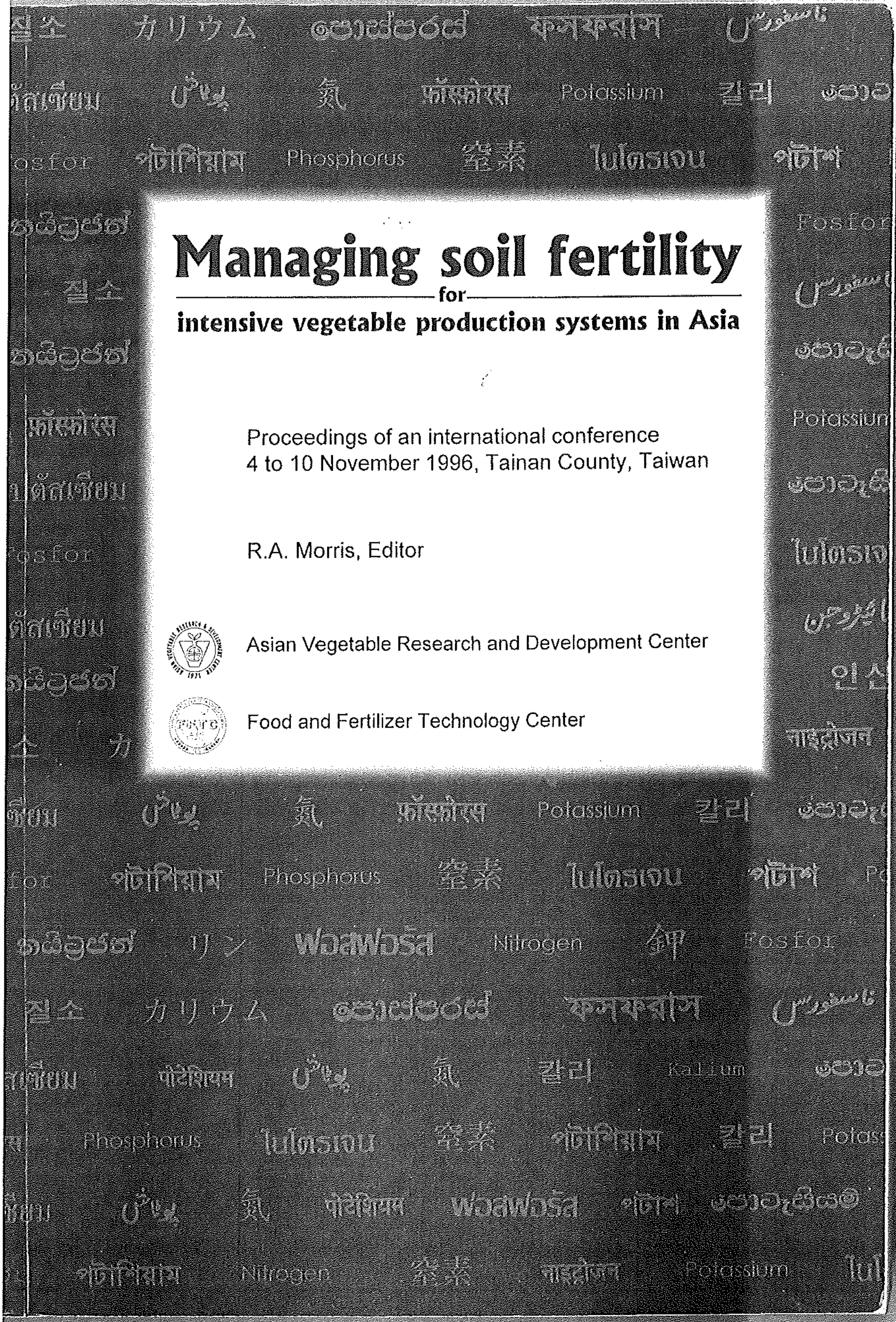

Managing soil fertility
for
intensive vegetable production systems in Asia

Proceedings of an international conference
4 to 10 November 1996, Tainan County, Taiwan

R.A. Morris, Editor

Asian Vegetable Research and Development Center

Food and Fertilizer Technology Center

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Tracking Nutrient Flows in a Multi-Enterprise Farming System with a Mass-Balance Model (ECOPATH)

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Abstract

Whether grown for sale or for on-farm consumption, vegetables and other crops are often managed as stand-alone, monoculture enterprises. Integrated farming can help improve the nutrient output-input balance sheet and efficiency, not only for each component, but for the whole farm agroecosystem. Quantitative methods that can assist farmers and researchers improve diversified and integrated natural resources management systems are emerging from the agricultural and ecological sciences. Modeling nutrient flows can help assess changes in management and production systems and help compare the impact of different agricultural scenarios on nutrient balances, productive capacity, and agroecological performance. ECOPATH, a mass-balance application program developed to model and assess the ecological state and performance of aquatic ecosystems, and which is now also applied to agroecosystems, is introduced. The analytical framework is illustrated by way of its application in the Philippines, to two smallholder rice farm scenarios with vegetable components.

Smallholder Agroecosystems

Tropical smallholder farms are often dominated by a particular component, typically a staple food crop, e.g., rice, wheat, maize, or banana, with other components, such as vegetables, (fruit) trees, livestock, and fish, making up the remainder of the farm system. These other "secondary" components might be comparatively small in terms of land area, labor requirements, biomass production, or yield, but can be important in other ways, for instance in terms of their economic contribution to household income and cash flow, as nutritional supplements to the predominant food staple, in risk management, and as useful ingredients in strategies of diversification and integrated resources management.

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In the type of agrarian scenario presented here, vegetable cultivation within smallholder lowland rice farming in the Philippines, vegetables often receive comparatively large amounts of externally supplied nutrients in the form of inorganic fertilizers. Not only do they command large nutrient imports, they also export large quantities of harvested biomass. They thus have an appreciable impact on the farm system's nutrient throughput and balance. Examples of common vegetable cash crops include chillie and bell peppers, gourds, eggplant, beans, pumpkin, tomato, watermelon, and water spinach. Under well-irrigated conditions, these vegetables can be grown in parallel with rice throughout the year. Where irrigation water is insufficient for dry season rice cultivation, a portion of the fallow rice land is often used for dry season vegetable cultivation.

Another common practice is to maintain small plots of vegetables for on-farm consumption. Their contribution to farm productivity and income is negligible. Their purpose is to add variety, spice, and nutrients to the household diet, rather than forming part of the strategy of cash generation, enterprise diversification, and risk reduction.

Integrated Nutrient Management

Irrespective of purpose, vegetables are usually grown separately as stand-alone crops. Opportunities exist, however, for integration with other plant and animal components, offering ways to improve the nutrient balance sheet and resource use efficiency of the whole farm agroecosystem. Whereas individual enterprise nutrient balances are important for efficient, profitable, short-term component management, the overall farm nutrient availability and balance is important with respect to the longer-term performance of the whole farm agroecosystem. Where maintaining the productive capacity of the system is a priority, one must consider the general ecological state and health of the entire farm.

By adopting a systems perspective, the term "balance" can be applied broadly. Looking beyond the input-output sum of the individual enterprise, a balance can be seen as a measure not only of the entire farm's input-output sheet, but also as an expression of the mixture and composition of farm components. How, for instance, is the agroecosystem designed (balanced) with respect to the combination of plants and animals, or in terms of short-lived productive organisms such as field crops and longer-lived organisms such as trees and livestock, which store biomass and buffer the system? How are inputs allocated (balanced) between components? Are there nutrient sinks and sources within the system, whose incorporation might help alleviate resource constraints (imbalances)? What might be the impact of alternative management strategies on the balance sheet?

To address such questions requires "stepping backwards" to take a look not only at individual enterprises but also at their (potential) linkages and interaction with other parts of the farm agroecosystem. Enterprises can be managed separately or they can be combined. Crop residues, grasses, weeds, and tree leaves can be used as animal fodder and green manure, and animal wastes can in turn fertilize field crops. Internally generated resources can help lessen the dependence on external feed and fertilizer inputs. There are multiple well-known and well-documented ways of integrating and recycling biomaterials within farms. There are also many less known and non-documented strategies for intensive, integrated resources management, developed by experimenting and innovative farmers.

The reasons why the integration potential in smallholder farming rarely is fully utilized are manifold: lack of tenure or insecure tenure discourages longer-term planning and investment of capital, skill, and labor in resource conservation and rehabilitation; shortage of or limited access to labor, capital, and seed material can inhibit innovation, experimentation with, and adoption of new components and technologies; and the general notion that integrated farming is synonymous with low output, i.e., unproductive farming, often prevails in the minds of researchers, advisers, and farmers.

There is growing evidence and documentation, however, that show that integrated farming need not be low-output farming. For general overviews of concepts and successful experiences with integrated natural resources management, see for instance Reijntjes et al. (1992) and Pretty (1995). Integrated and diversified farming, in the sense applied here, does not exclude the use of external inputs. Agrochemicals are important and often indispensable ingredients in the successful management of agricultural systems. Substituting non-chemical for chemical inputs does not by itself guarantee ecologically sound farming, but where the scope exists for replacing imports with resources generated within the system, and for capitalizing on synergisms from component interaction, this can benefit both the ecological and economic performance of the farm agroecosystem (Lightfoot et al., 1993a; Dalsgaard and Oficial, in press,b).

Where agroecosystems are inherently poor or degraded, rehabilitation might, besides conservation measures, require substantial nutrient injections, possibly over extended periods of time. In other cases, imports can be partly or almost completely replaced by the nutrients fixed, captured, and released within the agroecosystem itself. Any notion to rule out the potential for agricultural intensification through diversification, integration, and enhancement of existing resources is just as ill-founded as the sentiment that the use of agrochemicals should be abandoned altogether. Neither such extreme, generalized view is very productive. Recommendations for improved natural resources management must be location-specific, particularly with respect to heterogeneous smallholder agriculture situated in marginal, complex, and risk-prone environments.

Picturing Farms with Farmers

Ideas on productive and ecologically sound farming can be solicited from both resource managers (farmers) and researchers. Rarely, however, do the two groups find fora in which to interact to exchange ideas and insights. That the potential for fruitful communication does exist is now becoming increasingly evident through the development and application of participatory research and development methods – see for instance Mikkelsen (1995).

One such approach is being developed at ICLARM, in an effort to generate new integrated agriculture-aquaculture farms (Fig. 1). The RESTORE framework (Research Tools for Natural Resources Management, Monitoring and Evaluation) consists of the following elements: field appraisal methods for mapping and assessing community resources; bioresource flow diagramming tools for farmers and researchers to brainstorm ideas on technologies, experimentation, and farm-level resource management; field sheets for on-farm monitoring and data collection; and a software package for data entry, storage, and analysis of farm-level bio-economic performances[2] (Lightfoot et al., in press; Villanueva et al., in press).

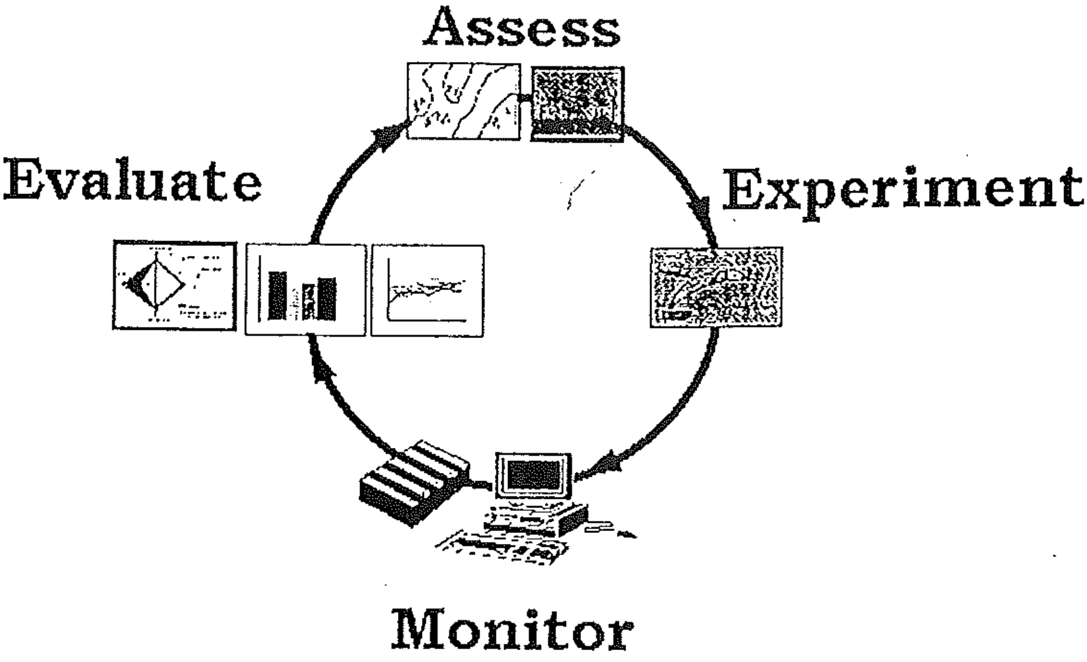

Fig. 1. The RESTORE process (Source: Lightfoot et al., in press)

Figures 2 and 3 show the bioresource flow diagrams of two different Philippine smallholder rice farm scenarios. The diagrams display plant and animal components and the bioresource flows (arrows) farmers use to integrate them. Such pictures can be generated with farm households based on past, present, or future (experimental) systems. They help to visualize the nature and structure of the farm agroecosystem and its constraints and opportunities for management changes, e.g., through diversification, integration, and intensified resource use. The diagrams also serve as a basis for on-farm monitoring and data collection for subsequent farm system analyses.

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[2] The software is currently undergoing beta-testing and the RESTORE package, including field and software manuals, is expected to be ready for distribution in 1997. For more information, contact Dr. Mark Prein, Program Leader, Integrated Aquaculture Agriculture Systems Program, ICLARM, MCPO Box 2631, 0718 Makati City, Philippines. Tel: + 63-2 818-0466. Fax: + 63-2 816-3183. E-mail: m.prein@cgnet.com

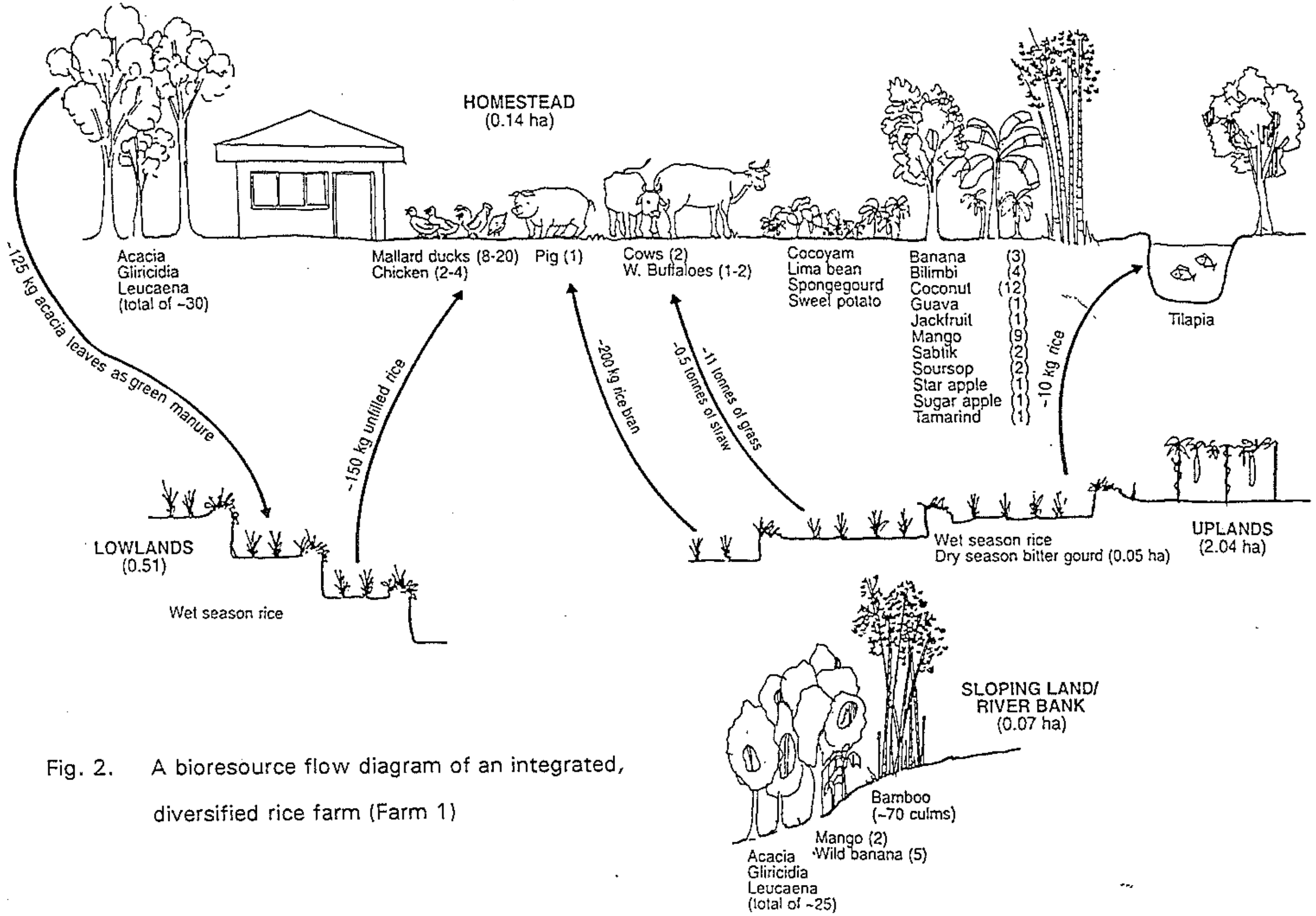
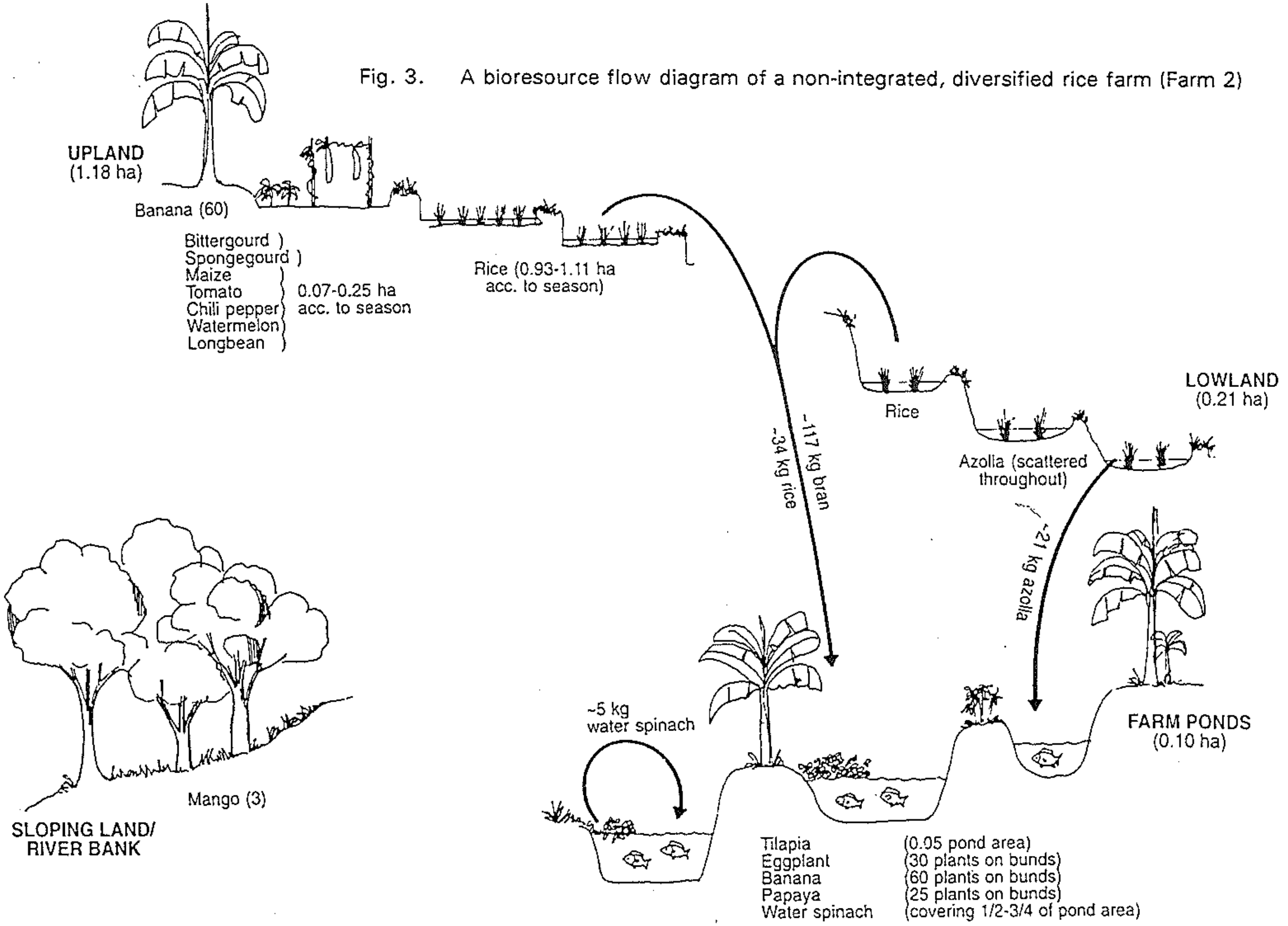


Fig. 2. A bioresource flow diagram of an integrated, diversified rice farm (Farm 1)

Fig. 3. A bioresource flow diagram of a non-integrated, diversified rice farm (Farm 2)



The two smallholder rice farms presented here are located within an agricultural region known primarily for its rice and vegetable production. They are situated on similar soils, but differ in terms of water availability and agroecosystem design and management:

- During the wet season from June to November, Farm 1 cultivates one rice cash crop, a few vegetables (chillie pepper, bottle gourd, lima bean, sweet potato, and yam), and fish (tilapia) primarily for home consumption. Dry season activities include animal management (cow, water buffalo, ducks, chickens, pigs), fruit production, bamboo cutting, and bitter gourd cash cropping. The 2.76 ha agroecosystem receives a total of 126 kg of inorganic fertilizer (urea) per year, equivalent to approximately 21 kg N per ha per year. This is supplemented with green manuring (acacia leaves) on the lowland rice crop.

- Farm 2 cultivates more than two rice crops a year, together with a range of vegetable cash crops (bitter gourd, bottle gourd, chillie pepper, long bean, maize, tomato, watermelon, and water spinach) grown either in monoculture or as vegetable intercrops. The vegetables occupy approximately 20% of the total farm area. Other components include fruit trees and fish. The 1.51 ha agroecosystem receives a total of 775 kg of inorganic fertilizer (urea and complete fertilizer) per year, equivalent to 167 kg N per ha per year, most of which is applied on the vegetables. This farm is also characterized by a high number of cultivated plant species, but few animals and almost no component integration in terms of material flows.

- Farm 1 represents what could be labeled a diversified and integrated rice farm agroecosystem with cycling of rice products, grasses, weeds, tree leaves, and manures, whereas Farm 2 represents a diversified but non-integrated rice system.

Modeling Nutrient Flows with ECOPATH

The basic concept of the bioresource flow diagram – a model of stocks and flows – is identical to that employed by researchers and modelers when analyzing complex ecological systems (Jørgensen, 1994). By determining the sizes of stocks and flows in the bioresource flow diagram we therefore have the basis for a quantitative description, modeling and performance evaluation of a farm agroecosystem.

To perform an in-depth agroecological analysis, the ECOPATH modeling software[3] was applied. ECOPATH was developed to model and analyze trophic flow networks in aquatic ecosystems (Christensen and Pauly, 1992, 1993), but the underlying mass-balance and mass-conservation principles also apply to terrestrial based systems (Dalsgaard and Christensen, 1997; Dalsgaard and Oficial, in press,a). The software has already been used in the descriptive modeling and analysis of field and farm-level agriculture-aquaculture agroecosystems (Lightfoot et al., 1993a; Dalsgaard et al., 1995; Dalsgaard and Oficial, in press,b). In principle, the mass-balance approach can be applied at any spatial scale across the landscape (Dalsgaard and Oficial, 1995).

Figures 4 and 5 show the ECOPATH flow models of the two farms. All stocks and flows are expressed in kg N per ha per year. These two models were derived from a one-year intensive monitoring and comparison of different Philippine smallholder rice farm scenarios (Dalsgaard and Oficial, MS). In order to construct an ECOPATH model, the following basic information is required for each plant and animal component: its average biomass (B); its growth or production (P) expressed as the P/B ratio; its consumption (Q) expressed as the Q/B ratio; harvests and other exports, including losses; imports (e.g., feeds) and the diet composition. The parameters are quantified in a common unit, usually in energy or in nutrient terms. These input data can be obtained through direct on-farm measurements, extracted from the literature, or through combined use of primary and secondary data. From the parameter sets, the software computes a number of summary statistics and indices which are used to assess a given system's ecological state and productive performance. Dalsgaard and Oficial (in press,a) provide a detailed account of field methods and procedures for model development.

The approach can also be used to address the issue of nutrient balances. The mass-conservation and mass-balance principles imply that all stocks (components), stock changes, and flows into and out of stocks are accounted for within a model. For example, the quantity of nutrients "consumed" by a

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[3] The ECOPATH software and related publications can be obtained from Villy Christensen, ICLARM, MCPO Box 2631, 0718 Makati City, Philippines. E-mail: v.christensen@cgnet.com

field crop, i.e., plant nutrient uptake from the soil, must equal the amount of nutrients in the plant biomass, part of which is exported from the farm through harvest and removal of residues and part of which is returned to the soil when residues are left to decompose. By-products may also be used for animal fodder. Whatever their destiny, the in- and outflows for each component should be identified, quantified, and balanced out before data entry. On the basis of a system of coupled linear equations, the software can, to some extent, assist in generating some parameters.

A model thus developed is essentially a description, or a "snapshot", of the average state of a particular system over a particular period of time. This approach has several utilities. First, it renders the farm as an agroecosystem, a useful perspective as we move from a problem focus to a natural resource focus, looking beyond technologies to solve specific commodity production problems, towards interventions to manage and rehabilitate the resource base of the whole agroecosystem (Lightfoot et al., in press). Second, the summary statistics computed through the analytical routines in ECOPATH are used to assess the ecological state and productive performance of an agroecosystem and to carry out quantitative evaluations and comparisons of different agricultural scenarios and management strategies (Dalsgaard et al., 1995; Dalsgaard and Oficial, in press,b). Last, it is useful for addressing the issue of nutrient balances in agroecological systems. An obstacle to the wider implementation of this type of approach is the (present) shortage of systems-oriented agroecologial data sets.

Agroecosystem Nutrient Balance Analysis

Nitrogen enters and leaves a rice farm through a series of mechanisms, including biological nitrogen fixation (BNF), run-on with incoming irrigation water, and dry and wet atmospheric deposition. It is lost through a number of processes, including erosion, runoff, leaching, volatilization, and denitrification. In the cases presented here, data on these gains and losses were not measured *in situ*, but derived from the literature[4]. Most of the fluxes are not easily quantified and estimates often vary by an order of magnitude, depending

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[4] For a comprehensive overview of nutrient management and fluxes in rice floodwaters, see Roger (1996)

on environmental conditions and farm management practices. Average estimates were applied in the present study.

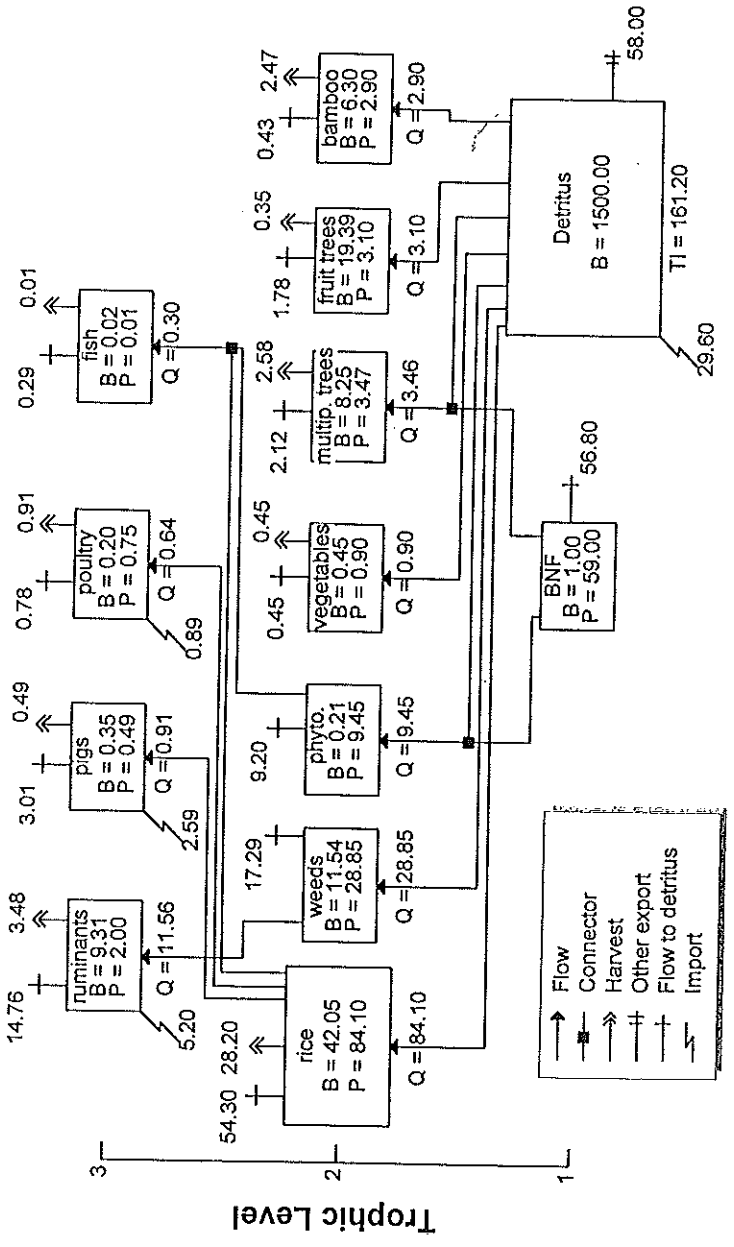

Fig. 4. ECOPATH flow diagram of Farm 1, with all stocks and flows expressed in kg N/ha/year

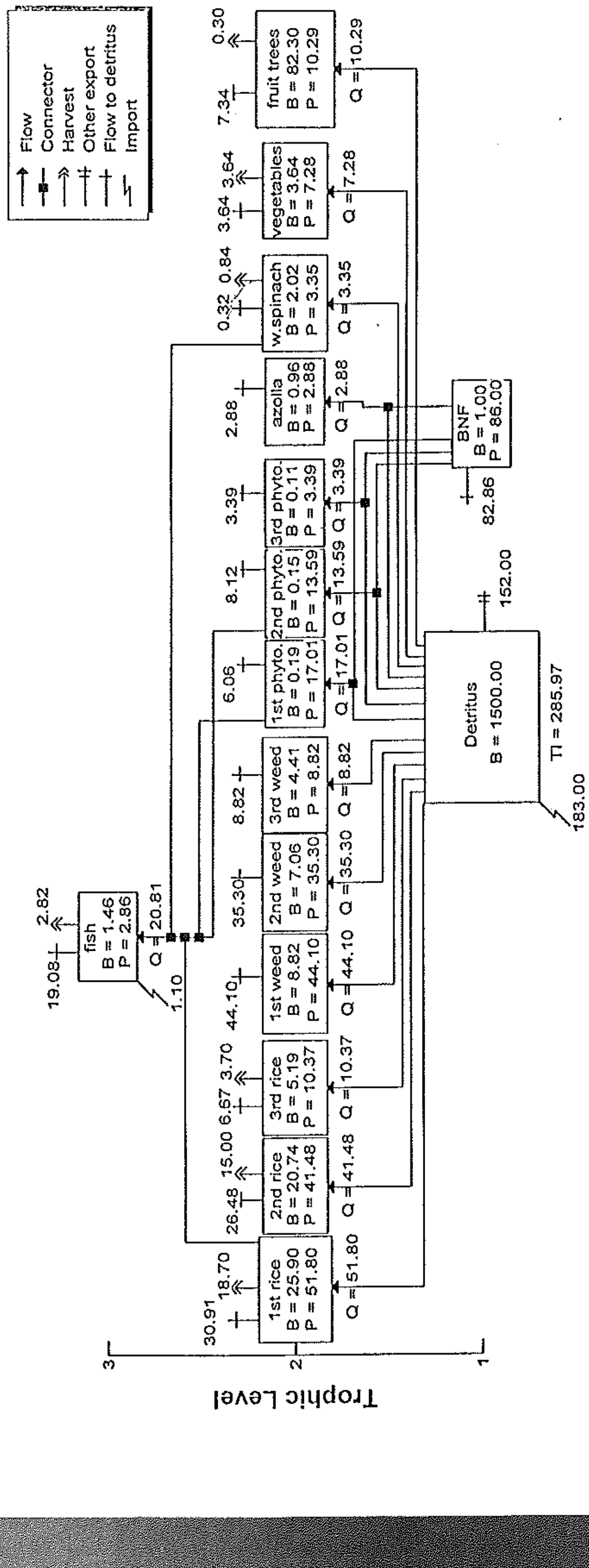

Fig. 5. ECOPATH flow diagram of Farm 2, with all stocks and flows expressed in kg N/ha/year

Substantial N losses from ricefields occur through volatilization and denitrification, and only around 50% of BNF-N (Kundu and Ladha, 1995) and 30 to 40% of N applied in inorganic fertilizers (Lightfoot et al., 1993a) was assumed utilized by the crops. Most of the non-utilized N volatilizes or denitrifies. Losses from erosion, runoff, and leaching from ricefields were assumed to be negligible. If poorly managed, however, irrigation floodwater can carry away substantial amounts of newly applied fertilizer. In the case of Farm 1, N was also lost from the production system in unutilized manure. The following equation was used to compute the N balances:

Farm agroecosystem balance =

(feed and fertilizer inputs) + (BNF) + (run-on with incoming irrigation water) + (dry and wet atmospheric deposition) − (net harvest) − (erosion + runoff) − (leaching) − (volatilization + denitrification)[5].

This gave the following budgets for the two farms (Figs. 6, 7)[6]:

Farm 1 =

30 + 59 + 2 + 7 − 32 − (0) − (0) − (14 + 30 + 14) = ~ <u>1 kg N per ha per year</u>

Farm 2 =

167 + 86 + 2 + 14 − 45 − (0) − (0) − (109 + 43 + 0) = ~ <u>72 kg N per ha per year</u>

Farm 2 imports a substantial amount of N through inorganic fertilizers (167 kg N per ha per year) although the continuous rice cultivation and almost permanent flooding of fields in itself creates a microenvironment very conducive to biological nitrogen fixation (estimated at 86 kg N per ha per year). Farm 2 also has a large export of N through harvest and gaseous losses − 45 kg and 152 kg N per ha per year, respectively − and is characterized by a large throughflow as expected for a high-input system. The losses indicate

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[5] Volatilization and denitrification are here partitioned into three: loss of N from inorganic fertilizers; loss of biologically fixed N; and loss of N from animal manures

[6] Notice the different scales on the Y-axis

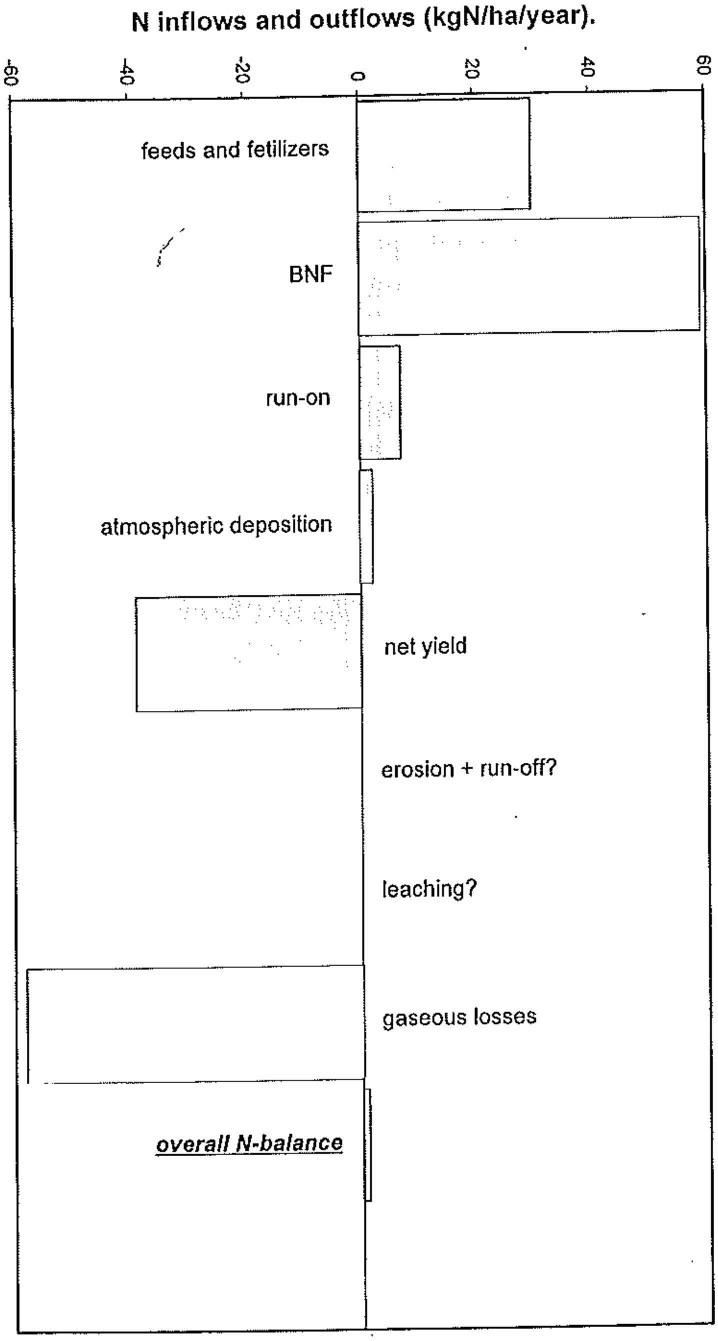

Fig. 6. N-budget for the integrated and diversified system (Farm 1)

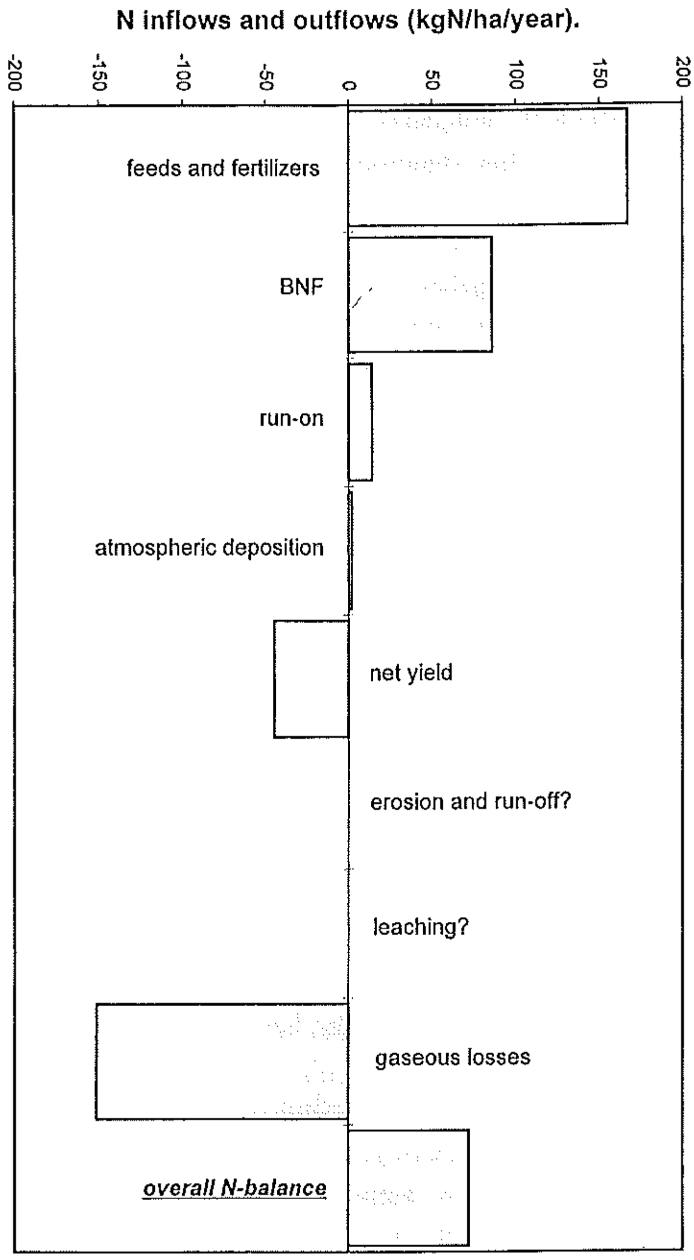

Fig. 7. N-budget for the non-integrated and diversified system (Farm 2)

a negative (pollutive) impact on the surrounding environment. The estimated annual surplus of 72 kg N per ha is rather high and suggests that not all losses were accounted for and that gaps might exist in our knowledge regarding the magnitude(s) of the various N pathways out of the farm system. Given the low inputs of N into Farm 1, a balance very close to zero is an encouraging finding, which suggests that integrated nutrient management benefits the balance sheet.

Farm 2 is the more productive, i.e., the higher yielding of the two systems – 45 kg N per ha per year as opposed to 39 kg N on Farm 1. Farm 1, however, still performs comparatively well, given the inadequate water supply and the inability to cultivate rice during the dry season. This suggests efficient use of available resources (nutrients) within the integrated farm agroecosystem. The efficiency on Farm 1 could be further improved through better utilization of manures and incorporation of nutrients stored in the biomass (especially leaves and twigs) of leguminous trees. On Farm 2, the immediate challenge for improved nutrient management appears to lie in a more judicious use of inorganic fertilizers. There are sufficient weeds, straw, and rice bran being produced to feed more livestock on Farm 2.

The analysis also highlights the importance of re-using and reincorporating crop residues. Although not the case on either of the farms presented here, it is common practice in Philippine rice farming to burn straw and hulls after rice harvest. Nearly all N contained in the burnt material is thus lost. – This is significant given that straw can contain more than 50% of above-ground rice crop N. Straw burning would result in negative N balances within both of the farm systems presented here.

Conclusion

The agroecosystem view signifies a shift in focus from a narrow preoccupation with enterprise productivity, yield, and efficiency, towards a broader appreciation of the performance of the farm as a "mini-ecosystem". The nutrient balance represents one key indicator of how well a system is doing. Computing accurate nutrient budgets and balances at the field and farm level is difficult, however, and the balance concept is perhaps more feasibly applied on a larger spatial scale, e.g., at the watershed level.

The proposed modeling framework can be used as a basis for quantifying additional performance measures, including system productivity (yield), efficiency, agricultural diversity, nutrient recycling, and other aggregate properties of agroecological systems. Such quantifiable indicators are useful for addressing the sustainability issue, and preliminary investigations along these lines suggest that smallholder integrated and diversified rice-based systems can compete with high-input monoculture farming in both economic and ecological terms (Dalsgaard and Oficial, in press,b). Adding the benefits accruing to society from an environmentally sound and less polluting agriculture will no doubt make the arguments for researching and generating new integrated farm agroecosystems even more compelling.

Acknowledgments

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