N uptake

Rice grain yield responded to the N savings and/or N adding effects (BNF) of the dry-to-wet transition season treatments (Table 4, 5 and 7). The lowest rice grain yield of 1.7 Mg ha^{-1} (average of 2001 and 2003) was obtained from the plots where rice was grown after a bare fallow and where large amounts of NO_3-N disappeared during DWT by leaching and denitrification. The application of wheat straw alone significantly increased the rice grain yield to 2.6 Mg ha^{-1}. Straw application in combination with maize, mungbean and mucuna resulted in 2.5, 2.9 and 3.7 Mg ha^{-1}

(average of 2001 and 2003), respectively. The highest grain yields of 3.61 Mg ha^{-1} in 2001 and of 3.79 Mg ha^{-1} in 2003 were observed in the wheat straw-amended mucuna treatment. Similar to the grain yield, large differences in N uptake by wet season rice were observed among treatments. The lowest N uptake of 32 kg ha^{-1} was determined in the bare fallow pre-treatment and the highest N uptake of 77 kg ha^{-1} was determined where mucuna biomass had been incorporated together with previously applied wheat straw. The application of wheat straw in the fallow land during DWT enhanced rice N uptake by 62% compared to bare fallow (Table 7). It could be the reflection of N savings during DWT by means of temporary immobilization of N_{min} and remineralization during rice growing wet season.

Table. 7. Grain yield in Mg ha^{-1} and N uptake in kg ha^{-1} by wet season rice as affected by crops and straw management treatments applied during the dry-to-wet season transition period (field experiments, Chitwan province, Nepal, 2001 and 2003).

Management treatments	On-station experiment (n = 4 reps)					
	2001		2003		Average	
	----------------------------Grain yield (Mg ha^{-1}) and N uptake (kg ha^{-1})-------------------------------					
	Grain yield	N uptake	Grain yield	N uptake	Grain yield	N-uptake
Bare fallow	1.72c*	30e	1.68f	33e	1.70	32.0
Fallow+straw	2.54b	47cd	2.67cd	57bc	2.61	52.0
Maize	2.31bc	43cd	2.04ef	41de	2.18	42.0
Maize+straw	2.71ab	51bc	2.32de	48cd	2.52	50.0
Mungbean	2.85ab	58b	3.09b	65b	2.97	62.0
Mungbean+straw*	3.12ab	61b	2.72c	59b	2.92	60.0
Mucuna	2.65b	53bc	3.42b	77a	3.05	65.0
Mucuna+straw	3.61a	72a	3.79a	83a	3.70	78.0

*Values follow by the same letter in one column do not differ significantly by DMRT (P = 0.05).

The highest N uptake of 78 kg ha^{-1} determined in the wheat straw amended mucuna pre-treatment was possibly associated with combined effects of N savings by mucuna in the plant biomass, N addition by the atmospheric N_2 fixation and soil N_{min}

immobilization in the soil microbial biomass. Thus, combining wheat straw application with the growth of green manure legumes appears an effective way to reduce N losses and to increase grain yield and N uptake of rice.

4.2.4. Dry (wheat-growing) season

After harvesting wet season rice, wheat was grown on residual soil moisture in aerobic soil during the cold and dry winter season. The residual effects of crops and straw management treatments applied during pre-rice season (DWT) on the N nutrition and grain yield of wheat were evaluated.

a).Soil N_{min} dynamics

Initially, the NH_4-N present in the soil was relatively high and it gradually decreased with the growth of wheat. These initial values ranged from 32- 33 kg ha^{-1} of NH_4-N with straw-amended mucuna and mungbean pre-treatments to 15-16 kg ha^{-1} in maize and fallow control treatments. The soil nitrate dynamics followed a similar pattern with maximum values of >30 kg ha^{-1} in straw-amended legume and <20 kg ha^{-1} in maize and bare fallow control pre-treatments (Table. 8). However, peak soil N_{min} levels under wheat was considerably less than those determined during DWT (>50 kg NO_3-N ha^{-1}.) or the rice-growing season (>50 kg NH_4-N ha^{-1}). Accordingly, N losses by nitrate leaching during the dry season were 0.6-1.6 kg ha^{-1} compared to >12 kg NO_3-N ha^{-1} lost during DWT (Table 9).

b). Wheat yield and N uptake

The soil N management treatments applied during DWT also produced significant residual or carry-over effects on both the yield and N nutrition effects of soil N management treatments applied during DWT period on N uptake of wheat. The highest wheat grain yield of 1.84 Mg ha^{-1} and N uptake of 52 kg ha^{-1} was obtained from the wheat straw-amended mucuna pre-treatment while the lowest grain yield of 1.2 Mg ha^{-1} of grain yield and N uptake of 31 kg ha^{-1}of wheat were obtained in the bare fallow pre-treatment. Generally grain yields were higher with pre-rice legume than with pre-rice fallow or maize treatments. Straw incorporation during DWT improved the N nutrition of wheat but without significant yield effects (Table 10).

Table. 8. Dynamics of soil N_{min} (kg ha^{-1}) during the wheat growing season under aerobic soil condition as affected by crop and wheat straw management options applied during the dry-to-wet transition season (on-station field experiment, Rampur, Nepal, 2003).

Soil management	Time after wheat seeding (weeks)							
	Initial	2	4	6	8	10	12	14
	---------------------------------------NH_4-N (kg ha^{-1})---							
Bare fallow	16.0d	17.1cd	15.3bc	19.9e	21.9cd	16.6b	12.7cd	9.1ed
Fallow+straw	22.3c	20.8c	17.1b	23.5d	23.0c	17.9b	15.9abc	10.0cd
Maize	15.1d	15.3d	11.5e	19.4e	18.3e	11.1d	8.9e	7.7e
Maize+straw	15.4d	16.8cd	16.6b	20.2e	20.4d	13.5c	11.3de	10.8cd
Mungbean	25.5b	25.7b	14.0cd	25.7cd	31.0b	22.1a	14.4bcd	11.7c
Mungbean+straw*	32.5a	30.2a	23.1a	28.6bc	31.1b	23.3a	16.4ab	11.3c
Mucuna	31.8a	31.2a	12.8de	31.8b	30.7b	22.6a	14.2bcd	14.3b
Mucuna+straw	32.7a	33.6a	17.3b	35.2a	33.7a	23.7a	19.1a	16.6a
	--- NO_3-N (kg ha^{-1})--							
Bare fallow	12.9b	19.4d	13.3e	8.1e	5.3e	6.4d	6.8def	4.4d
Fallow+straw	16.7ab	23.8c	17.4d	11.0cd	14.0bc	12.8bc	15.6a	4.5d
Maize	15.5ab	12.8e	10.0f	8.8e	5.9de	7.1d	5.9ef	5.8c
Maize+straw	15.9ab	15.3e	11.9ef	9.5de	7.5d	8.0d	5.3f	6.2bc
Mungbean	16.4ab	25.6c	21.7c	14.3b	12.8c	11.8c	8.1cd	5.9c
Mungbean+straw**	19.0a	33.5ab	27.1b	15.0b	15.5b	14.1b	7.6cde	7.5a
Mucuna	17.6a	31.4b	27.4b	12.1c	12.6c	12.5bc	9.3c	5.3cd
Mucuna+straw	18.1a*	36.1a	31.7a	17.7a	20.8a	16.5a	11.8b	7.1ab

*Values followed by the same letter within one column do not differ significantly by DMRT (P=0.05)

**3 Mg ha^{-1} wheat straw incorporated at 0-15 cm

Table. 9. Cumulative NO_3-N leaching losses from the top soil (0-15cm) determined by ion-exchange resins of the dry-to-wet transition season, the rice-growing wet season and the wheat-growing dry

seasons as affected by crops and wheat straw management treatments applied during the dry-to-wet transition season (on-station experiment, Rampur, Chitwan province, Nepal, 2003).

Management treatments	------------------------------Nitrate leaching (kg N ha^{-1})------------------------------		
	Dry-to-wet transition season (Mar. - Jul.)	Wet season (Jul. - Nov.)	Dry season (Nov. - Mar.)
Bare fallow (control)	12.2a	0.6a	1.0b
Fallow+straw	3.0b	0.6a	1.2ab
Maize	0.7d	0.9a	0.9b
Maize+straw	0.6d	0.8a	0.9b
Mungbean	2.2bc	0.7a	1.6a
Mungbean+straw	1.3cd	0.7a	1.6a
Mucuna	0.6d	0.6a	1.5a
Mucuna+straw*	0.6d**	0.8a	1.5a

2 Mg ha^{-1} of wheat straw incorporated at 0-20 cm depth.

**Values follow by the same letter within one column do not differ significantly by DMRT (0.05).

Table. 10. Grain yield and N uptake by wheat crop during the cold and dry winter season as affected by crop and wheat straw management treatments applied during the dry-to-wet season transition period (field experiment, Rampur, Chitwan Province, Nepal, 2003).

Management treatments	Grain yield (Mg ha^{-1})	N uptake (kg ha^{-1})
Bare fallow	1.17cd	31.0c
Fallow+Straw	1.36bc	40.0b
Maize	0.87d	26.0c
Maize+Straw	0.91d	27.0c
Mungbean	1.45bc	41.0b
Mungbean+Straw	1.51abc	44.0ab
Mucuna	1.60ab	45.0ab
Mucuna+Straw	1.84a*	52.0a

*Values follow by the same letter within one column do not differ significantly by DMRT (P = 0.05).

4.3. On-farm validation

To validate the findings obtained from the greenhouse and on station experiments, three representative farmers' fields were selected in different locations of Chitwan province of Nepal and transition season treatments mucuna, mungbean, maize and bare fallow control were evaluated at two levels of straw management (0 and 2 Mg ha^{-1}). While the treatments were proposed and established by the researcher, further field operations were conducted by the farmers according to local soil and crop management practices. Data are presented as mean values of the three farms.

4.3.1. Nitrogen dynamics during the transition season

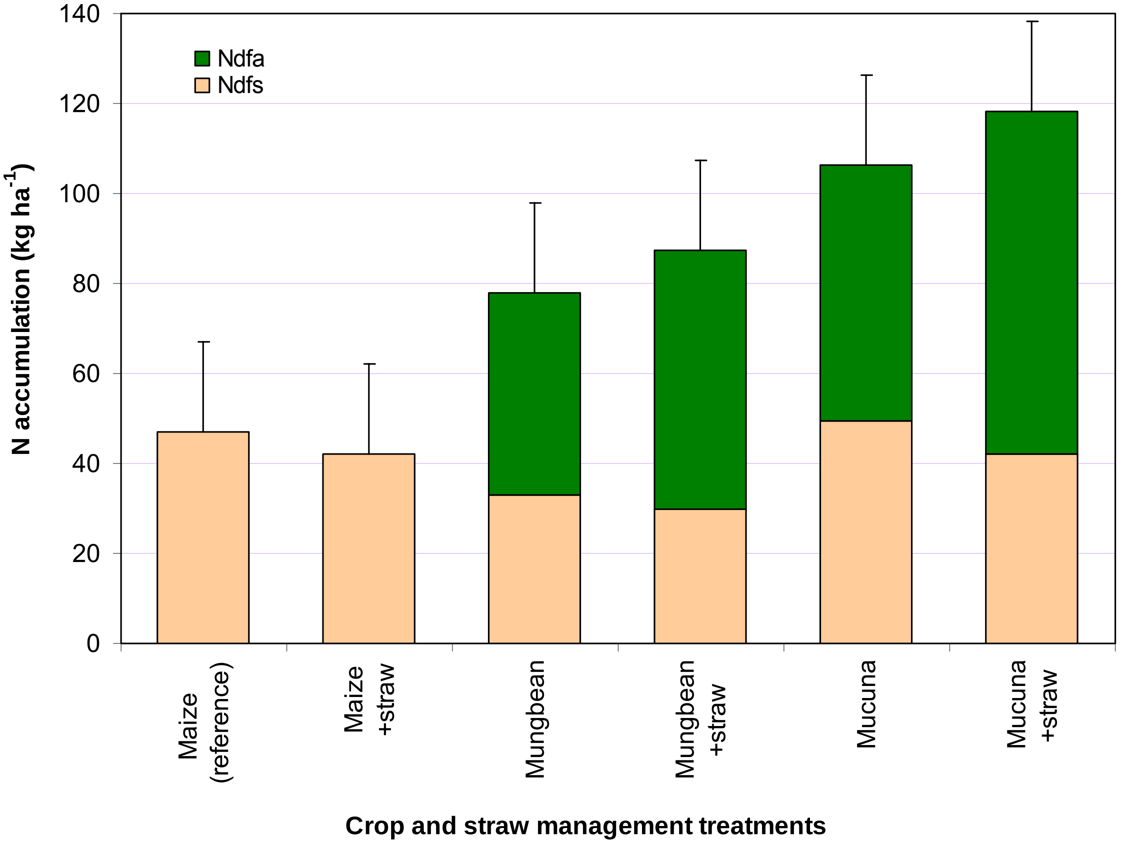

Figure 18. N accumulation and atmospheric N_2 fixation ($\delta^{15}N$ dilution method) in the biomass of 10 weeks-old crops grown during the dry-to-wet transition season (on-farm experiment, Rampur, Chitwan province, Nepal, 2003). Bars present standard errors of the mean (n=3).

Similar to pot and on-station experiments, large differences in total N accumulation by DWT crops were observed. The lowest N accumulation of 40 kg ha^{-1} was observed in straw-amended maize. As maize is a cereal and it depends solely on soil

N_{min} for its nutrition, a reduced N uptake with straw amendment was possibly associated with N_{min} immobilization in the soil microbial biomass. The highest N accumulation (105-123 kg ha^{-1}) was determined in the mucuna treatments with a larger share (50-60%) being derived from atmospheric N_2 fixation (Fig. 18). The uptake of soil derived N ranged from 27 to 50 kg ha^{-1} in all crops, and was 4-8 kg ha^{-1} less when wheat straw was applied.

Nitrate leaching from the surface soil during DWT ranged from 1 to 7.6 kg ha^{-1}. As in the on-station experiment, the highest NO_3-N leaching loss (7.6 kg ha^{-1}) was observed in the bare fallow and the lowest (1 kg ha^{-1}) was observed in the straw-amended mucuna treatment (Fig. 19).

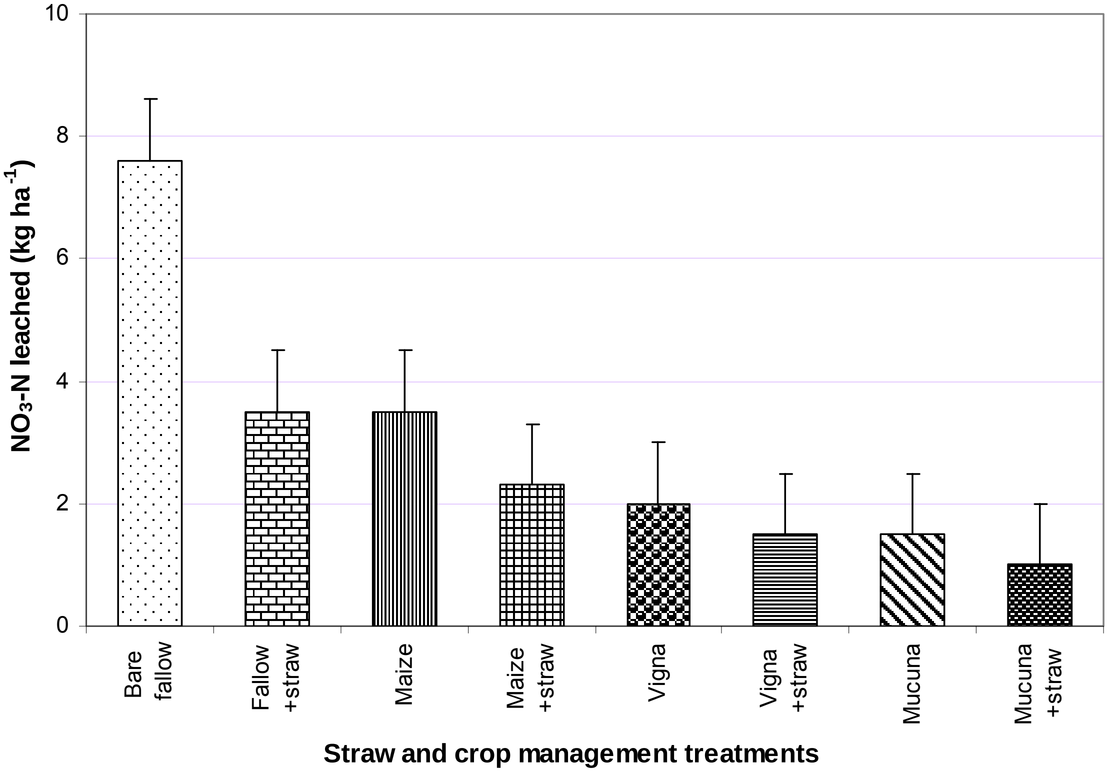

Figure 19. Cumulative NO_3-N leaching losses from the topsoil (0-15 cm) determined in ion-exchange resin during the transition season as affected by crops and straw management options applied (on-farm experiment, Rampur, Chitwan province, Nepal, 2003). Bars present standard errors of the mean (n=3).

4.3.2. Rice grain yield and N uptake

Similar to on-station experiment, the highest grain yield of 3.6 Mg ha^{-1} was observed in the straw-amended mucuna followed by straw amended mungbean treatment. There was no significant differences in grain yield between straw amended and unamended legumes (mucuna and mungbean) treatments. The lowest grain yield of 1.5 Mg ha^{-1} was observed in the bare fallow control (Fig. 20). Rice N uptake differed among the DWT pre-treatments. The highest N accumulation of 76 kg N ha^{-1} of was observed in wheat straw amended mungbean and mucuna treatments while the lowest N accumulation of 31 kg N ha^{-1} of was observed in the bare fallow control (Fig. 21).

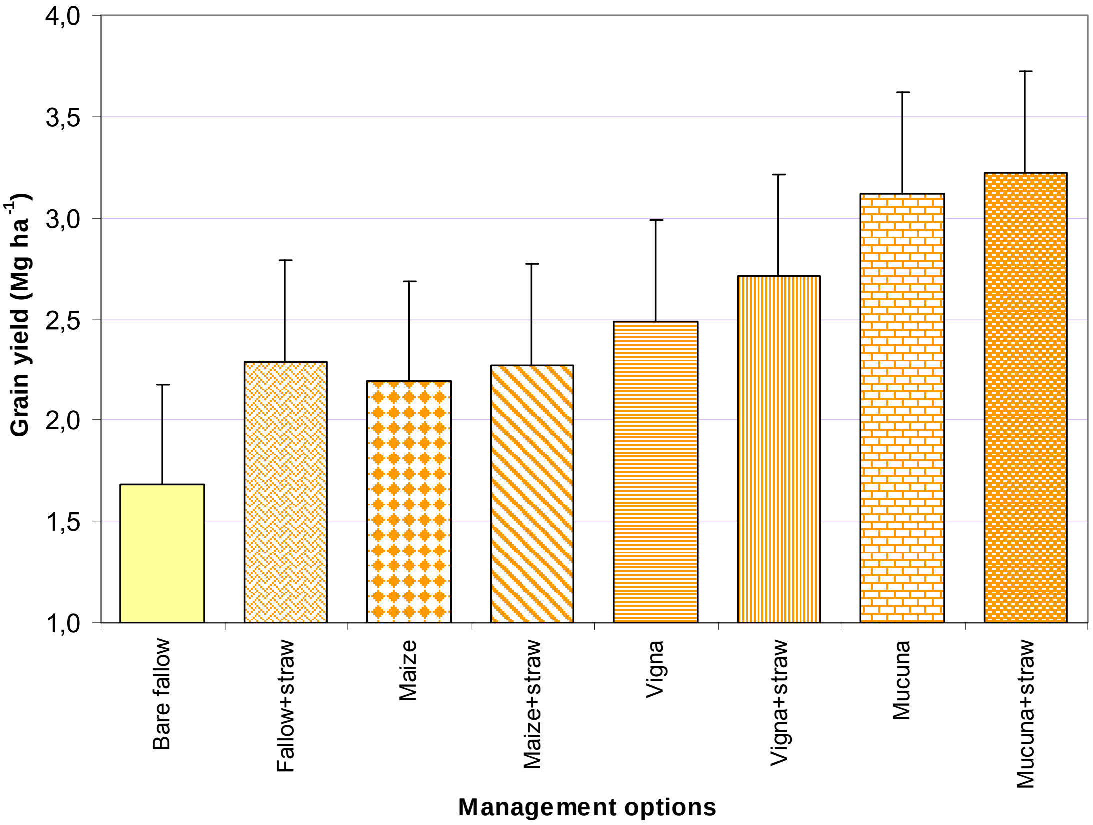

Figure 20. Grain yield (Mg ha^{-1}) of wet season rice as affected by crops and straw management treatments applied during the dry-to-wet season transition period (on-farm experiment, Rampur, Chitwan province, Nepal, 2003). Bars presents standard errors of the means (n=3).

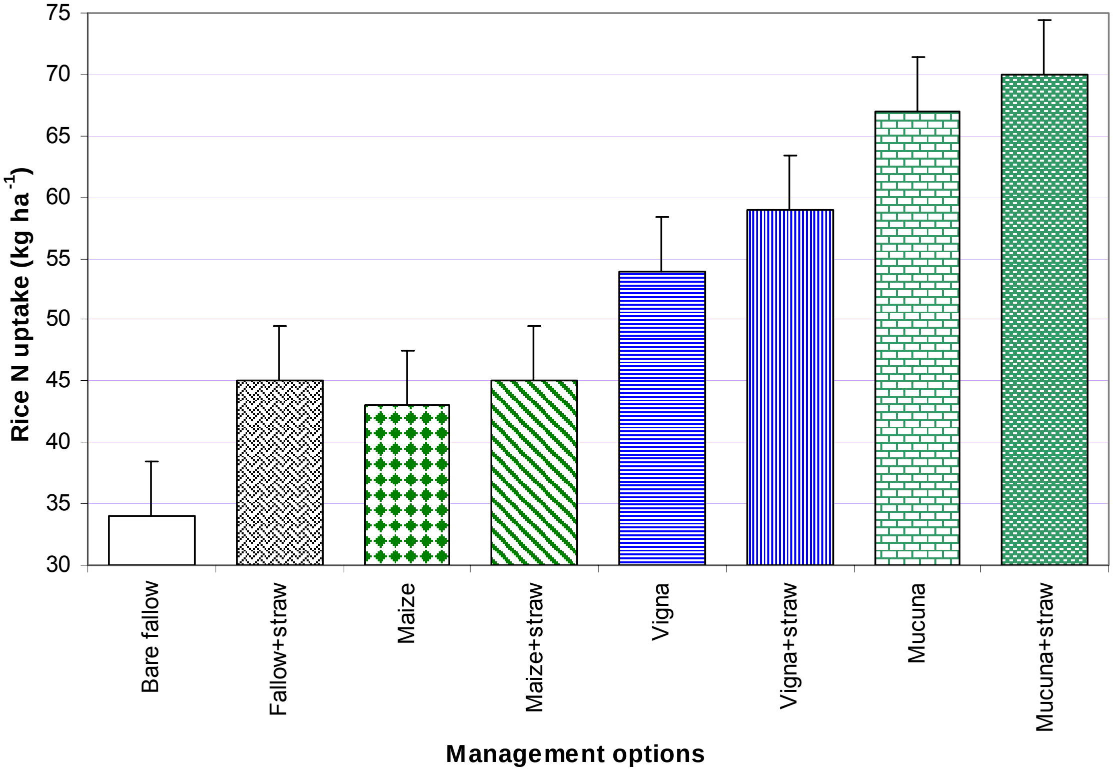

Figure 21. N uptake by summer season rice as affected by straw and crop management during dry-to-wet season transition (on-farm experiment, Rampur, Chitwan province, Nepal, 2003). Bars presents standard errors of the means (n=3).

4.4. Nitrogen balance (on-farm and on-station field experiments)

Straw and crop management options applied during DWT affected the extent of soil N conservation. At the end of the DWT, 8-12 kg N ha^{-1} has been lost by nitrate leaching from bare fallow (control) plots. The largest native soil N depletion occurred with maize cultivation as much crop biomass was removed from the system for food and feed purpose.

Both legumes (mucuna and mungbean) were able to conserve soil N while adding additional N from atmospheric N_2 fixation. At the end of the DWT, the N balance was positive in the wheat straw amended mucuna (85-89 kg N ha^{-1}), the wheat straw-amended mungbean (47-70 kg N ha^{-1}). The mucuna (55 kg N ha^{-1}) and the mungbean treatments (24-45 kg N ha^{-1}) primarily as the result of atmospheric N addition (44-80kg N ha^{-1}) and reduced nitrate leaching (7-12 kg N ha^{-1}). In contrast, the N balance was generally negative in control and maize treatments (-8 to -24 kg N ha^{-1}) and neutral with straw application to the bare fallow (Table 11).

Table. 11. Nitrogen balance (kg ha^{-1}) at the end of the dry-to-wet transition season in a rice-wheat cropping system as affected by soil and crop management treatments applied during the transition season (field experiment, Chitwan province, Nepal, 2001 and 2003).

	--------------------Treatments applied in dry-to-wet transition season-----------------------------							
Experiment	Bare fallow (control)	Maize	Fallow + straw	Maize + straw	Mungbean	Mungbean + straw	Mucuna	Mucuna + straw
On-station trial 2001 (n=4)	-12	-9	+7	+2	+22	+53	+42	+71
On-station trial 2003 (n=4)	-12	-24	+7	-9	+44	+70	+55	+89
On-farm trial 2003 (n=3)	-8	-24	-7	-11	+25	+47	+55	+85
Mean N balance (n=11)	-11	-19	+2	-6	+30	+57	+51	+81
Mean N balance corrected for native soil N supply	±0	-8	13	+5,	+41	+68	+62	+92

The differences in the balance at the end of the DWT were reflected in the N nutrition of a succeeding crop of rice with the lowest rice N uptake in the bare fallow control and the highest in the wheat straw-amended mucuna treatments. At the end of wet season, N balances were negative irrespective of the DWT treatments. The highest N depletion of 89 kg ha^{-1} (sum of DWT and wet season) was observed in the maize pre- treatment, while the lowest N depletion was observed in the wheat straw-amended mungbean (9.7 Mg ha^{-1}) and mucuna (6 Mg ha^{-1}) pre- treatments. (Table 12). Immobilization of soil N_{min} in the microbial and plant biomass and large amount of N addition via BNF are possibly responsible for less negative N balance in these treatments).

The N balances observed at the end of DWT and rice seasons also affected the grain yield and N uptake by wheat. The additional N depletion by wheat amounted to 31 kg ha^{-1} in the bare fallow control to 26 kg N ha^{-1} in the maize treatment.

The largest N (52 kg ha^{-1}) depletion during the winter season was occurred in the wheat straw amended mucuna pre-treatment. Positive N balance after rice and higher N uptake by wheat indicate significant residual effects of wheat straw-amended mucuna pre-treatment on N nutrition of winter season wheat. At the end of the cropping cycle, the net N balance was calculated and the negative N balance was most pronounced in the control and maize treatments and least in the straw amended legumes. These better treatments also resulted in the largest cumulative grain yields (rice+wheat) which exceeded those of the bare fallow controls by 1.2-3.1 Mg ha^{-1} (Table 13).

Table. 12. Nitrogen balance (kg ha^{-1}) of the transition and rice-growing season in a rice-wheat cropping system as affected by soil and crop management treatments applied during the dry-to-wet season transition season (field experiment, Chitwan province, Nepal, 2001 and 2003).

Experiment	---------------------Treatments applied in dry-to-wet transition season------------------------------							
	Bare fallow (control)	Maize	Fallow + straw	Maize + straw	Mungbean	Mungbean + straw	Mucuna	Mucuna + straw
On-station trial 2001 (n=4)	-30	-38	-52	-48	-34	-7	-10	+1
On-station trial 2003 (n=4)	-46	-41	-66	-58	-21	+10	-22	+6
On-farm trial 2003 (n=3)	-43	-40	-67	-57	-30	-14	-12	+14
Mean N balance (n=11)	-40	-40	-62	-54	-28	-4	-15	+7
Mean N balance corrected for native soil N supply	±0	±0	-22	-14	+12	+36	+25	+47

Table. 13. Nitrogen balance (kg ha^{-1}) of a rice-wheat cropping system as affected by soil and crop management treatments applied during the dry-to-wet season transition season (on-station experiment, Chitwan province, Nepal, 2003, n=4 reps.).

Cropping Season	Parameters	Treatments applied during the dry-to-wet season transition period of 2003							
		Bare fallow	Fallow + straw[1]	Maize	Maize + straw	Mungbean	Mungbean + straw	Mucuna	Mucuna + straw
Dry-to-wet season transition period	N addition by straw[1]	0.0b	+10.0a*	0.0b	+10.0a	0.0b	+10.0a	0.0b	+10.0a
	N addition by BNF[2] (δ^{15}N estimate)	0.0d	0.0d	0.0d	0.0d	+52.0c	+67.0b	+56.0c	+80.0a
	N removal by crops	0.0a	0.0a	-54.0b	-48.0b	-80.0c	-90.0c	-108.0d	-116.0e
	N returned by crop residues	0.0e	0.0e	+31.0d	+30.0d	+75.0c	+84.0c	+108.0b	+116.0a
	N loss by leaching[3]	-12.2d	-3.0c	-0.7a	-0.6a	-2.2bc	-1.3ab	-0.6a	-0.6a
	N balance at the end of DWT[4] (excluding gaseous losses)	-12.2e	+7.0d	-23.7f	-9.4e	+44.8c	+69.7b	+55.4c	+89.4a
Wet season (Rice-growing season)	N removal by crops (grain+straw)	-33.0a	-47.0bc	-41.0ab	-47.8bc	-64.8d	-59.3cd	-77.2e	-82.6e
	N loss by leaching	-0.6a	-0.6a	-0.9a	-0.8a	-0.7a	-0.7a	-0.6a	-0.8a
	N balance after rice harvest (excluding gaseous losses)	-33.6a	-47.6bc	-41.9ab	-48.6bc	-65.5d	-60.0d	-77.9e	-83.4e
Dry (wheat-growing) season	N removal by crops (grain+straw)	-31.0a	-41.0b	-26.0a	-27.0a	-41.5b	-44.5bc	-45.0bc	-52.0c
	N loss by leaching	-1.0ab	-1.2abc	-0.9a	-0.9a	-1.6c	-1.6c	-1.5bc	-1.5bc
	N balance after wheat harvest (excluding gaseous losses)	-32.0a	-42.2b	-26.9a	-27.9a	-43.1b	-46.1bc	-46.5bc	-53.5c
Whole cropping system (transition, wet and dry seasons)	N balance at the end of DWT (excluding gaseous losses)	-12.2e	+7.0d	-23.7f	-9.4e	+44.8c	+69.7b	+55.4c	+89.4a
	N balance after rice harvest (excluding gaseous losses)	-33.6a	-47.6bc	-41.9ab	-48.6bc	-65.5d	-60.0d	-77.9e	-83.4e
	N balance after wheat harvest (excluding gaseous losses)	-32.0a	-42.2b	-26.9a	-27.9a	-43.1b	-46.1bc	-46.5bc	-53.5c
	Total N balance in the system	-77.8de	-82.8ef	-92.5f	-85.9ef	-63.8c	-36.4a	-69.0cd	-47.5b

*Values follow by the same letter within one row do not differ significantly by DMRT (0.05).

[1] Incorporation of 2 Mg ha^{-1} of wheat straw from the preceeding wheat crop

[2] Biological Nitrogen Fixation

[3] determined by using ion exchange resin tubes

[4] DWT indicates Dry-to-wet season transition period

5. Discussion

The present research could show that soil N follows very dynamic transformation processes in rice-wheat rotation systems. Most intense mineralization and loss processes occur during the transition season (DWT) between the harvest of wheat and the transplanting of flooded rice. Depending on climatic conditions, the soil type, and the duration of DWT and in the absence of conservation measures 51-75 kg NO_3-N ha^{-1} can accumulate in the topsoil with the onset of the rainy season and are nearly completely lost via leaching and denitrification as the soil gets saturated at the onset of the main monsoon season. Such massive N losses are particularly unacceptable in the low-input production systems of Nepal, where mineral N fertilizer use is very low, where crops rely largely on native soil N for their nutrition, and where the yields of both rice and wheat are widely limited by N deficiency.

The following chapters will discuss the dynamics, processes and the extent of soil and crop N transformations in rice-wheat rotation system of Nepal and provide a critical evaluation of the diverse management options aiming at soil N conservation.

5.1. Soil N dynamics

Understanding the factors governing the transformation of organic amendments and of soil organic matter is essential for managing nitrogen in the soil. The soil temperature, soil moisture, quality of organic amendments, soil physico-chemical properties and soil microbial activity are the main determining factors in native soil N dynamics.

With the onset of monsoon rains, lowland rice is transplanted and mineral N available in the soil is gradually taken up and used by the growing crop. During the initial two weeks after rice transplanting seedlings are still weak, taking up very little N and there is potential for soil N losses to occur. After that stage soil N losses are reduced as the result of rapidly increasing N uptake by growing rice. However, as rice in Nepal is grown under flooded condition and the day temperature in the floodwater can be high, losses by ammonia volatilisation may occur. With nitrification being inhibited in the anaerobic soil and the commonly practiced soil puddling results in the formation of an impermeable layer below the root zone (hard pan), leaching losses are minimal during the rice-growing period.

After rice harvest during the cold and dry winter season, wheat is grown on residual moisture under aerobic conditions. Here, nitrification can occur and leaching of nitrate is possible because of soil ploughing and a partial destruction of the hard pan before wheat seeding. In the present study, N losses by nitrate leaching were very low, irrespective of the management pre-treatment applied. Continuous N uptake by growing wheat plants and a very low rainfall on unsaturated soil has possibly minimized the potential for leaching to occur.

Hence during both the anaerobic rice growing and the aerobic wheat-growing phase native soil N losses by leaching or denitrification were low. This situation was dramatically changed during the 6-12 weeks-long transition period, when soils are bare of vegetation and the soil aeration status gradually changes from aerobic to anaerobic conditions (see conceptual diagram).

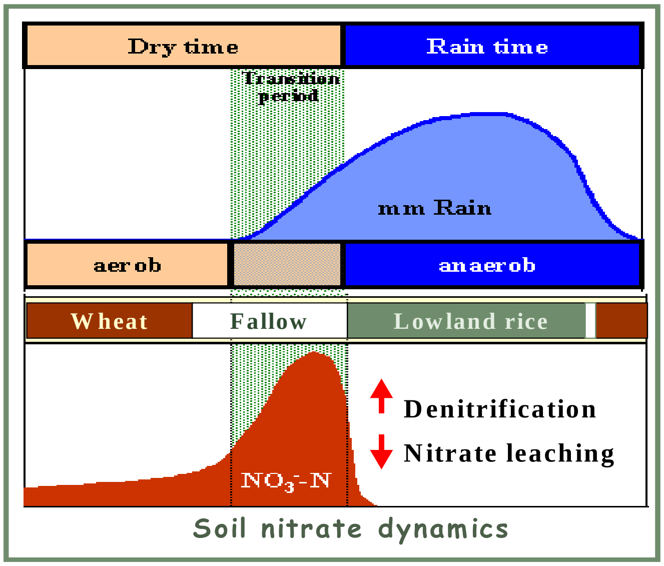

Figure 22. Conceptual relationships between season, soil aeration status and soil nitrate (adapted from Bognonkpe and Becker, 2000).

During this relatively short transition period, soil undergoes under several cycles of drying and wetting until soil submergence at the onset of the monsoon rains. Soil N mineralization is stimulated, initially aerobic conditions favour the microbial oxidation of ammonium into nitrate (nitrification), and subsequent soil submergence will favour both leaching and microbial reduction processes (including denitrification).

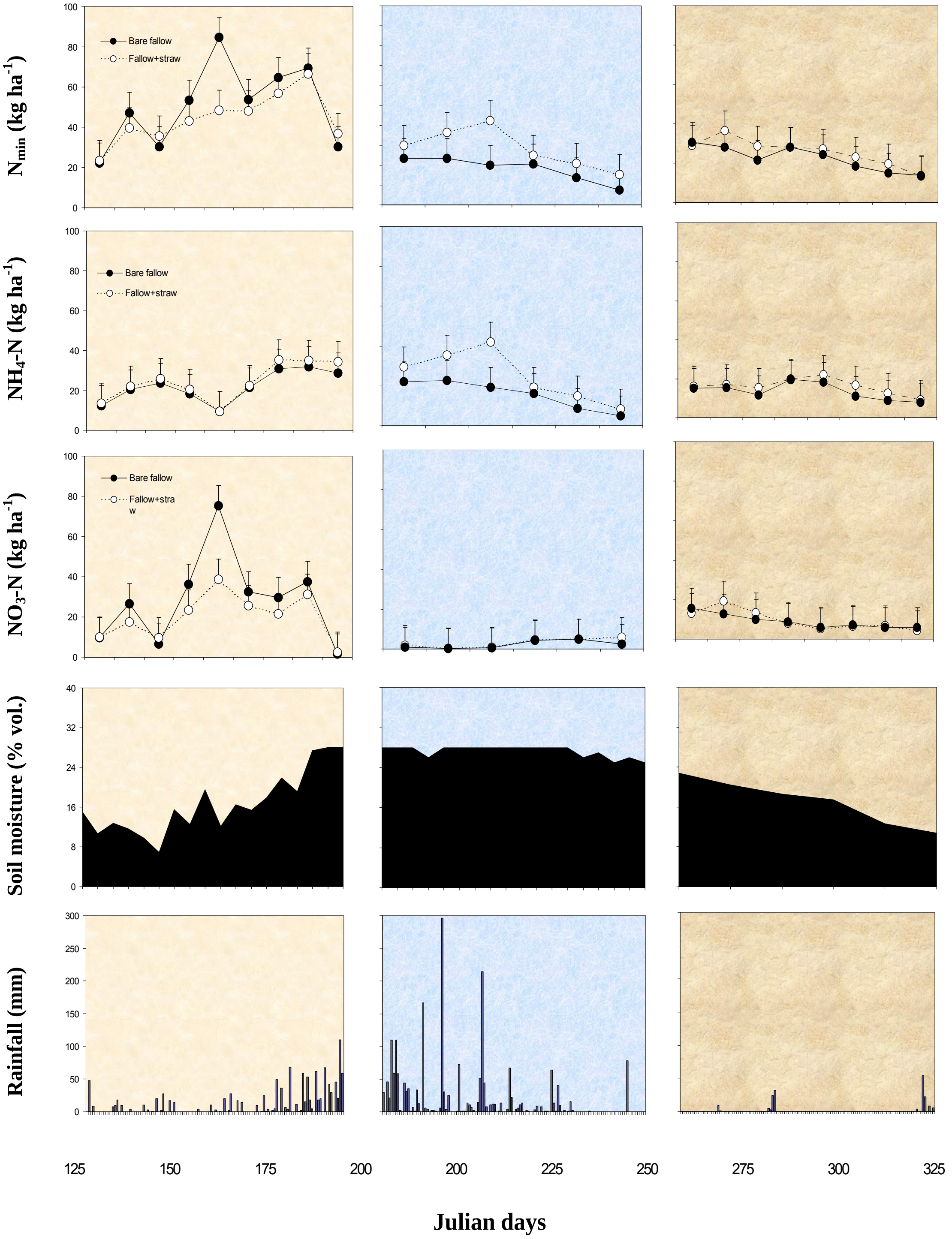

Figure 23. Effects of wheat straw application during the dry-to-wet transition season on dynamics of soil N_{min} (nitrate and ammonium) (on-farm experiment, Rampur, Chitwan province, Nepal, 2003). Bars presents standard errors of the means (n=3).

As reported by Hynes, (1986), Addiscott, (1983), and Kanal, (1995), soil organic matter decomposition and N mineralization show complex interactions with microbial populations and environmental factors, particularly with soil moisture and temperature. In the present study, soil N dynamics were linked to variations in soil moisture content, a modification of the C:N-ratio via straw addition (temporary microbial N immobilization), and N uptake by crops grown during the transition season (N immobilization in the plant biomass.

Soil N mineralization showed high temporal dynamics and was strongly affected by management options. Generally, the highest NO_3-N built up was observed at soil moisture content of 60-75% FC under bare fallow management (farmers' practice). Other workers observed peak microbial activities at similar soil moisture levels in incubation studies and under field conditions (Inubushi *et al.,* 1996) peak at 60% FC and Flessa *et al.,* (1996) and Bollmann and Conrad, (1998) at <80% FC). Thus, it appears that 60-75% FC is most favourable for the activity of nitrifying bacteria. This peak of soil NO_3-N observed in 2003 was much higher than in 2001 in the same plot. In 2003 the soil drying and wetting cycles were more frequent and more severe than in 2001. Larger soil N_{min} peaks under frequent soil drying and wetting than under continuous soil moisture conditions have been linked to an enhanced activity of nitrifying bacteria resulting in large amounts of NO_3-N built up in the soil (Müller, et al., 2002, Sehy, et al., 2004).

A number of studies on the N dynamics in seasonally flooded soils of South Asia, Southeast Asia, and West Africa highlighted the occurrence of the Birch effect (N mineralization peak) after the first rains and the near complete disappearance of the nitrate fraction at the beginning of the main wet season (Pande and Becker, 2003, George *et al.,* 1995, Bognongkpe and Becker, 2000, Engels *et al.,* 1995, Shrestha *et al*., 1998, Shrestha and Ladha, 1998). Estimated amounts of N lost in the course of soil flooding ranged from 20 to 90 kg ha^{-1} and were generally more in Molli- and heavy textured Inceptisols than in the Alfi- and Ultisols. Furthermore, both mineralization and subsequent nitrate losses were enhanced by intense soil tillage in the course of land preparation during the transition season (George *et al.,* 1992).

As nitrate is soluble in water and not sorbed onto the negative charge sites of the clay minerals, leaching losses are likely to account for much of the reported N losses on light textured soils and in the absence of a hard pan. On the other hand, the microbial reduction of nitrate (denitrification) is hypothesized to have accounted for nitrate disappearance in clay and in soils with large amounts of easily mineralizable organic material. Thus, numerous authors reported large N losses by denitrification after soil flooding (Bacon *et al.,* 1986, Bognongkpe and Becker, 2000, Davidson *et al.,* 1986). We conclude that the disappearance of 7-25 mg NO_3-N kg^{-1} soil in the pot experiments and of 47-73 kg NO_3-N ha^{-1} in the field during DWT may be attributed to denitrification in the greenhouse study (closed-bottom pots) and probably a combination of nitrate leaching and denitrification under the field conditions. However the determined amounts of up to 20 kg ha^{-1} of nitrate leaching and up to x μM N_2O h^{-1} m^{-2} do not fully account for the measured native soil N losses of up to 70 kg ha^{-1}.

Crop residues with a wide C: N ratio such as straw can temporarily immobilize soil N in the microbial biomass, resulting in less soil N_{min} available for plant uptake but also for microbial transformation or physical movements. Nitrogen immobilization in lowland soils after application of crop residues with a wide carbon to nitrogen (C:N) or lignin to nitrogen ratio (L:N) has been reported (Becker *et al.,* 1994, Motavalli and Diambra, 1996, Haynes, 1986). In the pot experiment in the greenhouse, we observed a reduction in soil NO_3-N content from 25 to 0.3 mg N kg^{-1} after 3 weeks of straw application. Similarly, a temporary immobilization of soil N after incorporation of rice straw into lowland Mollisol in the Philippines (Becker *et al.,* 1994) and after application of Municipality Solid Waste Compost with a C: N ratio of 40:1 in an Alfisol of East Africa (George *et al.,* 1999) has been reported. In the present study the peak of soil NO_3-N reduced by 47% after application of wheat straw at the rate of 3 Mg ha^{-1} in the green house and by 50-75% after incorporation of wheat straw (depending on the rate and the application method) in the field in Nepal. A reduction in soil N_{min} after the application of wheat straw was linked to a parallel increase in the amount of soil microbial biomass N under greenhouse conditions.

5.1.1. N losses from seasonally wet soils:

A number of studies on the N dynamics in seasonally flooded soils of South Asia, Southeast Asia, and West Africa highlighted the occurrence of the Birch effect (N mineralization peak) after the first rains and the near complete disappearance of the nitrate fraction at the beginning of the main wet season (Pande and Becker, 2003, George *et al.,* 1995, Bognongkpe and Becker, 2000, Engels *et al.,* 1995, Shrestha et al., 1998, Shrestha and Ladha, 1998). Estimated amounts of N lost in the course of soil flooding ranged from 20 to 90 kg ha^{-1} and were generally more in Molli- and heavy textured Inceptisols than in the Alfi- and Ultisols. Furthermore, both mineralization and subsequent nitrate losses were enhanced by intense soil tillage in the course of land preparation during the transition season (George *et al*., 1992). As nitrate is soluble in water and not sorbed onto the negative charge sites of the clay minerals, leaching losses are likely to account for much of the reported N losses on light textured soils and in the absence of a hard pan. On the other hand, the microbial reduction of nitrate (denitrification) is hypothesized to have accounted for nitrate disappearance in clay and in soils with large amounts of easily mineralizable organic material. Thus, numerous authors reported large N losses by denitrification after soil flooding (Bacon *et al.,* 1986, Bognongkpe and Becker, 2000, Davidson *et al*., 1986). We conclude that the disappearance of 7-25 mg NO_3-N kg^{-1} soil in the pot experiments and of 47-73 kg NO_3-N ha^{-1} in the field during DWT may be attributed to denitrification in the greenhouse study (closed-bottom pots) and probably a combination of nitrate leaching and denitrification under the field conditions. However the determined amounts of up to 20 kg ha^{-1} of nitrate leaching and up to x μM N_2O h^{-1} m^{-2} do not fully account for the measured native soil N losses of up to 70 kg ha^{-1}.

5.1.2. Reduced soil N mineralization

The extent of soil N losses will in the first place depend on the amount of N_{min} present in the soil and hence prone to loss mechanisms. Reducing the available soil N_{min} or avoiding its build-up will reduce the loss potential. Possible options include soil N absorbance by growing crops, its temporary immobilization in the microbial biomass or other (chemical and biological) means that minimize the activity of nitrifying bacteria (i.e. nitrification inhibitors such as neem tree extract, nytropyrin, or di-cyan-diamid or ecological conditions affecting nitrification such as reduced redox potential and soil acidification).

a). Temporary immobilization in SMB

Crop residues with a wide C/N-ratio such as straw can temporarily immobilize soil N in the microbial biomass, resulting in less soil N_{min} available for plant uptake but also for microbial transformation or physical movements. N net N immobilization after application of crop residues with a wide carbon to nitrogen (C:N) or lignin to nitrogen ratio (L:N) was previously reported (Becker *et al.,* 1994, Motavalli and Diambra, 1996, Haynes, 1986). In the pot experiment in the greenhouse, we observed a reduction in soil NO_3-N content from 25 to 0,3 mg N kg^{-1} after 3 weeks of straw application. Similarly, observed a temporary immobilization of soil N after incorporation of rice straw into a lowland Mollisol in the Philippines (Becker *et al.,* 1994) and George *et al.,* (1999) observed a large N immobilization with the application of Municipality Solid Waste Compost (MSWC) with a C: N ratio of 40:1, in an Alfisol in the fields with an inverse relationship between the amount of MSWC used and the extent of nitrate immobilization. In present study the peak of soil NO_3-N reduced by 47% after application of wheat straw at the rate of 3 Mg ha^{-1} in the greenhouse and by 75% after incorporation of wheat straw (at the rate of 2 Mg ha^{-1}) in the field in Nepal. The reduced N_{min} after the application of wheat straw was linked to the microbial biomass N present in the soil.

Micro-organisms are the driving force for organic matter mineralization, build-up and nutrients transformations in the soil. Their activity depends on both the quantity and the quality of organic amendments (Kumar and Goh, 2000). In general, organic materials with C/N-ratio >30 will cause temporary immobilization of soil or fertilizer N, while substrates with a C/N-ratio of ≤20 will result in net nutrient release (Jenkinson, 1990). Malik *et al.,* (1998) observed a large increase in soil microbial biomass after incorporation of organic substrates such as wheat straw and green manure in rice-wheat cropping systems of India. Beri *et al.,* (1992) and Sidhu *et al.,* (1995) observed 5-10 times more soil aerobic bacteria and 1.5 to 11 times more soil fungi in crop residue amended soils than in soils where crop residue had been removed or burned. Stevenson (1986) observed soil N immobilization with the application of low quality crop residues associated with an increase in soil microbial biomass. The present study in the greenhouse showed three times more soil microbial biomass N (SMB-N) with wheat straw incorporation than with wheat straw mulching, and up to 5 times more SMB-N than in the unamended control. Similar results were observed by Kumar and Goh, (2000), Malik *et al.,* (1998), and Sidhu *et al.,* (1995).

Similar to the method of application, SMB-N increased with the amount of straw applied, at approximately the same rate as soil N_{min} declined. Larger amounts of straw applied to the soil provide more energy substrates to the microbial population for their growth. However, the size and the composition of the microbial community depend also on the quality of the residues applied (Broder and Wagner, 1988).

Kumar, (1998) and Campbell *et al*., (1991) observed increased fungal community size after application of non-legume residues and increased bacterial populations after application of legumes residues to the soil. In the present field experiments both wheat straw (non-legume residue) and green manure (legume residue) were incorporated, thus both fungi and bacterial communities are likely to have increased.

b). Absorbance by growing vegetation:

Compared to the bare fallow control (farmers' practice in Nepal), growth of the "nitrate catch crops" mucuna, maize and mungbean during DWT reduced soil NO_3^-N by 88% in the greenhouse and by 67-86% in the field and that was closely related to the N uptake by the crops from the soil pool. Maintaining a vegetative cover of the soil during DWT acted as a sink for soil N by absorbing between 15 kg N ha^{-1} in weedy fallow (West Africa) and 65 kg N ha^{-1} in *Sesbania sp*. (The Philippines) and thus preventing N losses. Shrestha and Ladha (1998) reported 10 to 68% reduction in soil nitrate from rice-sweet pepper cropping system when crops (maize, indigo, and mungbean) were grown as N-catch crops during DWT on an Inceptisol. George *et al.,* (1994) reported a reduction in nitrate-N losses from 107 to less than 20 kg ha^{-1} when green manure legumes occupied the field during DWT on a Mollisol in rainfed lowlands of the Philippines. Buresh *et al.,* (1989) observed an inverse relation between N accumulation by dry season crops (legumes and weeds) and NO_3-N content in the soil. Hartemink *et al.,* (1996) observed significantly (P=0.05) reduced NO_3-N content in the topsoil when growing sesbania, maize and weeds rather than leaving the land to bare fallow in the humid zone of Kenya. Similarly, our observations in Nepal showed an inverse relation between N accumulation by plant and soil nitrate concentration.

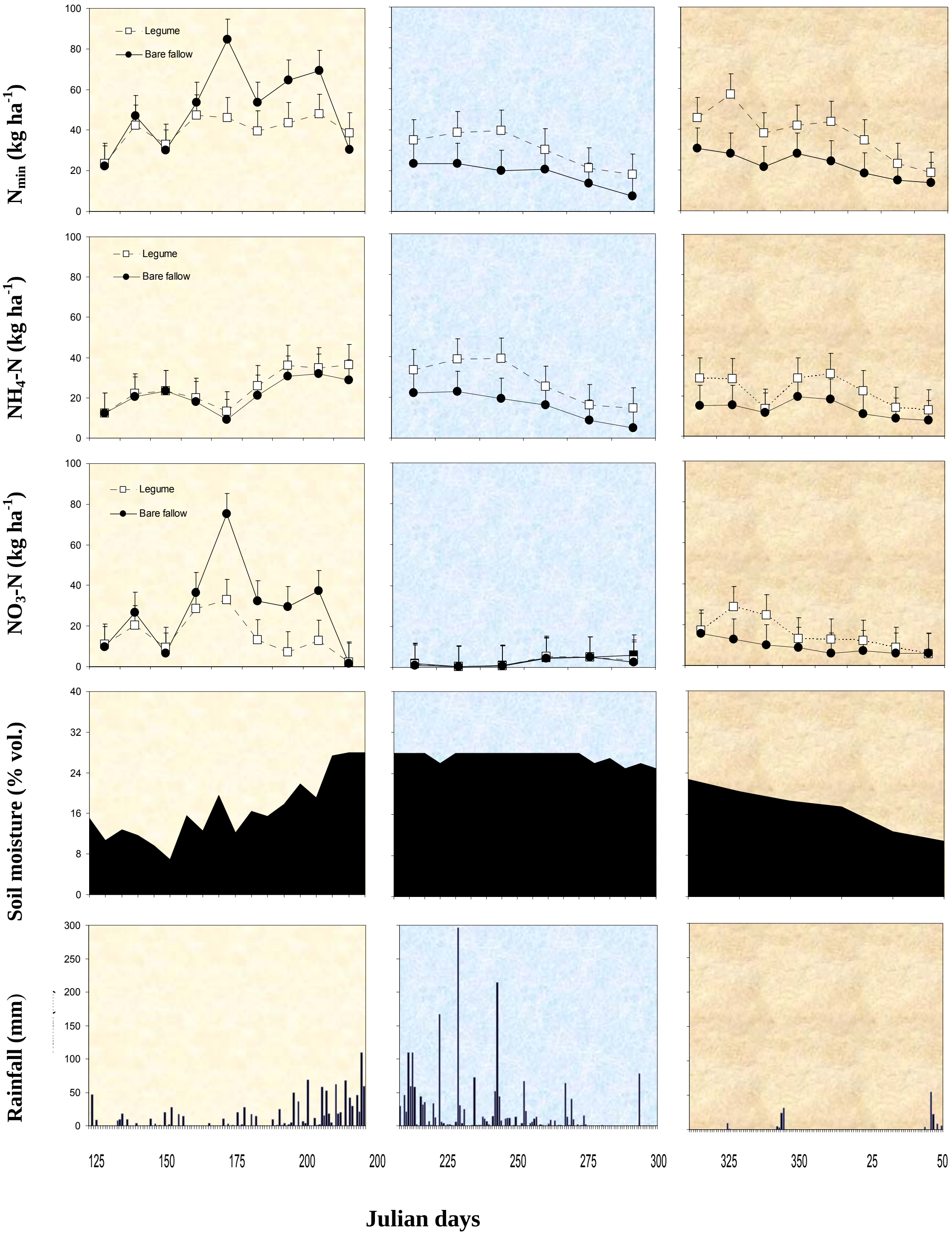

Figure 24. Effects of growing legumes during the dry-to-wet transition season on dynamics of soil N_{min} (nitrate and ammonium). On-farm experiment, Rampur, Chitwan province, Nepal, 2003. Bars presents standard errors of the means (n=3).

5.1.3. Denitrification

As NO_3-N is negatively charged and not sorbed onto clay particles, it is prone to losses, particularly by leaching in sandy soils but also by denitrification, particularly in saturated clay soils (Bacon *et al.,* 1986, Bognongkpe and Becker, 2000, Davidson *et al.,* 1986).

In present study, large nitrous oxide emissions observed from the lowland fields of rice-wheat annual rotation system in during DWT. Nitrous oxide (N_2O) is a climate-relevant trace gas contributing to an estimated 5% of the total global warming by direct absorbance of infrared radiation and by destructing the ozone layer (Crutzen, 1981). Its half-life (persistency) is 150 years (Bouwman, 1990) and there is no chemical sink for N_2O in the troposphere. About 50% of its production is derived from the soil and agricultural activities (Bauwman, 1996). In an incubation study, Hütsch *et al.,* (1999) observed a significantly higher amount of emission by changing the soil water content from 60% to 120% FC. Inubushi et al, (1996) observed an increased N_2O emission in NH_4-N amended soil with a sharp declining NH_4-N and increasing NO_3-N concentrations in soil at 60% FC. Flessa *et al.,* (1996) and Bollmann and Conrad (1998) determined nitrification as the main determining process for N_2O emission in soil with < 80% FC. Abbasi *et al.,* (2003) observed a significantly reduced NO_3-N formation and reduced N_2O emission in the soil after application of nitrification inhibitor nitrapyrin in incubation experiments. Linn and Doran (1984), Parton *et al.,* (1996) observed the best condition for nitrifiers at 60% FC with large associated N_2O emissions. They also observed a reduced nitrifying activity both below and above 60% FC soil moisture (Bollmann and Conrad, 1998). In rice fields, high emissions occurred with alternate drying and rewetting provided that mineral N was present in the soil before rewetting (Davidson, 1992, Yue *et al*, 1997). By alternate draining and flooding in rice fields Xing and Zhu (1997) observed 4 times higher N_2O emission than with continuous flooding in southern China. A study conducted from 1992 to 1997 in Germany, reported reduced N losses in the form of N_2O from six arable field soils by increasing the efficiency of crop production and N uptake (Kaiser and Ruser, 2000). The present study showed peaks of N_2O emissions under bare fallow management during DWT at a soil moisture of 75% FC as well as immediately after soil flooding. The initial peak was probably associated with nitrification and the later peak with denitrification. Application of wheat straw and growth of DWT crops significantly (P=0.05) reduced both NO_3-N built-up in the soil as well as N_2O emissions. The lowest emissions were recorded in wheat straw amended mucuna plots where both N_{min} immobilizations by plants and in the microbial biomass resulted in a massive reduction of soil N_{min}. In Nepalese rice wheat system especially in small scale farming; the use of nitrification inhibitor nitrapyrin is impracticable because of poverty of he farmers and unavailability of the chemicals. Thus, growth of DWT crops like mucuna in combination with wheat straw could be one best option to reduce the nitrate built up in the lowland fields.

5.1.4. Nitrate leaching

NO_3-N being negatively charged and highly soluble in water is prone to be moved in the soil profile and between field plots by irrigation- and rainwater. Moreels *et al.,* 2003 and Mary *et al.,* 1999) summarized the factors governing N losses by percolation and runoff. While the cationic ammonium-N is being adsorbed, the anionic NO_3-N cannot be sorbed onto clay minerals. It is highly soluble in water and leaching losses are likely to increasingly occur with nitrate content, soil pore size distribution, pore space and pore water saturation as well as the amount and intensity of rainfall or irrigation events.

Kladivko *et al*, (2004) observed reduced nitrate leaching from a topsoil of Indiana by growing nitrate trap crops in corn-soybean rotation system during the fallow period, Shrestha and Ladha (1998) observed significantly (P=0.05) reduced NO_3-N leaching from the plots where maize, indigo, and mungbean were grown as N-catch crops during DWT than bare fallow control on an Inceptisol in the Philippines, integration of *Sesbania sesban*, *Zea mays* and weedy fallow into agricultural land use system Hartemink *et al.,* (1996) observed a significantly reduced NO_3-N leaching from the topsoil than bare fallow and there was increased utilization of subsoil N under Sesbania and weedy fallow treatments than maize and bare fallow and Woodard *et al* observed significantly reduced nitrate leaching from topsoil in Burmuda grass-rye rotation system with an inverse relation of nitrate leaching and N uptake efficiency of the grown crop.

In present study, the highest amount of NO_3-N leaching was observed in the bare fallow treatment during DWT. The application of wheat straw significantly (P=0.05) reduced the leaching loss and it could be associated with the reduced build up of

NO_3-N in the soil caused by immobilization of soil N_{min} in the microbial biomass N. The lowest amount of leached NO_3-N was observed in the wheat straw amended mucuna treatment where the combined effects of soil N immobilization in the microbial biomass N and efficient uptake of soil N_{min} by the growing mucuna crop have minimized the potential for N losses to occur. This conservation of native soil N during DWT may help in N nutrition of succeeding crops.

In the seasonally wet soils of the rice-wheat rotation, massive soil N losses occur during the dry-to-wet season transition period. Their extent is determined by the soil N mineralization rate and potential and is in most cases linked to the nitrate form. Both nitrate leaching and the microbial reduction of nitrate are responsible for N_{min} losses during the transition season. Any technical option that avoids N mineralization or the build-up of nitrate in the soil will contribute to reduce N losses and to conserve native soil N. The efficiency of temporary immobilization in the soil microbial biomass, e.g. by wheat straw application, depends on application rate and method. Soil N absorption by growing crops depends on the climatic conditions for crop growth and on growth vigour and N uptake potential. Irrespective of the site, the soil or the year, combining wheat straw incorporation with green manure growth was most effective in avoiding soil N mineralization and limiting N losses by leaching and denitrification.

5.2. Crop N dynamics

Nitrogen accumulation by a crop depends upon the amounts of mineral N present in the soil, the prevailing climatic conditions and the capacity and efficiency of the plant for N uptake. In present study, N accumulation by maize was 48 kg ha^{-1} (average of on-farm and on-station experiments) but N accumulation by both mucuna and mungbean was much higher. The high N accumulation by both legumes was associated with a large share of atmospheric N fixation. The N accumulation by maize was reduced with wheat straw amendment. As maize is almost depending on soil N_{min} for its nutrition, wheat straw application has resulted in a temporary immobilization of soil mineral N. However, wheat straw amendment increased the N accumulation by the legumes by about 40% (>20 kg ha^{-1} in the case of mucuna and by >15 kg ha^{-1} in the case of mungbean). This wheat straw-induced increase was related to a significant stimulation of N_2 fixation, while soil N uptake was reduced as observed in the case of maize. Combined nitrogen (from soil N_{min} or mineral fertilizer sources) competes with biological N_2 fixation for energy and carbohydrates for N assimilation.

Hence, a reduction in the amount of available N_{min} avoids the occurrence of an N-induced BNF inhibition and can reportedly stimulate not only the share (%Ndfa) but also the amount (kg N ha^{-1}) of N_2 fixation by root-nodulating legumes (George *et al.,* 1994, Becker and George, 1995). Additionally, wheat straw amendment can increase the availability of energy substrates and thus enhance the activity of root-associated N_2-fixing bacteria (Ladha *et al.,* 1992). As wheat straw in Nepal is frequently burnt in the field, its application will not only enhance BNF of legumes but also contribute to the recycling of substantial amounts of K substantial amounts (0.61-0.98% in straw – Dobermann and Witt, 2003, Samra *et al*., 2003).

Plate 3. Vegetative growth of mucuna under field conditions during the dry-to-wet season transition period (Field experiment, Rampur, Chitwan province, Nepal, 2003).

Plate 4. Mungbean grown under the field conditions during the dry-to-wet season transition period (Field experiment, Rampur, Chitwan province, Nepal, 2003).

Grain yield is related to the amount of available N in the soil pool and to the N uptake capacity of the crop (Cassman *et al*., 1997). In the present study, the lowest N uptake by rice was observed following a bare fallow, a treatment which was associated with large N losses during DWT. On the other hand, soil amendment with low-quality (high C/N or L/N-ratio) crop residues also reduces the availability of soil N_{min}, i.e. by temporarily immobilizing soil N_{min} in the microbial biomass (Becker *et al.,* 1994). This “saved” N may however become plant available later and benefit the following crop of rice or the N balance of the production system. The effects of wheat straw incorporation on the grain yield of rice appear to be highly dependant on the soil and site characteristics as well as on the amount and the application method of straw. In a field experiment on a sandy loam Inceptisol in Haryana, India, Agrawal *et al.,* (1995) found no significant difference in rice yields between wheat straw incorporation and removal. However, Sharma and Mitra, (1992) observed significantly increased rice yield as well as residual effects on a succeeding crop of wheat with wheat straw incorporation in an acid clay loam soil in West Bengal. Other workers (Zia *et al*., 1992, Becker *et al.,* 1994, Sarkar, 1997,) reported direct beneficial effects of straw amendment on rice grain yield but only marginal or not significant carry-over effects on a subsequent crop. In the present study, the incorporation of wheat straw during DWT improved the N nutrition of wet season rice with significantly higher grain yield than in the bare fallow control. Conservation of mineral N during DWT in the microbial biomass N and avoidance of N losses by reducing the build up of NO_3-N during DWT had improved the N nutrition of rice and tended to increase N uptake by a subsequent crop of wheat. Application of wheat straw can be adopted in the mid-hills of Nepal where dry-to-wet season transition period is short and wheat straw has no economic value and farmers burn it in the field or in the threshing floor thinking that wheat straw is unfertile for the coming crops.

Growing legumes and recycling their biomass can improve soil fertility, increase the yield of the subsequent rice crop and reduces the requirement for chemical N fertilizer (Becker *et al.*, 1990, Ladha and Reddy, 2003, Becker 2002). The nitrogen fertilizer equivalence (NFE) for green manures and grain legume residues range from 37 to 120 kg ha^{-1} (Peoples *et al*., 1995, Becker, 2002). Differences in the N accumulation by legumes, in the recovery of incorporated N by rice and in the synchrony between residue N supply and crop N demand may explain the wide range in NFE (Becker and Ladha, 1996). Climatic conditions during the rice-growing season also considerably influence legume N use efficiency in lowland rice (Kundu *et al,* 1991). The comparative N contributions of green manure and dual purpose legumes to a succeeding rice crop depend on the nitrogen harvest index (NHI). Cowpea has lower NHI than soybean and mungbean (Myers and Wood, 1987). In a study in the Philippines, 40-day-old mungbean incorporated as a green manure accumulated 93 kg N ha^{-1}, where as matured mungbean produced 1.1 Mg ha^{-1} grain and its above ground residue contained only 31 kg N ha^{-1}. Grain yield of the following rice was higher after green manure (3.2 Mg ha^{-1}) than after residue incorporation (2.3 Mg ha^{-1}) (IRRI, 1984). In another study conducted in a nearby field, the differences in grain yield of rice following the incorporation of cowpea at flowering stage as a green manure (66 kg N ha^{-1}, C: N=15) and incorporation of cowpea residues after removal of grain and pods from mature plants (54 kg N ha^{-1}, C:N=28) were not significant (John *et al.,* 1989). Not all legumes seem to be able to efficiently absorb the available soil nitrate and thus protect it from losses during DWT. Giller (2001), Evans *et al.,* (1991); Herridge *et al.,* (1994b) and Herridge and Bergersen, (1988) reported this such called “nitrate sparring effect” on a wide range of mostly perennial legumes. If a crop does not absorb the available soil N, there is potential for substantial N losses (De Datta and Buresh, 1989, Vlek and Craswell, 1981).

Synchronization between N mineralization and plant uptake has been shown previously to contribute to reduced N losses and more increased N use efficiency by rice (Becker *et al*., 1994a). The N uptake by wet season rice both in the pot and the field experiment corresponded to the amounts of N conserved and/ or added during the transition period. Consequently, the highest rice yields were observed in straw amended green manure plots. In this case, wheat straw not only conserved soil N during DWT, but may also have improved the synchrony between the N supply from the soil with the N demand of rice as reflected in the increased agronomic use efficiency of applied green manure N. Similar findings were reported from studies by Becker *et al.,* (1994b) in the Philippines and Malik *et al*., (1997) in India. Other papers showed lowland rice yield increases above the bare fallow control treatments ranging from 0.4 to 1.2 Mg ha^{-1} depending on the site and the type of DWT vegetation (George *et al*., 1995, Shrestha and Ladha, 1999b, Bognonkpe and Becker, 2000).

The reported results show substantial yield gains with improved DWT crop and residue management. However, these rice yields were still low compared to the South Asian average of 3.5 Mg ha^{-1} (McLean, 1997) or the reported yield potential for Nepal of 8.1 Mg ha^{-1} (Rajbhandari and Upreti, 1997). This demonstrates the large potential for further productivity gains in rice-wheat systems of Nepal. While the proposed management strategies can effectively enhance N cycling in rice-wheat rotation. Bhardwaj *et al.,* (1981), Sharma and Mitra, (1988), Diekmann *et al.,* (1993) and Morris *et al.,* (1989) observed a significantly increased grain yield of the succeeding wheat crop when green manure legumes incorporated into the soil before rice. A residual effect of green manure N on second rice however was not detectable in 4 years of field experiments with green manure applications averaging 83 kg N ha^{-1} to wet season rice (Morris *et al.,* 1986). In the present study, the legume and the combination of straw and legume treatments applied during DWT significantly increased the grain yield and N uptake of both the rice and the wheat. The residual effects of green manure applied during rice and wheat straw applied during DWT on second rice was not studied.

Although the research results presented here are highly encouraging, the grain yield of rice is still low compared to the South Asian average. The production potential of 8

Mg ha^{-1} reported from Nepal (Rajbhandari and Upreti, 1997) underline the large remaining gap between actual and potential yields and thus, the potential to further improve the productivity of current rice-wheat systems in Nepal. The N balance study at the end of wheat harvest showed the lowest depletion of native soil N in wheat straw amended legume (mucuna and mungbean) treatments. However, there remains a large N depletion in all treatments. Hence, crop yields cannot be sustained in the long-term without the additional application of mineral fertilizers and/or compost and strategies that increase the efficiency of their use. The optimisation of the proposed systems, their extrapolation to suitable target environments and the further development site-, system- and season-specific production systems and technical options requires more and also longer-term research in a range of environments. Ideally this could happen along gradients from the mountains into the Terai or from strictly rural to market-oriented peri-urban areas. Finally, to ensure the adoption of proposed options, farmers’ participation in further activities will be imperative.

6. General Discussion

Periodic changes in soil aeration status stimulate the mineralization of soil organic matter, increase the emission of climate relevant trace gases and can result in substantial N losses. In natural wetland systems, trace gas emissions are largely restricted to methane, while mineral soil N is taken up by growing vegetation and gaseous N losses are minimal (Wassmann *et al.,* 2002, Sharma *et al.,* 2003). In anthropogenic systems, such as the rice-wheat rotations of S-Asia, soil tillage further stimulates mineralization and the absence of a crop cover during the phase of changing soil aeration status favours the occurrence of N losses. The present research has conclusively shown that much of the soil N mineralization and most nitrate-N losses occur during the dry-to-wet season transition period. These N losses are seen to be partially responsible for the low productivity and the reported declining production potential of the rice-wheat rotations of Nepal (Regmi, *et al.,* 2002). Characterized by low-input management with minimal additions of external N fertilizers (organic or inorganic), both crops largely rely on native soil N supply and N losses during the transition season will be reflected in N deficiency, low crop yields and largely negative N balances. Conserving native soil N, particularly during the transition season, is seen to be imperative for sustaining current production levels and avoid further productivity declines. Technical options may target either the avoidance of mineralization and/or the accumulation of nitrate or the (temporary) immobilization of soil N during DWT. Possible approaches include zero-tillage to minimize soil N mineralization (Carter and Rennie, 1982, Yamulki, S. and Jarvis, S.C., 2002), nitrification inhibitors to maintain soil N_{min} in the ammonium form, hence limiting N losses by leaching and denitrification (Menyailo and Huwe, 1999), or the conservation of soil N in the microbial biomass or in growing vegetation. Zero tillage is not applicable in rice-wheat rotations, where soil puddling before rice transplanting is required to reduce water percolation in the paddy field. Nitrification inhibitors such as DCD or ‘Didin’ and unavailable or expensive and the use of locally available neem extract has been reported to be effective (neem foundation) and but not economical. The two approaches discussed in this thesis, wheat straw application and transition season cropping, are seen to be the only available options for the Nepal situation. The present research has conclusively shown from both greenhouse experiments and in on-station and on-farm experiments at various field sites in Nepal that soil N can be managed more effectively than under the present farmers' practice with resulting benefits in terms of grain yields and systems' N balances. Nevertheless, the applicability of these options is likely to depend on the prevailing biophysical and socioeconomic conditions and needs to be discussed in a farming systems context. This involves (1) the existing cropping calendar with a length of DTW that varies along an altitude gradient between the lowlands and the mountains, and (2) the available resource base and the requirements of the farm households, which depend on production orientation, market access, and the presence of cattle.

The production of rice and wheat in the annual double cropping system in Nepal is widely constraint by N deficiency under the prevailing low-input management. Large N losses during the transition season with its characteristic change from aerobic to anaerobic soil conditions have been identified as the main culprit for declining soil N content and low yields. Effective technical options to reduce soil N mineralization and the build up of nitrate-N in the soil include wheat straw application and transition seasons cropping. Both options will eventually lead to an increased amount of available soil N during the main cropping period.

Grain yield is related to the amount of available N in the soil pool and to the N uptake capacity of the crop (Cassman *et al*., 1997). Increased rice grain yield in wheat straw-amended plots were observed in both the greenhouse and in various field situations. However, wheat straw application does not necessarily increase the yield of a subsequent crop. While soil N conservation will generally be achieved, the beneficial effects of straw depend on the time of application, the amount of straw, the duration of straw decomposition before rice transplanting and the soil type. Thus, the grain yield and the N uptake of rice can reportedly be reduced when the time for straw mineralization is too short (Stirzaker and Bunn, 1996). Immobilization of N in the microbial biomass and a temporary accumulation of phytotoxic substances can negatively affect rice (Bhogal *et al.,* 1997). In the present study, when wheat straw was applied three months prior to rice transplanting, phytotoxicity and N immobilization problems could be avoided and straw application resulted higher yields. However, with the shortened transition season in the pot experiment as well as in at the mid-hill field site, beneficial effects of straw were less and possibly related to an insufficient duration of DWT for straw decomposition.

In this study, wheat straw application in a slightly acidic sandy-loam increased grain yield of rice. A similar treatment applied on a neutral clay loam of Hariyana showed no effect on rice (Agrawal *et al.,* 1995). On the other hand, straw application in acid clay soils of West Bengal was able to increase grain yield of rice (Sharma and Mittra, 1992). In some instances and soil types, the positive effects of straw application were linked to the addition of K, P, Mn and Zn (Verma and Bhagat, 1992), in others solely to the N saving effect (Pande and Becker, 2001). It is apparent that the effects of applying different amounts and quality of straw and the duration and soil conditions during the straw decomposition period require further studies.

Under most conditions, complete removal and/or burning of crop residues such as wheat straw negatively affects soil physical properties (Prasad and Power, 1991). On the other hand, residue return can improve soil aggregation (Meelu *et al.,* 1994; Liu and Shen, 1992), reduce bulk density of the surface soils (Verma and Singh 1974), increase infiltration rates (Singh *et al.,* 1996), reduce soil compaction (Walia *et al.,* 1995), and increase soil microbial activities (Kumar and Gho, 2000). However, wheat straw has different uses in different places. In some areas it is used as thatching materials (roofing) or as bedding material for animals and other areas it is burn in the field to facilitate land preparation. At the rice-wheat sites of mid-hills and valleys where DWT is relatively short (insufficient time to grow nitrate catch crops) and in situations where wheat straw has no cash or other direct value, farmers can benefit from the application of wheat straw. These target sites need to be further defined to improve future technology targeting.

Transition season nitrate catch crops, specially green manure legumes and short-cycled grain legumes can be fitted into the cropping calendar between the harvest of wheat and the transplanting of rice when the transition season extends beyond 2 months and thus save more than 40% of NO_3-N which would otherwise be lost upon soil saturation. As the soil N uptake by mucuna and maize did not differ significantly, we conclude that no nitrate sparing effect (Giller, 2001) occurred. Besides soil N conservation, the legumes added substantial amounts (52-56 kg ha^{-1}) of atmospheric N to the system via BNF. The combined effects soil N savings and added atmospheric N was reflected in the N uptake and grain yield of rice and wheat. Depending on the type of legume, this resulted in direct (rice) and residual (wheat) increases of 24-42 kg N ha^{-1} yr^{-1} crop N uptake and of 1.2-2.1 Mg ha^{-1} yr^{-1} grain yield, while improving the overall N balance of the systems. The lower benefits were associated with the grain legume, (50% of the N assimilation removed by grain harvest), while the high benefits were obtained with green manures. About one third of these legume-induced productivity gains could be ascribed directly to the conservation of soil N.

However, the use of nitrate catch crops can be adopted only in the Terai and Inner Terai where the duration of the transition period and the soil moisture availability are sufficient for crop growth. On the other hand, farmers located near to local markets will probably favour high value crops (sesame, sweet corn etc.) over green manures or subsistence crops. The benefits of such non-fixing species will be limited to soil N savings in addition to the income-generating effect and they are likely to contribute little to an improved N balance of the production system. Again, possible extrapolation domains for the tested options need to be defined based on the biophysical and socioeconomic context.

Combining the application of wheat straw with the growth of legumes during DTW were most effective to conserve NO_3-N and add atmospheric N (67-80 kg ha^{-1}) and to increase grain yield of both rice and wheat. However, because of the available duration of the transition period, this option can only be applied in the Inner Terai and the Terai, and possibly only in the subsistence oriented production systems. Introduction of short duration high-yielding rice and wheat varieties may yet be another option to extend the transition season and allow for cultivation of crops without offsetting the existing calendar. In any event, these options will result in a substantial intensification of land use and an increased export of nutrients in the crop produce. Such increased cropping intensity is unlikely to be sustained by soil and BNF N management alone. Deficiencies in P, K and Boron are already apparent in some systems and sustaining current yield levels and productivity will require the application of external inputs such as organic or mineral fertilizers. Here again, further research of integrated mineral and organic application strategies is needed. In addition, possible effects of such technology on reduced emissions of climate relevant trace gases (ecosystem services) need to be included when estimating the benefits of such modified systems in the future.

7. Conclusion

Massive loss of native soil nitrogen occurs in rice-wheat rotations when fields are left to bare fallow during the dry-to-wet season transition period (conventional system).

Returning the straw of the preceding crop of wheat into the plots (instead of removal and burning) can reduce N_2O emission and nitrate leaching losses by temporary N immobilization in the microbial biomass. This, “preserved” soil N results in increased rice yields and improved N uptake by a subsequent crop of wheat.

Growing crops during the transition season can immobilize soil N in the plant biomass in addition to adding N from the atmosphere. Similar to the straw option, reduced amounts of available soil N_{min} as a result of crop growth during DWT results in reduced N losses and substantial increases in grain yields of both rice and wheat.

While these management strategies can effectively enhance N cycling in rice-wheat rotation system, N balances indicate that in the long term, crop yields cannot be sustained without the additional application of mineral fertilizers and/or compost. The combination of the proposed options with the application of other organic manures (compost) and chemical fertilizers are further study options to improve currentlz negative N balances.

Targeting of technical options needs to consider the diversity of biophysical and socio-economic conditions, requiring farmer participatory technology evaluation.

Possible changes in existing cropping calendars require the selection and adoption of system specifically adopted rice and wheat cultivars in terms of cropping calendar, phenology and cold tolerance.

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9. Appendices

Appendix 1. Nitrogen balance (kg ha^{-1}) of a rice-wheat cropping system in Chitwan province, Nepal as affected by soil and crop management treatments applied during the dry-to-wet season transition period of 2003 (on-farm experiment, n=3 farms).

Cropping Season	Parameters	Treatments applied during the dry-to-wet season transition period of 2003							
		Bare fallow	Fallow + straw[1]	Maize	Maize + straw	Mungbean	Mungbean + straw	Mucuna	Mucuna + straw
Dry-to-wet season transition period	N addition by straw[1]	0.0b	+10.0a*	0.0b	+10.0a	0.0b	+10.0a	0.0b	+10.0a
	N addition by BNF[2] ($\delta^{15}N$ estimate)	0.0d	0.0d	0.0d	0.0d	+44.6c	57.3b	56.9b	+76.0a
	N removal by crops	0.0a	0.0a	-47.0b	-42.0b	-77.9c	-87.4d	-106.0e	-118.0f
	N returned by crop residues	0.0f	0.0f	+26.8e	+23.7e	+60.1d	+68.4c	+106.0b	+118.0a
	N loss by leaching[3]	-7.6c	-3.5b	-3.5b	-2.3ab	-2.0ab	-1.5a	-1.5a	-1.0a
	N balance at the end of DWT[4] (excluding gaseous losses)	-7.6e	+6.5d	-23.7f	-10.6e	+24.8c	+46.8b	+55.4b	+85.0a
Wet season (Rice-growing season)	N removal by crops (grain+straw)	-34.4a	-45.2b	-43.0b	-45.3b	-54.1c	-59.5cd	-66.5de	-70.1e
	N loss by leaching	-0.9ab	-0.8ab	-0.6a	-0.7ab	-1.0b	-0.9ab	-1.0b	-0.9ab
	N balance after rice harvest (excluding gaseous losses)	-35.3a	-46.0b	-43.6ab	-46.0b	-55.1c	-60.3cd	-67.5de	-71.0e
Total N balance (transition and wet season)		-42.9c	-39.5c	-67.3d	-56.6d	-30.3c	-13.6b	-12.1b	+14.0a

*Values follow by the same letter within one row do not differ significantly by DMRT (0.05).

[1] Incorporation of 2 Mg ha^{-1} of wheat straw from the preceeding wheat crop

[2] Biological Nitrogen Fixation

[3] determined by using ion exchange resin tubes

[4] DWT indicates Dry-to-wet season transition period

Appendix 2. Nitrogen accumulation and atmospheric N_2 fixation ($\delta^{15}N$ dilution method) by different crops grown during the dry-to-wet season transition period in Rampur, Chitwan province, Nepal, 2003.

Treatments	Ndfs%	Ndfs* (kg ha^{-1})	Ndfa%	Ndfa** (kg ha^{-1})	Total N (kg ha^{-1})
On-station experiment (n=4 reps) 2001/2002					
Maize	100	43	0	0	43
Maize+straw	100	37	0	0	37
Vigna	47	26	53	27	53
Vigna+straw	22	19	78	48	66
Mucuna	44	37	56	43	80
Mucuna+straw	28	30	72	62	92
Maize	100	43	0	0	43
Maize+straw	100	37	0	0	37
On-station experiment (n=4 reps) 2003/2004					
Maize (reference)	100	54	0	0	54
Maize+straw	100	48	0	0	48
Vigna	35	28	65	52	80
Vigna+straw	25	23	75	67	90
Mucuna	48	52	52	56	108
Mucuna+straw	31	36	69	80	116
On-farm experiment (n=3 farms) 2003/2004					
Maize (reference)	100	47	0	0	47
Maize+straw	100	42	0	0	42
Vigna	42	33	58	45	78
Vigna+straw	34	30	66	57	87
Mucuna	46	49	54	57	106
Mucuna+straw	36	42	64	76	118

*N derived from the soil

** N derived from the atmosphere

Appendix 3. Experimental set-up of the greenhouse experiment in potted soil (Bonn, Germany, 2001).

Appendix 4. Rice close to maturitz after application of mucuna and wheat straw (field experiment, Rampur, Chitwan province, Nepal, 2001).

Management der saisonalen Bodenstickstoffdynamik in Reis-Weizen Rotationen Nepals

10. Deutsche Kurzfassung

10.1. Einleitung und Problemstellung

Das Anbausystem mit einem Fruchtwechsel von Reis während der Monsunzeit und Weizen während der kalten Trockenzeit dominiert weite Teile des subtropischen Südasiens, wo es mit nahezu 15 Millionen Hektar die bedeutendste Form der Landnutzung zur Nahrungsmittelerzeugung darstellt. In Nepal sind derzeit knapp 600.000 Hektar unter Reis-Weizen-Rotation und sichern die Kalorienbedarf von über 20 Millionen Menschen. Im Gegensatz zu Indien und Bangladesch erfolgt die Erzeugung von Reis und Weizen in Nepal weitgehend ohne den Einsatz externer Produktionsmittel und die Mineralstoffversorgung der Kulturen wird vornehmlich aus Bodenreserven und zum geringeren Teil über Wirtschaftsdünger gedeckt. Darüber hinaus kennzeichnet eine weitere Besonderheit den Anbau in Nepal: Reis-Weizen Rotationen erstrecken sich vom (sub)tropischen Tiefland des Terai über den subtropischen himalayischen Piemont bis in die temperierten Bergregionen von bis zu 2600 Metern Höhe. Aufgrund der relativ stark verwitterten und häufig sauren Böden (Ultisol) und der „low-input“ Orientierung der Produktionssysteme, liegt das Ertragsniveau beider Getreidearten mit knapp 2 Mg ha^{-1} für Reis und <1 Mg ha^{-1} für Weizen weit unter dem asiatischen Durchschnitt oder dem auf Versuchsstationen erzielten Kornertrag. Während der Ertrag in den intensiven Anbausystemen Indiens vorwiegend durch Pflanzenschädlinge und Mikronährstoffmangel (Bor) begrenzt wird und auch langfristige Ertragsrückgänge beobachtet werden, ist der Anbau von Reis und Weizen in Nepal in erster Linie durch Stickstoffmangel gekennzeichnet.

Die aufgrund des demographischen Wachstums erforderlichen Ertragszuwächse auf den bestehenden Flächen müssen zunächst über das Management und das Recycling von systeminternen Ressourcen erwirkt werden, wobei dem Stickstoff dabei eine herausragende Rolle zukommt. Hierzu gehört in erster Linie die Vermeidung von Verlusten von Bodenstickstoff, die Rückführung von N aus Ernterückständen sowie die Zufuhr von biologisch gebundenem N.

Eine Besonderheit der Reis-Weizen-Rotation ist der saisonale Wechsel von aeroben (Weizen) und anaeroben (Reis) Bodenbedingungen. Dieser ist besonders ausgeprägt der 1-3monatigen Zwischensaison nach der Ernte der Winterfrucht und vor dem Auspflanzen von Nassreis. Typisch für das traditionelle Reis-Weizensystem in Nepal ist dabei eine Nacktbrache während dieser Zwischensaison. Besonders nach der Weizenernte führt das Einsetzen der Regenzeit zu einer raschen Mineralisierung von Boden-N und dessen Aufoxidierung zu Nitrat (Birch-Effekt) und daran anschließend die Verluste dieses Nitrats über Auswaschung und mikrobielle Reduktion (Denitrifikation) im Zuge des Bodenüberstaus mit Einsetzen der Monsun-Regenfälle. Gerade in einem Anbausystem, das weitgehend ohne externe Produktionsmittel auskommen muss und durch teilweise erheblichen N-Mangel gekennzeichnet ist, ist es unabdingbar solche unkontrollierten und periodisch wiederkehrenden Zyklen von N-Verlusten zu vermeiden.

Ziel der vorliegenden Untersuchungen war es folglich, die Boden-N-Dynamik in traditionellen Reis-Weizen Rotationen im Jahresverlauf zu quantifizieren, wobei das Hauptaugenmerk auf der Zwischensaison lag. Darüber hinaus sollten Managementoptionen, die ausschließlich auf systeminterne Ressourcen zurückgreifen, hinsichtlich ihres Potentials zur Verbesserung der N-Versorgung der Kulturen und ihrer Einsatzmöglichkeiten an repräsentativen Standorten in Nepal bewertet werden.

10.2. Material und Methoden

Untersuchungen erfolgten unter klimakontrollierten Bedingungen im Gewächshaus in Bonn, auf landwirtschaftlichen Versuchsstationen an zwei kontrastierenden Standorten in Nepal sowie auf drei typischen Reis-Weizen Betrieben im subtropischen Tiefland des Terai zwischen 2001 und 2004. Anhand wöchentlicher Probenahmen wurden Prozesse und die zeitliche Dynamik der Stickstofftransformation quantifiziert. Untersuchungen beinhalteten die Boden-N-Mineralisierung (Ammonium und Nitrat) über die N_{min} Extraktionen, die Nitratauswaschung mit Hilfe von Ionenaustauschharzen, die temporäre N-Immobilisierung in der mikrobiellen Biomasse mit der Fumigations-Extraktions-Methode, Lachgasemissionen über die „Close-Chamber Methode“ mit anschließender gaschromatographischer Gasanalyse sowie die N-Aufnahme durch die Kulturpflanzen und die N-Partitionierung in Korn und Ernterückständen. Mögliche Verluste über Ammoniak-Volatilisierung wurden im Rahmen der Untersuchungen nicht erfasst. Technologieoptionen während der Zwischensaison, die mit der traditionellen Nacktbrache vergleichend bewertet wurden beinhalteten:

(1) N_{min} Immobilisierung in der mikrobiellen Biomasse im Boden infolge der Zufuhr von Weizenstroh (0, 1.5 und 3.0 Mg ha^{-1}, entweder als Mulch oder eingepflügt);
(2) N_{min}-Immobilisierung über Aufnahme durch Zwischenfrüchte (Mais, Gründüngung, Körnerleguminosen);
(3) N-Zufuhr über die biologische N_2 Bindung von Leguminosen (∂^{15}N Methode);
(4) Kombinationen von Stroh und Zwischenfrüchten.

Während sich die Gefäßversuche im Gewächshaus auf eine 4-8wöchige Zwischensaison und eine 10wöchige Reiswachstumsphase beschränkten, erfolgten die Felduntersuchungen in Nepal über zwei gesamte Jahre mit jeweils Trockenzeit, Zwischensaison und Regenzeit (April 2001–Januar 2002 und April 2003–März 2004). Im Jahr 2002 mussten die Felduntersuchungen aufgrund der angespannten politischen Situation aus Sicherheitsgründen ausgesetzt werden.

10.3. Ergebnisse

N-Dynamik im traditionellen System mit Nacktbrache während der Zwischensaison:

Die Untersuchungen zur Boden-N_{min} Kinetik im Jahresverlauf zeigten unabhängig vom Versuchsansatz (Gefäß, Feld) oder vom Standort die mit Abstand deutlichsten N-Dynamiken während der Zwischensaison nach der Ernte von Weizen und vor dem Auspflanzen von Nassreis. Während der überstauten Nassreisphase war der Boden N_{min}-Pool nahezu ausschließlich durch die Ammonium-Form gekennzeichnet. Ein anfänglicher Peak von etwa 35 kg N ha^{-1} verschwand graduell, im gleichen Maße wie sich der Reisbestand entwickelte und Boden-N aufnahm. Während der aeroben Weizenanbauphase lag der Boden N_{min} Gehalt nahezu durchgehend bei etwa 20 kg N ha^{-1}, wobei Ammonium und Nitrat in etwa gleichen Mengen vorgefunden wurden, im Zeitverlauf allerdings gegenläufige Trends aufwiesen (die Abnahme von Ammonium ging mit einem Anstieg von Nitrat einher). Ganz anders verhielt sich die N-Dynamik während der Zwischensaison. Nach der Weizenernte und mit Beginn der Regenzeit setzte ein Mineralisierungsschub ein, der je nach Standort und Jahr zu einem N_{min}- Peak von 48-82 kg N ha^{-1} führte. Der Peak war eindeutig von der Nitratform dominiert, die allerdings mit steigendem Bodenwassergehalt rasch abnahm und bei komplettem Wasserüberstau völlig verschwunden war. Rechnerisch ergaben sich daraus N-Verluste während der Zwischensaison von 32-78 kg N ha^{-1} im Feld und 61-82 mg N kg^{-1} Boden im Gefäßversuch. Knapp 30% dieser N-Verluste konnten der Nitrat-Auswaschung zugerechnet werden, womit etwa 2/3 der Verluste auf die Lachgasbildung zurückzuführen wären. Dies spiegelt sich in Emissions-Peaks im Gefäßversuch von etwa 80 mmol N_2O m^{-2} h^{-1} während der Nitrifikationsphase (25-50% Feldkapazität) und über 150 mmol N_2O m^{-2} h^{-1} während der Denitrifikationsphase (100% Feldkapazität–Überstau) wieder. Im Feldversuch lag der Nitrifikations-Peak der Lachgasemissionen bei knapp 250 und der Denitrifikations-Peak bei deutlich über 400 mmol N_2O m^{-2} h^{-1}. Es bleibt festzuhalten, dass im traditionellen Anbausystem N-Verluste in einem Ausmaß auftreten, der in etwa der Gesamt-N-Aufnahme der Rotation von Weizen und Reis entspricht. Hiermit ist die Hypothese bestätigt, dass Interventionsstrategien zur N-Konservierung in Reis-Weizen Rotationen in Nepal sich auf die Zwischensaison konzentrieren müssen.

Einsatz von Weizenstroh zur Konservierung von Boden-N:

Die Ernterückstände von Weizen (Stroh, Stoppeln, etc.) wurden aufgrund ihres weiten C:N-Verhältnisses von etwa 80 eingesetzt, um über eine temporäre N-Sperre Boden-N-Verluste während der Zwischensaison zu reduzieren. Die Felduntersuchungen konzentrierten sich dabei vorwiegend auf den Hochlandstandort in Lumle, wo die Kürze der Zwischensaison (<8 Wochen) eine Bewertung der übrigen Technologieoptionen (siehe unten) nicht ermöglicht. Je nach Applikationsmenge (0, 1.5 oder 3.0 Mg ha^{-1}) und Ausbringungsart (mulchen oder einpflügen), reduzierte eine Strohanwendung den N_{min} Gehalt im Boden um 10-50% im Gefäßversuch und den Nitratgehalt um >70% unter Feldbedingungen. Daraus ergab sich eine Verminderung der Nitratauswaschungen im Feld während der Zwischensaison auf etwa 10% der Nitrat-N-Verluste unter Nacktbrache und der Lachgasemissionen auf weniger als die Hälfte. Die N-Aufnahme der Folgekultur Nassreis war im Gefäßversuch allerdings nur dann signifikant erhöht, wenn das Stroh in den Boden eingepflügt und die Mineralisierungszeit (Dauer der Zwischensaison) >8 Wochen betrug. Im Feld führte einzig die Einarbeitung von Weizenstroh von 3 Mg ha^{-1} bei einer >8-wöchigen Zwischensaison zu einer signifikanten Steigerung des Reiskornertrags, wobei der Residual-Effekt auf die Folgefrucht Weizen sich auf die N-Aufnahme beschränkte und keine signifikanten

Kornertragseffekte nachzuweisen waren. Während N-Konservierung, Reduktion von gasförmigen N- und Nitrat-Auswaschungsverlusten und N-Aufnahme- und Ertragseffekte eindeutig positiv durch Strohdüngung beeinflusst wurden, blieb die Gesamt-N-Bilanz des Aufbausystems bei alleiniger Strohdüngung, wie schon bei der Nacktbrache mit –80 kg N ha^{-1} stark negativ, was mittelfristig die Probleme von N-Mangel noch verstärken dürfte. Darüber hinaus muss berücksichtigt werden, dass in Regionen mit extrem kurzer Zwischensaison (Bergregionen in >1500 m Höhe), Weizenstroh in der Regel als Einstreu für Tiere, zum Decken von Hausdächern oder als Brennmaterial geschätzt und verwendet wird und ein Einsatz zur Boden-N-Konservierung mit anderen ökonomisch attraktiven Einsatzfeldern konkurrieren muss.

Zwischenfruchtanbau zur Konservierung von Boden-N:

In Regionen, in denen die Zwischensaison hinreichend lang ist und nicht durch Wassermangel begrenzt wird, erscheint der Einsatz von Zwischenfrüchten möglich. Solche Zwischenfrüchte können Boden-N aufnehmen, der im traditionellen System durch Auswaschung und Denitrifikation typischerweise verloren geht. Beim Einsatz von Leguminosen kann dem System darüber hinaus auch atmosphärischer Stickstoff zuführen werden. Da in den Bergregionen der Anbau von Zwischenfrüchten durch die Länge der Zwischensaison von <8 Wochen limitiert ist und dort somit gezwungenermaßen zu einer Verschiebung des Anbaukalenders führen muss, wurden der Einfluss des Anbaus von Süßmais, einer Gründungung mit *Mucuna pruriens* und der Körnerleguminose *Vigna radiata* (green gram) allein oder in Kombination mit Strohdüngung nur an den Standorten im subtropischen Tiefland des Terai untersucht.

Der Zwischenfruchtanbau war in Abhängigkeit von Standort, Anbaujahr und Kultur in der Lage zwischen 25 und 68 kg ha^{-1} Bodenstickstoff aufzunehmen, der dann über die Einarbeitung der Ernterückstände dem System zurückgeführt werden konnte. Im Fall von Leguminosen wurden darüber hinaus zwischen 20 und 74 kg N ha^{-1} aus der biologischen N_2-Bindung zugeführt. Der Anteil der N_2-Bindung sowie die Gesamtmenge der N-Akkumulation der Leguminosen war bei gleichzeitiger Strohdüngung um 12-40% erhöht. Zwischenfrüchte reduzierten die Nitratauswaschung während der Zwischensaison auf 0.2 bis 3.5 kg Nitrat-N ha^{-1} und reduzierten die Lachgasemissionen bis an die analytische Nachweisgrenze. Mit Ausnahme der Süßmaisvariante erwirkten alle übrigen Anbauoptionen einen signifikanten Anstieg des Reiskornertrags, und im Fall der kombinierten Grün- + Strohdüngung auch einen signifikanten Residual-Ertragseffekt auf die Folgekultur Weizen. Allerdings waren die N-Bilanzen aller untersuchten Anbausysteme durchweg negativ. Während die traditionelle Kontrolle (Nacktbrache) und die Maisvarianten mit –63 bis –95 kg N ha^{-1} a^{-1} zu Buche schlugen, war die N-Bilanz bei Leguminosen- + Weizenstrohdüngung mit –25 bis –48 kg N ha^{-1} a^{-1} immer noch hinreichend negativ um auf Dauer zu einer Boden-N-Verarmung und zu massivem N-Mangel zu führen. Die Bilanzierung macht deutlich, dass auf eine auf Entzug basierte Zusatzdüngung mit Wirtschaftsdüngern, Komposten oder mineralischen N-Düngern mittelfristig nicht verzichtet werden kann.

Schlussfolgerungen

Die intensive Dynamik der N-Transformationsprozesse im Boden während der Zwischensaison führt zu erheblichen N Verlusten, die zumindest teilweise das niedrige Ertragsniveau von Reis und Weizen erklären.

Strategien zum Erhalt dieses Bodenstickstoffs während der Zwischensaison, die ausschließlich auf systeminterne Ressourcen zurückgreifen, beinhalten die Rückführung von Weizenstroh und den Zwischenfruchtanbau, vorzugsweise mit N_2-bindenden Leguminosen. Alle der hier dargestellten Maßnahmen zur N-Konservierung erhöhen die Produktivität der Reis-Weizen Rotation über die Steigerung des Kornertrags von Reis (Strohmanagement) oder von sowohl Reis als auch Weizen (Leguminosen und Kombinationen von Stroh und Gründüngung).

Unabhängig von der Effizienz der jeweiligen Maßnahme zur Produktivitätssteigerung bleiben die Gesamt-N-Bilanzen aller untersuchten Systeme deutlich negativ. Es wird somit mittelfristig unabdingbar sein, den N-Entzug durch externe organische oder mineralische Dünger zu ersetzen.

Mit zunehmender Intensivierung der Anbausysteme ist zu erwarten, dass auch andere Nährstoffe (wie bereits in Indien und Bangladesch) zu limitierenden Faktoren werden (z.B. P und B). Hierzu sind zunächst Stoffbilanzierungen anderer Nährelemente als N erforderlich.

Gerade der Zwischenfruchtanbau bietet neben der Boden-N-Konservierung bzw. N-Zufuhr weitere, auch direkte ökonomische Anreize, die mit zunehmender Landknappheit an Bedeutung gewinnen dürften. Dabei ist abzusehen, dass der Anbau von hochwertigen Verkaufsfrüchten während der Zwischensaison bei marktorientierter Produktion der reinen Gründüngung vermutlich vorgezogen wird. Der Anbau von Kartoffeln, Sesam, oder Körnerleguminosen, deren Wachstumsdauer bei 3-4 Monaten liegt, führt zwangsläufig zu einer Verschiebung der Anbaukalender und drängt die kritischen Wachstumsstadien von Reis (Blüte, Abreife) in die kalte Jahreszeit. Hier besteht Forschungsbedarf für die Entwicklung und phänologische Anpassung von Reis- und Weizengenotypen an die veränderten Anbaukalender.

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