Journal of Agriculture in the Tropics and Subtropics
Volume 102, No. 2, October 2001, pp. 91 - 108

Potential and limitations of green manure technology in lowland rice

Mathias Becker [1]

Keywords: Biological N fixation, Nitrogen, N fertilizer, *Oryza sativa*

Abstract

The growing popular concern about the sustainability of agricultural systems and an increasing awareness about environmentally-friendly agricultural production and healthy nutrition stands in striking contrast to a worldwide decline in the use of green manures. It is timely to assess the future role that soil-improving legumes may play in agricultural systems. This paper reviews potential and limitations of green manure technology, using lowland rice cropping systems as the example. A review of more than 250 published references indicates that the average amounts of N accumulated by green manures can entirely substitute for mineral fertilizer N at current average application rates. With similar N use efficiencies, green manure N is less prone to loss mechanisms than mineral N fertilizers and may therefore contribute to long-term residual effects on soil productivity. The considerable genetic variability in the available legume germplasm allows the selection of appropriate legumes to most conditions with positive effects on soil physical and chemical parameters. However, the use of green manure legumes for lowland rice production has declined dramatically world-wide over the last 30 years. Socio-economic factors like the cost of land, labor, and mineral N fertilizer are seen to determine the cost-effectiveness and thereby farmers' adoption of green manure technology. Hydrology and soil texture determine the agronomic competitiveness of a green manure with N fertilizers and with alternative cash crops. With a rapidly-growing demand for rice and growing land and labor scarcity, green manure use is not seen to become a relevant feature of favorable irrigated rice-growing environments in the foreseeable future. On the other hand, in environments where soil properties and hydrology are marginal for food crop production (flood-prone rainfed lowlands with coarse-textured soils), but which farmers may be compelled to cultivate in order to meet their subsistence food requirements, green manures may have a realistic and applicable potential.

---

[1] Agrikulturchemisches Institut (ACI), Universität Bonn, Karlrobert Kreiten Str. 13, D-53115 Bonn. Email: mathias.becker@uni-bonn.de

1 Introduction

Growing popular concern about environmental issues and increasing awareness about healthy nutrition results in a growing demand for "ecologically"-grown food. With a production of 550 million tons of rough grain, rice (*Oryza sativa* L.) is the most important food crop worldwide (McLean, 1997). Irrigated and rainfed lowland ecologies dominate the production areas. It is therefore timely to asses the potential and the limitations of organically-grown lowland rice, and particularly the use of green manure legumes to substitute for mineral N fertilizers, the main chemical input into wetland rice cultivation systems. While this paper focuses on green manure use in lowland rice-based cropping systems, the general conclusions are applicable to a wider range of crops and ecosystems.

Throughout tropical rice farming systems, there are concerns about sustainability as most countries move into a post-green revolution phase (Cassman and Pingali, 1994). Intensive cultivation has been shown to potentially degrade the resource base (Pingali *et al.*, 1990). When faced with declining crop yield, farmers and researchers have traditionally opted for crop diversification, crop rotation, and the insertion of green manures into the farming system (King, 1911). This is also consistent with a growing concern about environmental issues associated with "conventional" agricultural practices and an increasing demand for "ecologically-grown" food stuff. Green manures can be fitted into rice farming systems in either the pre-rice or post-rice phase (Garrity and Flinn, 1988). Pre-rice green manures are cultivated for 6 to 10 weeks before the establishment of the rice crop and incorporated into the soil during land preparation. Post-rice green manures are relay-established into the growing rice (Liu, 1988) or sown after rice harvest (Chen, 1988), when the period available for growth is usually longer than that of pre-rice legumes. Post-rice green manures have historically played a greater role than pre-rice species and are exemplified by *Astragalus sinicus* for the cool tropics (Chen, 1988) and *Indigofera tinctoria* (Ali and Narciso, 1993), *Calopogonium* spp. (Becker *et al.*, 1997), *Crotalaria juncea*, *Clitoria ternatea*, *Desmanthus virgatus* and *Macroptilium atropurpureum* (Ladha *et al.*, 1994) in the warm tropics. Prototype species for the pre-rice niche include flood-tolerant legume species such as *Sesbania* and *Aeschynomene* spp. (Ladha *et al.*, 1992) or more on less drought-tolerant species of the genera *Crotalaria* and *Tephrosia* spp. (Abrol and Palaniappan, 1988). Flood-tolerant legumes have been most prominent in recent research, a development that was triggered by the recognition of their high N_2-fixing capacity and the world-wide spread of the stem-nodulating *Sesbania rostrata*. Numerous studies have examined growth and nitrogen fixation of legumes and the effects of green manure on soils and on the succeeding rice crop (Becker *et al.*, 1990; Buresh and De Datta, 1991; Ladha *et al.*, 1992; Singh *et al.*, 1991). They have concluded that incorporation of green manure legumes can add large quantities of biologically fixed N to lowland rice cropping systems and improve the soil productivity. However, the adoption of sustainable green manure technology in tropical lowland rice farming systems has been limited in the past and their use is currently declining. Are green manures a viable option to mineral fertilizer use in producing and satisfying a growing demand for (organically-grown) rice? To answer these questions, a critical analysis of the potential and the limiting factors of green manure technology is needed in order to assess the future scope for soil-improving legumes in tropical agriculture. Such analysis may help the scientific community to target future green manure research activities and funding agencies to justify further investments in research on soil-improving legumes.

2 Potential benefits from green manure use

2.1 Green manure species

Relatively few species of green manure legumes have been historically encountered in lowland rice-based cropping systems. In the cool tropics of Asia (China, Japan) the post-rice niche is dominated by *Astragalus sinicus* (LIU, 1988) and in the Americas by vetches and clovers (WESTCOTT and MIKKELSEN, 1988). In the warm tropical post-rice situation, legumes are seldom grown for the sole purpose of soil improvement; these legumes are exemplified by *Indigofera tinctoria* in Asia (ALI and NARCISO, 1995) and *Calopogonium* spp. in Africa (EVANS and ROTAR, 1987; ROY *et al.*, 1988). More common are forage legumes like *Stylosanthes, Desmodium*, and *Clitoria* spp. (LADHA *et al.*, 1994). This is particularly true for the South American post-rice situation (SCHULTZE-KRAFT, 1988).

Among the pre-rice green manures, *Sesbania cannabina* has been most widely used in the warm tropics of Africa and Asia. The stem-nodulating green manure S. *rostrata* (origin: West Africa) has been subjected to intense research since its introduction into Asia some 20 years ago. It is recommended as a green manure in both Asia and Africa and is currently grown on about 500,000 hectares in the Delta and the Central Plain of Myanmar (MAR *et al.*, 1995). *Sesbania sesban,* S. *speciosa* (ARUNIN *et al.*, 1988; LIU, 1988), and *Aeschynomene indica* (CROZAT and SANGCHYO-SAWAT, 1985) are less common but can be locally important. *Sesbania speciosa,* for example, is grown in parts of Thailand, where it provides edible flowers in addition to an N-rich biomass (EVANS and ROTAR, 1987). Stem-nodulating *A. afraspera* and *A. nilotica* have only recently been domesticated (ALAZARD and BECKER, 1987) and their use is still largely limited to research farms and extension demonstration trials. This rather narrow germplam base (particularly in the case of pre-rice species) has been considerably broadened in recent years. With the screening and evaluation of more than 120 pre-rice and post-rice legumes, promising accessions have been identified that are adapted to adverse environmental conditions such as marginal soils, short photoperiod, and unfavorable hydrology (BECKER and LADHA, 1997; BECKER and JOHNSON, 1998; BECKER 2000). Regional evaluations in Africa and Asia indicate that stem nodule formation does not convey a significant advantage to legumes grown under adverse soil conditions. However, flooding reduces N_2 fixation less in stem-nodulating than in solely root-nodulating species. In some species *(Aeschynomene afraspera* and S. *speciosa)* N accumulation was only marginally affected by short-day conditions (BECKER and LADHA, 1997). The considerable genetic variability in the germplasm screened allowed for the identification of potentially appropriate legumes to most conditions (Table 1; adapted from BECKER, 2000).

Table 1: Performance parameters and adaptation criteria of selected semi-aquatic legumes as green manure for lowland rice (adapted from BECKER, 2000).

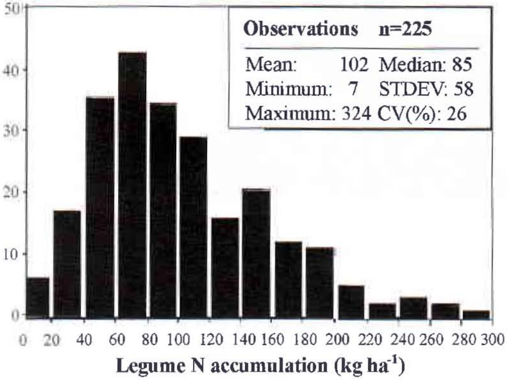
Desirable trait of legumes for use as green manure	*S. rostrata*	*S. cannabina*	*S. emerus*	*S. punctata*	*A. afraspera*	*A. scabra*	*S.* sp (22093)	*A. nilotica*	*S. speciosa*	*S. virgata*	*A. ciliata*
N accumulation											
High N yield	■	■	■	■	■	■	■	■	■	■	■
High N_2 fixation	■	■	■	■	■	■	■	■	■	■	■
Environmental conditions											
Short day length					■	■		■	■		■
Insect pest pressure		■	■						■		■
Soil flooding	■	■	■	■	■	■	■	■		■	■
Drought		■	■			■	■		■	■	
Edaphic conditions											
Sandy soil		■	■		■	■		■			■
P deficiency	■	■	■							■	
Salinity		■	■				■			■	
Acidity		■	■		■					■	

Black = criteria met ; Gray = criteria partially met; White = criteria not met.

2.2 Nitrogen accumulation

Very few papers report N accumulation and N_2 fixation data from post-rice green manures (reviewed in YOST and EVANS, 1988; CHRISTIANICK *et al.*, 1997). On the other hand, numerous papers (more than 200 observations) report N yield and N_2 fixation in few flood-tolerant legumes (reviewed in BECKER *et al.*, 1995). The amount of N accumulated in a 45-60-day-old green manure crop varies with species, season, and site. Values range from as low as 7 kg N ha^{-1} to more than 300 kg N ha^{-1} (Figure 1). An average N accumulation of 80 - 100 kg N ha^{-1} corresponds to the average amount of mineral fertilizer N applied to lowland rice in Asia (MCLEAN, 1997). For legumes to maintain or increase soil N as desired, they must fix large amounts of atmospheric N_2. A survey of the literature indicates that on average, 75 - 80% of green manure legume N is derived from the atmosphere. Difference and isotopic methods were used in the reported studies, and the choice of reference datum (soil exchangeable ammonium, uninoculated legumes, rice, weeds) seem to influence the estimates. This figure of 75 - 80% Ndfa is considerably higher than the reliance upon N_2 fixation commonly reported for grain legumes (reviewed by NORMAN, 1982; PEOPLES and HERRIDGE, 1990; PEOPLES *et al.*, 1995), underlining the high potential of green manure legumes to not only accumulate substantial amounts of N in their biomass, but also to add large quantities of atmospheric N to the soil.

Figure 1: N accumulation by annual legumes in lowland rice-based production systems (data compiled from 28 published papers, reviewed by BECKER, 2000).



2.3 Yield effects

Many studies have shown that the use of green manure legumes can increase the yield of a subsequent lowland rice crop, and reduce the requirements for inorganic N fertilizer (reviewed by BURESH and DE DATTA, 1991). Rice grain yield increases over unfertilized control treatments, range from 0.5 to 3.3 Mg grain ha^{-1} with an average of 1.7 Mg ha^{-1} (Figure 2). Assuming an average application rate of 80 kg N ha^{-1} (mean value for Asian rice lowlands; MCLEAN, 1997), green manure N shows an agronomic N use efficiency (kg rice grain increase over unfertilized control kg^{-1} N applied) of about 20. This figure is similar to the average N use efficiency of mineral N fertilizer in Asia (CASSMAN *et al.*, 1997). Lowland rice seems to be using organic N as efficiently as mineral fertilizer N (see also BECKER *et al.*, 1995 and PEOPLES *et al.*, 1995). However, the nature of this relationship seems to change slightly according to the amount of N input. Figure 3 indicate that mineral fertilizer equivalence increases with applied N rate though follows a quadratic response function. At application rates of less than 80 kg N ha^{-1}, lowland rice uses green manure N more efficiently than urea N. However, when green manure is applied in excess of 100 kg N ha^{-1}, organic fertilizer use efficiency declines more rapidly than that of urea. To target green manure N accumulation in excess of 100 kg N ha^{-1} may not be useful where a short-term increase in rice grain yield is the objective.

Figure 2: Green mnaure-mediated rice grain yield incraese over unfertilized control in lowland rice-based production systems
(data compiled from 26 published papers, reviewed by Becker, 2000).

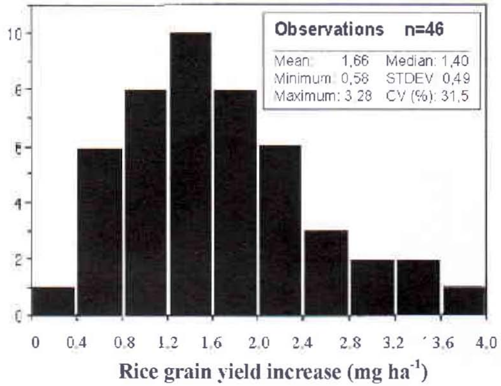
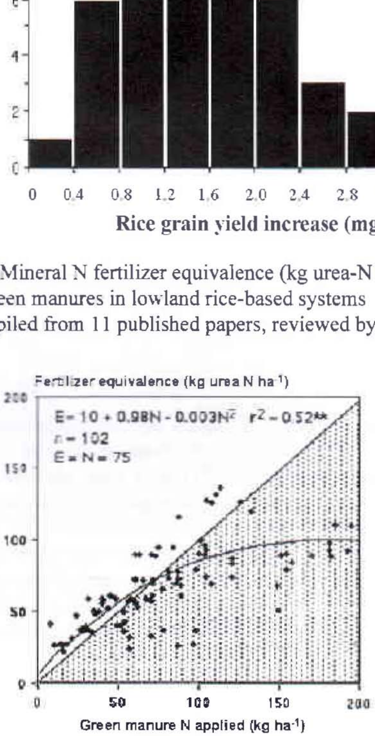


Figure 3: Mineral N fertilizer equivalence (kg urea-N ha^{-1} substited) by legume green manures in lowland rice-based systems
(data compiled from 11 published papers, reviewed by Becker, 2000).

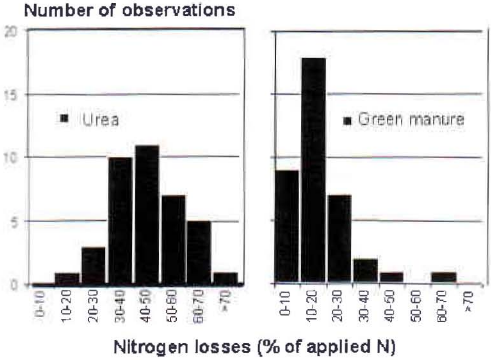


2.4 Nitrogen losses

In addition to the quantity of added green manure N and its mineralization rate, the N contribution of green manure (as for mineral fertilizer N) to rice depends on the magnitude of N losses. Mineral N fertilizers are generally not efficiently used by rice and are prone to high losses as N gases (Buresh and De Datta, 1991; Becker, 2000).

In flooded rice soils, ammonia volatilization is widely recognized as an important mechanism for loss of mineral fertilizer N applied to tropical lowland rice (VLEK *et al.*, 1995; 1997). High floodwater ammoniacal N concentrations following application of N fertilizer, high temperature, and elevated floodwater pH resulting from photosynthetic activity, create a favorable environment for ammonia loss (ROGER and WATANABE, 1986; VLEK and CRASWELL, 1981). In non-flooded soils, nitrate leaching and denitrification during the dry-wet transition period are the major N loss mechanisms (GEORGE *et al.*, 1992; BOGNONKPE and BECKER 2000). If fertilizer applications were well synchronized with plant N uptake patterns, N losses from lowland rice fields would be greatly reduced. Organic materials, acting as slow release source of N, are expected to more closely match N supply and rice N demand, and this can reportedly reduce N losses (BECKER and LADHA, 1996; MCGILL and MYERS, 1987). Nitrogen losses from applied mineral and organic fertilizers have been studied by a number of researchers, using different methods (BROADBENT, 1979; BECKER *et al.*, 1994a). Average N bosses in flooded soils from applied green manure are considerably lower (14%) than those from split-applied urea (35%), thus resulting in less pollution to the environment (Figure 4).

Figure 4: Reported N losses (frequency distribution histogram) from applied mineral and green manure nitrogen in lowland rice (data compiled from 18 published papers, reviewed by BECKER, 2000).



2.5 Residual effects

The facts that (a) the N input from mineral and organic N sources and their use efficiency by lowland rice are similar, and that (b) N bosses are less from green manure than from urea raises the question of the fate of the portion of the organic N that is neither lost nor taken up by the rice plant. It has been suggested that large portions of organically applied N remain undecomposed under flooded soil conditions and may be available for a subsequent crop (BECKER *et al.*, 1994b; BOULDIN, 1988).

Leguminous green manures incorporated before cropping with lowland rice were shown to increase grain yield of a following wheat (BHATTI *et al.*, 1985; LADHA *et al.*, 2000) or rice crop (BURESH and DE DATTA, 1991; SINGH *et al.*, 1991). Other authors, however, detected little on no residual response to green manure N (LADHA *et al.*, 1992; VENTURA *et al.*, 1987). A review of 16 published studies indicates an average residual effect of green manuring on the grain yield of a subsequent unfertilized cereal crop of 10-15%. This figure may appear small but such residual effects might in the long-run contribute to the restoration of degraded soils and the sustainability of rice-based cropping systems. However, no conclusive research data on such long-term effects of green manuring are currently available.

2.6 Non-N effects

Green manures frequently have positive effects on a subsequent rice crop, resulting from factors other than supplying N (rotation effects; reviewed by BECKER *et al.*, 1995 and BECKER 2000). Other nutritional effects include the mobilization of P, Si, Zn, Cu, Mn, and other nutrient elements as a result of increased microbial activity (CO_2 formation), a decrease in Redox potential, and the microbial reduction of pedogenus iron (Fe^3) oxides and hydroxides. Incorporation of an easily decomposable biomass with relatively high N content can lead to an increased mineralization of the organic soil fraction (priming effect) in rice soils and possibly enhance the heterotrophic N_2 fixation. The addition of organic material significantly increases microbial biomass in the soil and conserves N, P, K, and micronutrients in a "biological pool" with a high turnover. Incorporation of legume biomass can also improve soil physical parameters (soft puddle). Green manure can increase the cation exchange capacity, improve soil buffering capacity, decrease porosity in light-textured soils, and help reclaim alkaline and acid soils. A green manure can conserve nitrate that is mineralized during the dry fallow between two rice crops and that is prone to nitrate leaching and denitrification in the dry-wet transition before rice. Increased soil biological activity as a result of green manuring can accelerate the mineralization of persistent pesticides and their metabolites and has been shown to reduce the incidence of bacterial diseases in rice as a result of an enhanced biological barrier in the rhizosphere. Planting a legume instead of leaving the land fallow can help control weeds, particularly through the use of "creeping" cover crops in the post-rice niche. Furthermore, green manure legumes may offer the potential to reduce insect pest and nematode populations in the succeeding rice crop. Finally, many green manure species have additional uses such as food, feed, and fuel, on have medicinal properties.

2.7 Conclusions

In summary, many green manure legumes show a high potential for N accumulation of which the major portion is derived from biological N_2 fixation. At average N accumulation rates, green manures can entirely substitute for mineral fertilizer N at current average application rates. With similar N use efficiency, green manure N is less prone to loss than mineral fertilizer N, and continuous green manure use may improve physical and chemical soil properties. In the long run, green manure use may help restore degraded soils and enhance the production sustainability of rice-based systems.

3 Factors limiting adoption of green manures

Despite high N_2 fixation, reduced N losses, increased rice grain yields, and various positive effects on soil physical and chemical parameters, the use of green manure legumes in lowland rice production systems has been dramatically declining over the last 30 years (Roger and Watanabe, 1986; Rosegrant and Roumassett, 1988; Garrity and Becker, 1994). Today, green manures are estimated to cover less than 5 million hectares in topical Asia, confined mostly to China, Myanmar and Vietnam (Ladha and Garrity, 1995). In some countries like Nepal, Pakistan, and the Philippines where soil-improving legumes were once extensively used, these are now rarely encountered (Ali and Narciso, 1995). In Japan where green manures formerly played an important role in lowland rice culture, they have now literally disappeared (Ishikawa, 1988). In the United States, green manure crops have been widely grown in rotation with rice, but their use has declined to less than 5% of the planted rice area (Westcott and Mikkelsen, 1988). What are the possible reasons for this long-term trend, which includes the Peoples Republic of China (Chen, 1988)? Several reviews (Roger and Watanabe, 1986; Ladha *et al.*, 1992; Becker *et al.*, 1995) and surveys conducted by IRRI (Garrity and Flinn, 1988; Ali and Narciso, 1993) identified the major constraints to green manure use in lowland rice production systems to be: (1) the unavailability of appropriate green manure legume seeds; (2) large performance variability across environments; (3) shortage of land and labor, and (4) a relatively low mineral fertilizer price.

3.1 Agronomic factors

The availability of seeds is a limiting factor for any crop. Where seeds are not commercially available (most green manure species), farmers have to assure their own stock of quality seeds. However, seed production is a relatively costly and labor intensive aspects of green manure production (Palaniappan and Budhar, 1994). An unfavorable plant architecture, shattering of seeds, asynchronous flowering, and in many instances the need for seed scarification are some typical constraints related to the semi-domesticated nature of most green manure species. Furthermore, the degree of photoperiod sensitivity has major implications on the seasonal adaptation and seed production potential of legumes (Becker *et al.*, 1993). Seed production methods have been studied for *S. rostrata* and *A. afraspera,* and some promising concepts include the planting of seed legumes on bunds or widely spaced in the rice field (Pradhan and Garrity, 1994). Ideally, a soil-improving legume should produce sufficient seed before the time of green manure incorporation.

3.2 Economic factors

Economic feasibility determines the ultimate fate of any technology. A number of economic analyses indicate an unfavorable comparison of green manure vs. inorganic fertilizer use (Garrity and Flinn, 1988). The most important economic factors affecting green manure use are the input prices for land, labor and fertilizers. The land price is one of the dominant factors limiting green manure use. Whenever land can also be used for the production of cash crops, strictly soil-improving legumes can not compete. The place of green manure crops in well-drained irrigated fields is, therefore, very limited, since the period after cultivating major economic crops (rice and wheat) is preferred for cash crop production (mainly vegetables). A comparison of grain and soil-improving legumes at existing international grain and fertilizer prices indicates that a legume grain yield of 200 kg ha^{-1} is sufficient to make grain and green manure legumes equally beneficial (ALI and NARCISO, 1995). However, most economic evaluations of green manure production systems show an unfavorable comparison of green manure vs. mineral fertilizer N at current input prices. These studies consider the legumes solely as a N source and fail to account for residual on long-term effects and the numerous additional (non-N) benefits. The ready availability and relatively by cost of mineral N fertilizer (about 380 US\$ Mg^{-1} of urea N) also contributes to the current unfavorable economic comparison of green manures with mineral N. Since the manufacturing of N fertilizes requires energy, their cost is closely related to oil prices and the future exploitation of new energy sources. In many instances, however, the low fertilizer price is bought about by direct and indirect subsidies. In the period between 1960 and 2000, when green manure use declined to less than 5% of the lowland rice area, the consumption rate of mineral fertilizer increased by about 10% per annum (MCLEAN, 1997). However, mineral N fertilizer production uses large quantities of fossil fuel that may not always be available at current amounts and prices.

4 The suitable environment for green manure crops

The previous chapter has highlighted that non-adoption of green manures at farm level is probably related to the riskiness of green manures (seed supply, performance variability), lost opportunity costs, and by a relatively low mineral fertilizer price. These frame work conditions, however, vary not only by country and region but often also at small scale (e.g. market access), resulting in a multitude of environments and thus of potential niches for the use of soil-improving legumes. Increased green manure adoption at the farm-level requires the recognition and identification of such economic and biophysical scenarios within which green manures have a comparative advantage over other non-rice crops and mineral fertilizes.

4.1 Socioeconomic niches for green manure use

The economic environment for green manure cultivation is determined in the first place by the input prices for land and labor, and the ready availability and price of N fertilizer. At the country on regional level, national policy decisions vis-à-vis green manures (or for that matter mineral fertilizes) will affect the environment for green manure adoption. Policy environments differ drastically among counties. In China and Myanmar, for example, there is a strong government support for green manure. In Bhutan and a number of African counties, green manure use may be stimulated by the limited availability of inorganic fertilizers, while Taiwan is promoting green manure as a means to reduce the rice area (GARRITY and BECKER, 1994). Socio-economic conditions at the farm-level further refine this general pattern. Distance from the local market may determine farmers' access to mineral fertilizes. Labor availability and time allocation during the transition between two main crops have to be adequate for green manure seeding and incorporation operations. Finally, the incorporation of a relatively large biomass into the soil requires suitable implements and/or animal on mechanical traction.

4.2 Biophysical niches for green manure use

An analysis of 38 published references attempts an evaluation and extrapolation of the biophysical niches where green manures have a comparative advantage over mineral N fertilizer use (reviewed by Becker *et al.*, 1995). Within the major agroecological zones, soil type and hydrology seem to be the dominant spatial factors determining niches for green manure use. Legume N accumulation and mineral fertilizer equivalence of green manure seem to be generally higher in light-textured than in heavy soils. As the percentage sand content increases among experimental sites from various studies, there is a distinct tendency for N use efficiency to decrease. The nature of this relationship contrasts between the two N sources, as the N use efficiency of urea declines more drastically than that of green manure. The efficiency of both N sources is similar on clay soils, but tends to be substantially greater for green manures in sandy soils (Figure 5). This may be associated with an increased green manure N accumulation and higher N leaching losses from mineral compared to organic N in coarse-textured soils.

Hydrology is a dominant factor controlling the crop sequence and determining the adaptation of green manures in rice farming systems. Farmers prefer cash crops over green manures. However, where severe soil moisture deficit or water excess increases the risks in cash crop production, the likelihood increases for inclusion of pre-rice green manures in the cropping patterns. Severe flooding in the pre-rice situation eliminates most alternative food crops and consequently favors a flood-tolerant green manure legume. However, unreliable water availability associated with many rainfed situations also increases the riskiness and variability of green manure production. Hydrology further appears to determine the competitiveness of green manures with N fertilizers. Repeated soil drying and wetting cycles during rice growth in rainfed environments increase mineral N bosses by denitrification and leaching (George *et al.*, 1992; Bognonkpe and Becker, 2000; Pande and Becker, 2001). N use efficiency tends to be higher at all levels of urea application under irrigated compared to rainfed conditions. However, when nitrogen is supplied by green manure, N use efficiency is similar between irrigated and rainfed conditions (Figure 6). Consequently, green manure use may be preferable oven mineral N fertilizes in many unfavorable rainfed situations.

A step-wise identification of such economic and agronomic factors will allow the definition of extrapolation domains where a given green manure species or technology may be considered. According to this analysis, the socio-economic environment is recognized to determine the impact that any attempt to introduce changes in existing cropping patterns may have. In the biophysical environment, the suitability of a green manure measure seems to be principally determined by a relatively short time span available for green manure growth, "marginal" soil conditions and a moisture regime that is unfavorable for cash crop growth.

Figure 5: Effect of soil texture on the agronomic use efficiency of applied organic and mineral nitrogen in lowland rice
(data compiled from 13 published papers, reviewed by BECKER, 2000).

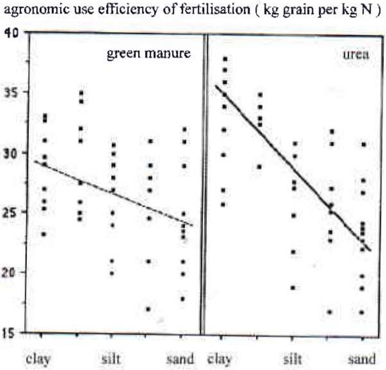
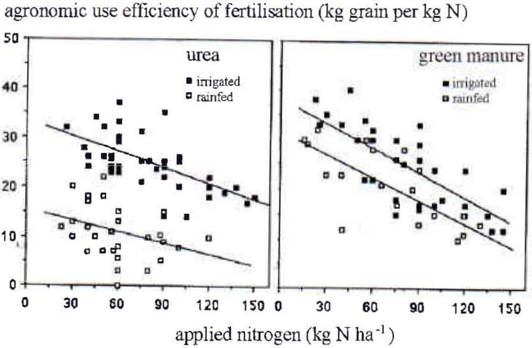


Figure 6: Effect of hydrology on the agronomic use efficiency of applied organic and mineral nitrogen in lowland rice
(data compiled from 11 publ. papers, reviewed by BECKER, 2000).



5 Prognosis for green manure use

What is the future of green manures ? The previous chapters highlight a clear comparative advantage of green manure over mineral fertilizers in light-textured soils with agronomic N use efficiencies of 15 and 20 kg grain kg^{-1} N for urea and legumes, respectively. Similarly, the mean agronomic efficiency of applied N in rainfed lowland environments is considerably higher with green manure than with mineral N (19 vs. 14 kg grain kg^{-1} N). Table 2 attempts an extrapolation of these findings to the whole of

Asia, comparing the generally heavy-textured irrigated lowland areas and the predominantly sandy-textured rainfed environments under two land use scenarios. The mineral N fertilizer scenario presents the available statistical data on mineral N application, N use efficiency, yield and regional rice production. It highlights that in the current scenario only one fifth of Asias regional rice production stems from the rainfed environments. Nearly 360 million tons of rice are produced in the irrigated lowlands and nearly one half of this production (163 million tons) can be ascribed to mineral N fertilizer application effects. The green manure scenario is strictly hypothetical and analyzes the case wherein all Asian rice lowlands are "fertilized" exclusively with green manure. Production has been estimated based on the above presented data for agronomic N use efficiency (Figure 4) in different soils (Figure 5) and hydrological situations (Figure 6). It becomes apparent that in irrigated lowlands, sole green manure use would result in a substantial decline in regional rice production, mainly as a result of a lower N input compared to mineral fertilizers. In addition, large-scale green manure use in irrigated environments is likely to result in increased emissions of the climate-relevant trace gaz methane (WASSMANN *et al.*, 1996). On the other hand, the higher N use efficiency from green manure in rainfed environments would result in regional production increases in the range of 16 million tons, an amount sufficient to meet the projected increase in the demand for rice, at least for the coming 1-2 decades.

Table 2: Expected changes in lowland rice production in irrigated and rainfed production systems of Asia with complete substitution of mineral fertilizer input by green manure (calculations based on 90 millionen ha irrigated and 36 millionen ha rainfed rice area)

	Current Scenario (Mineral N)		Hypothetical Scenario (Green manure)	
	Irrigated	Rainfed	Irrigated	Rainfed
Mean N application (kg N ha^{-1})	98 [a]	47 [b]	82	60
N use efficiency (kg grain kg^{-1} N)	19	14	19	18
Expected yield (Mg ha^{-1})	4.1 [a]	2.2	3.7	2.7
Production (Mio Mg)	359	81 [c]	334	97
Hypothetical change with exclusive use of green manure (Mio Mg)			-25 [d]	+16 [e]

[a] Mean of 9 countries corresponding to 51% of irrigated rice area

[b] Mean of 11 countries, corresponding to 82% of rainfed area

[c] Total regional production (Reis Almanach, IRRI, 1997)

[d] Based on total irrigated area of Asia (approx. 89 millionen ha)

[e] Based on 57% of potentially favorable rainfed lowlands of Asia

6 Conclusions

It may be concluded that with a rapidly-growing demand for rice and growing land and labor scarcity, green manure use is not seen to become a relevant feature of favorable irrigated rice-growing environments in the foreseeable future. On the other hand, in environments where soil properties and hydrology are marginal for food crop production, but which farmers may be compelled to cultivate in order to meet their subsistence food requirements, green manures may have a realistic and applicable potential. This prognosis may change in favor of green manures (also in irrigated rice-growing environments) when mineral fertilizer prices increase substantially and in situations where consumers are prepared to pay higher prices for organically-grown food. Two further factors may determine the scale of farmers' future acceptance of soil improving legumes: (1) Green manure species and systems will have to provide multiple use solutions to be acceptable, since farmers are looking for direct returns to their investments. In these situations the green manure performs additional functions beside being an N source: it must provide food, fodder, fuel or industrial products. Green manures with direct economic functions will be the key in most situations. However, very little is known about the potential additional uses of current green manure species. (2) The niches where single purpose green manures fit will be limited to conditions where alternative crops are not competitive or where green manure provides more than just N (e.g. increased soil water-holding capacity, alleviation of toxicities, weed suppression). The target environments for green manure use appear in many instances to be marginal for cash crop production. However, with growing pressure on the topical world's band for food production, marginal areas are increasingly being cultivated. Green manure legumes may be a vital component in the sustainable agricultural use of such unfavorable environments. Sandy-textured rainfed lowland environments are seen to be the main target area for green manure use. Socioeconomic determinants (land price, labor availability, market access) will help to refine extrapolation domains and their GIS-based visualtization may further improve technology targeting. Development of appropriate technology packages for unfavorable environments is seen to be a rewarding area of research, wherein breakthroughs could help the resource-poor farmers to sustain and improve their food production.

7 References

ABROL P. and PALANIAPPAN S.P., 1988: Green manure crops in irrigated and rainfed lowland rice-based cropping systems. *In*: Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños, IRRI. Philippines. pp 71-82.

ALAZARD D. and BECKER M., 1987: *Aeschynornene* as green manure for rice. Plant and Soil 101, 141-143.

ALI M. and NARCISO J.H., 1993: The perception and reality of GM use in rice: An economic evaluation. IRRI Social Science Division Paper Series. The International Rice Research Institute, Los Baños, Philippines. 42 pp.

ALI M. and NARCISO J.H., 1995: Comparative evaluation and farmer's perceptions of green manure use in the rice-based farming systems. *In*: Proceedings of the

International Rice Research Conference. The International Rice Research Institute. Los Baños, Philippines. pp 234-248.

Arunin S., Dissataporn C., Anuluxtipan Y. and Nana D., 1988: Potential of *Sesbania* as green manure in saline rice soils in Thailand. *In* Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños. IRRI, Philippines. pp 83-95.

Becker M., 1990: Potential use of the stem-nodulating legumes *Sesbania rostrata* and *Aeschynomene afraspera* as green manure for lowland rice *(Oryza sativa* L.). Ph.D. Thesis, University of Giessen, Germany. 113 pp.

Becker M., 1993: Flood-tolerant legumes as green manures for lowland rice-based cropping systems. Terminal Report. The International Rice Research Institute, Los Baños, Philippines. 130 pp.

Becker M., 2000: Potential von Leguminosen zur Gründüngung und Einsatzmöglichkeiten im tropischen Reisanbau. Habilitationsschrift, Universität Giessen, Germany. 137 pp.

Becker M., Ladha J.K., Simpson I.C. and J.C.G. Ottow, 1994a: Parameters affecting residue nitrogen mineralization in flooded soils. Soil Sci. Soc. Am. J. 58, 1666-1671.

Becker M., Ladha J.K. and Ottow J.C.G., 1994b: Nitrogen losses and lowland rice yield as affected by residue N release. Soil Sci. Soc. Am. J. 58, 1660-1665

Becker M., Ladha J.K. and Ali M., 1995: Green manure technology: Potential usage, limitations. A case study for lowland rice. Plant and Soil 174, 181-194.

Becker M. and Ladha J.K., 1996: Synchronizing residue N mineralization with rice N demand in flooded conditions. *In*: Giller K and Cadisch G (*eds*) Driven by nature: Plant litter quality and decomposition. CAB International, London. pp. 231-238.

Becker M. and Ladha J.K., 1997: Adaptation of green manure legumes to adverse conditions in rice lowlands. Biol. Fertil. Soils 23, 243-248.

Becker M. and Johnson D.E., 1998: Legumes as dry season fallow in upland rice-based systems of West Africa. Biol. Fertil. Soils 27(4), 358-367.

Bhatti H.M., Yasin M. and Rashid M., 1985: Evaluation of *Sesbania* green manuring in nice-wheat rotation. *In*: Nitrogen and the Environment. Malik KA, Naqvi SHM and Aleem MTH (eds). Nuclear Institute for Agriculture and Biology, Faisalabad, Pakistan. pp 275-284.

Bognonkpe J.P. and Becker M., 2000: Soil nitrogen use efficiency by lowland rice as a function of slope management. *In*: Universität Hohenheim and ATSAF e.V. (eds) International agricultural research: A contribution to crisis prevention. Margraf Publishers, Weikersheim, Germany. p 197.

Bouldin D.R., 1988: Effect of green manure on soil organic matter content and nitrogen availability. *In*: Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños, Philippines. pp 151-164.

Broadbent F.E., 1979: Losses of nitrogen from some flooded soils in tracer experiments. *In*: Nitrogen and Rice. The International Rice Research Institute, Los Baños, Philippines. pp 105-117.

Buresh R.J. and De Datta S.K., 1991: Nitrogen dynamics and management of rice-legume cropping systems. Adv. Agron. 45, 1-59.

Cassman K.G. and Pingali P.L., 1994: Extrapolating trends from long-term experiments to farmers fields: the case of irrigated nice systems in Asia. *In* Agricultural Sustainability in Economic, Environmental and Statistical Terms. V Varnett, Payne P and Steiner R (eds) John Wiley & Sons Ltd., London, UK.

Cassman K.G., Gines G.C., Dizon M.A., Samson M.I. and Alcantara J.M., 1997: Nitrogen use efficiency in tropical lowland rice systems: Contributions from indigenous and applied nitrogen. Field Crops Res. 47, 1-12.

Chen L., 1988: Green manure cultivation and use for nice in China. *In* Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños, Philippines. pp 63-70.

Christianick A., Probst K. and Schulze-Kraft R., 1997: Ecological impact of tropical pastures and the potential of forage plants for sustainable land use systems in the tropics. PLITS 15(1). W. Kock Verlag Stuttgart, Germany. 149 pp.

Crozat T. and Sangchyo-Sawat C., 1985: Evaluation of different green manures on rice yield in Sonkla Laka Basin. J. Sci. Technol. 7, 391-397.

De Datta S.K. and Buresh R.J., 1989: Integrated nitrogen management in irrigated rice. Adv. Soil Sci. 10, 143-169.

Evans D.O. and Rotar P.P., 1987: *Sesbania* in agriculture. Westview Tropical Agriculture Series, No. 8. Westview Press, Boulder Colorado, USA. 32 pp.

Garrity D.P. and Flinn J.C., 1988: Farm-level management systems for green manure crops in Asian rice environments. *In*: Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños, IRRI, Philippines. pp 111-129.

Garrity D.P. and Becker M., 1994: Where do green manures fit in Asian rice farming Systems? *In*: Ladha J.K. and Garrity D.P. (eds) Green manure production systems for Asian ricelands. The International Rice Research Institute. Los Baños, Philippines pp 1-10.

George T., Ladha J.K., Buresh R.J. and Garrity D.P., 1992: Managing native and legume-fixed nitrogen in lowland rice-based cropping systems. Plant and Soil 141,69—91.

Ishikawa M., 1988: Green manure in rice: the Japan experience. *In*: Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños, Philippines. pp 45-61.

King F.H., 1911: Farmers of Forty Centuries or Permanent Agriculture in China. Korea and Japan. Rodale Press, Inc. Book Division, Pennsylvania, USA.

Ladha J.K., Fischer K.S., Hossain M., Hobbs P.R. and Hardy B., 2000: Improving the productivity and sustainability of rice-wheat systems in the Indo-Gangetic plains: A synthesis of NARS-IRRI partnership research. Discussion Paper Nr. 40, IRRI, Manila, Philippines. 31 pp.

Ladha J.K., Kundu D.K., Angeln-Van Coppenolle M.G., Peoples M.B., Carangal V.R. and Dart P.J., 1994: Grain and forage legume effects on soil nitrogen dynamics anti nitrogen availability to following rice crops. Soil Sci. Soc. Am. J. 58, 55-1262.

Ladha J.K. Pareek R.P. and Becker M., 1992: Stem-nodulating Legume - Rhizobium symbiosis and its agronomic use in lowland rice. Adv. Soil Sci. 20,147-92.

Liu C., 1988: Integrated use of green manure in rice fields in South China. *In*: Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños, Philippines. pp 319-331.

Mar M., Saing I., Thein U. and Paris R.K., 1995: *Sesbania* green manure program for rice farming in Myanmar. *In*: Proceedings of the International Rice Research Conference, 21-25 April 1992. The International Rice Research Institute, Los Baños, Philippines.

Mc Gili W.B. and Myers R.K., 1987: Controls on dynamics of soil and fertilizer nitrogen. Soil fertility and organic matter as critical components of production systems. Soil Sci. Soc. Am. Special Publ. No. 19, pp 73-99.

McLean J., 1997: Rice Almanac. The International Rice Research Institute, Manila, Philippines. 181 pp.

Palaniappan S.P. and Budhar M.N., 1994: Seed production, crop establishment, and incorporation practices as agronomic constraints in green manure production systems. *In*: Ladha, J.K. and Garrity D.P. (eds). Green manure production systems for Asian ricelands. The International Rice Research Institute. Los Baños, Philippines.pp 99-114.

Pande K.R. and Becker M., 2001: Managing seasonal soil N dynamics in rice-wheat cropping systems of Nepal. *In*: Universität Bonn and ATSAF e.V. (eds) One World: Research for a better quality of life. Margraf Publishers, Weikersheim, Germany. p 35.

Peoples M.B. and Herridge D.F., 1990: Nitrogen fixation by legumes in topical and sub-tropical agriculture. Adv. Agron. 44, 152—223.

Peoples M.B., Herridge D. and Ladha J.K., 1995: Biological nitrogen fixation: an efficient source of nitrogen for sustainable agricultural production. Plant and Soil 174, 3-28.

Pingali P.L., Moya P.F. and Velasco L.E., 1990: The post-green revolution blues in Asian rice production. IRRI Social Science Division Paper Series No 90-01. The International Rice Research Institute, Los Baños. Philippines. 29 pp.

Pradhan P. and Garrity D.P., 1994: Establishement practices for prerice green manures. *In*: Ladha J.K. and Garrity D.P. (eds). Green manure production systems for Asian ricelands. The International Rice Research Institute. Los Baños, Philippines pp 99-114.

Roger P.A. and Watanabe I., 1986: Technologies for utilizing biological nitrogen fixation in wetland rice: Potentialities, current usage and limiting factors. Fert. Res. 9, 39—77.

Rosegrant M.W. and Roumassett J.H., 1988: Economic feasibility of green manure in rice-based cropping systems. *In*: Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños, Philippines. pp 13-27.

Roy A.C., Wanki S.B.C. and Takow J.A., 1988: Use of green manure in rce farming systems in West and Northwest Cameroon. *In*: Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños, Philippines. pp 333-342.

Schultze-Kraft R., 1988: Collection anti evaluation of tropical legume germplasm. *In*: Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños, Philippines. pp 343-358.

Singh Y., Kind C.S. and Singh B., 1991: Efficient management of leguminous green manures in wetland rice. Adv. Agron. 45, 135-189.

Ventura W., Mascanina G.B., Furoc R.E. and Watanabe I., 1987: *Azolla* anti *Sesbania* as biofertilizers for lowland nice. Philipp. J Crop Sci. 12, 61-69.

Vlek P.L.G. and Craswell E.T., 1981: NH_3 volatilization from flooded soils. Fert. Res. 2:247-259.

Vlek P.L.G., Diakite M.Y. and Mueller H., 1995: The role of azolla in curbing ammonia volatilization from flooded rice systems. Fertil. Res. 42(1-3), 5-174.

Vlek P.L.G., Kühne R.F. and Denich M., 1997: Nutrient resources for crop production in the tropics. Biol. Sci. 352(1356), 5-984.

Wassmannn R., Shangguan X.J., Tölg M., Chen D.X., Wang M.X., Papen H., Rennenberg H. and Seiler W., 1996: Spatial and seasonal distribution of organic amendments effecting methane emission from Chinese rice fields. Biol. Fertil. Soils 22, 91-195.

Westcott M.P. and Mikkelsen D.S., 1988: Effect of green manure on rice soil fertility in the United States. *In* Sustainable Agriculture: Green Manure in Rice Farming. The International Rice Research Institute, Los Baños, Philippines. pp 257-274.

Yost R. and Evans D., 1988: Green manure anti legume covers in the tropics. HITAHR, University of Hawaii. Research Series 055. 443 pp.