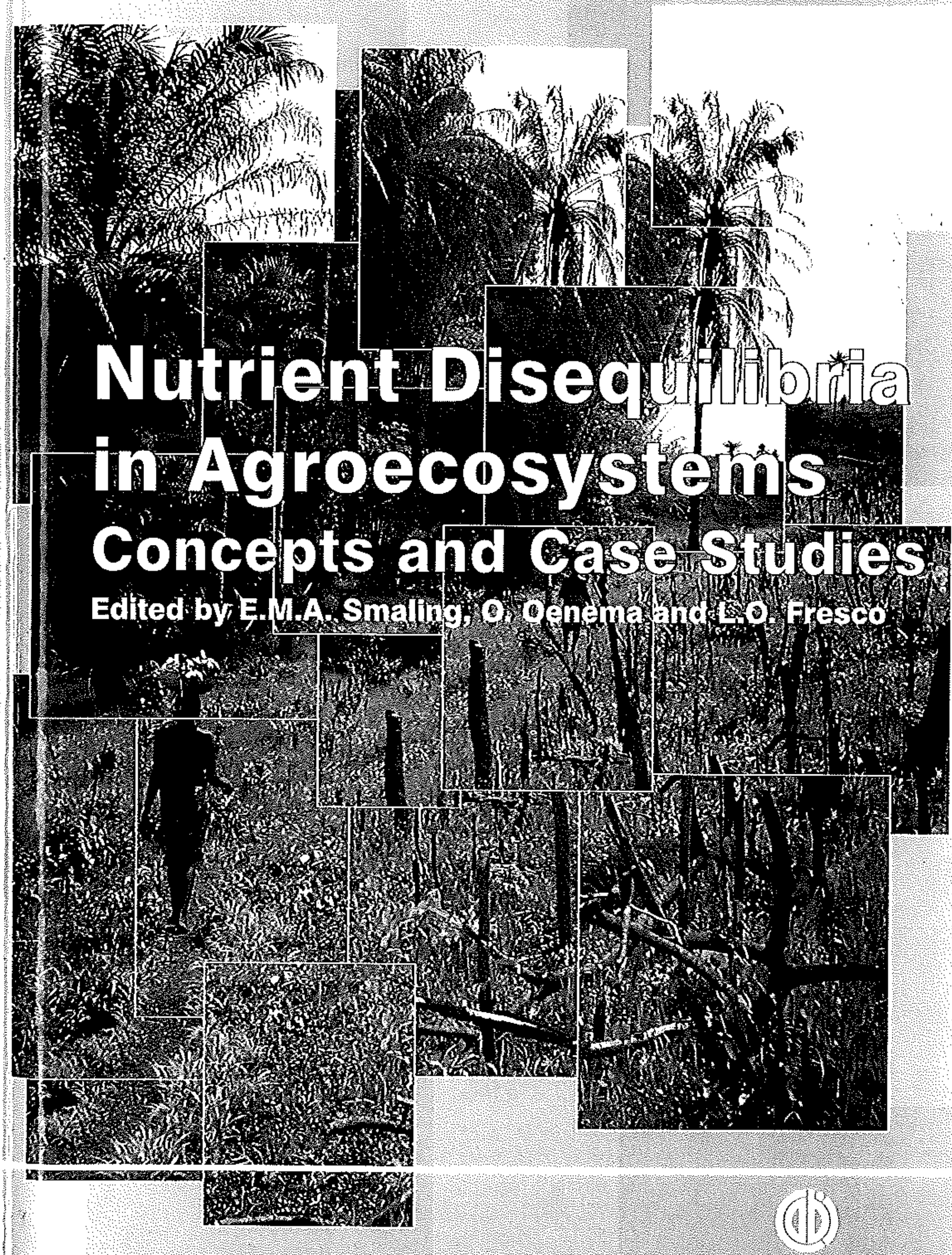
Nutrient Disequilibria in Agroecosystems

Concepts and Case Studies

Edited by E.M.A. Smaling, O. Oenema and L.O. Fresco



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Integrated Smallholder Agriculture–Aquaculture in Asia: Optimizing Trophic Flows

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ABSTRACT

A nutrient modelling approach was applied to show how the combination of crops, trees, livestock, and fish, that is, integrated agriculture–aquaculture (IAA), helps in optimizing trophic flows in Asian rice-based agroecosystems. Integrated natural resource management can benefit the farm's nutrient balance sheet and nutrient use efficiency, while generating productive systems. In the current study, N-efficiency and economic efficiency of IAA systems can be more than doubled compared with rice monoculture systems. The IAA system represents one potential avenue towards ecologically balanced and sustainable forms of tropical smallholder farming. The key question remains how to engineer the appropriate socioeconomic environment for the evolution of such systems.

INTRODUCTION

The ecological records of tropical agriculture and aquaculture (fish farming) share many features (Dalsgaard *et al.*, 1995). Where agrochemical inputs are easily available, affordable and applicable these are often (too) liberally applied; irrigated farming of high-yielding rice varieties in Asia is a case in point. The short-term outcome is productive and profitable agricultural systems. The longer-term impact is often one of declining yields and returns, alongside ecological deterioration both on-farm and downstream, particularly in rainfed areas (Cassman and Pingali, 1995; FARM, 1996).

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Modern rice farming is witnessing declining agronomic efficiency, in terms of yield per unit input. At the cropping system level, trends of stagnant yields and increasing input requirements to maintain yields are detected. Underlying causes may include a general degradation of soil quality such as a reduction in essential micronutrients, and a decline in soil N supplying capacity (Cassman and Pingali, 1995).

Intensive aquaculture (i.e. producing >15 t ha^{-1} year^{-1}) is 7–31 and 3–11 times as polluting as semi-intensive systems (i.e. producing in the range of 1–20 t ha^{-1} year^{-1}), in terms of quantities of nitrogen (N) and phosphorus (P) released to the environment per kilogram of fish produced (Edwards, 1993). Intensive fish farms are also heavy users of antibiotics and disinfectants (Pullin, 1993). Stand-alone fish farms (i.e. without other enterprises of crop and livestock production) are risky ventures for smallholders and show a record of financial and environmental disaster in Africa and Asia (Cross, 1991; McClellan, 1991).

At the opposite end of the spectrum, in low-external-input smallholder farming, ecological constraints are also being encountered. Here, part of the problem is that of inadequate access to external nutrient inputs (Brummett, 1996; R.E. Brummett, 1999, unpublished observations). These are often needed to complement internal resources in order to revive the production system (Reijntjes *et al.*, 1992). Where nutrients and on-farm labour are available, examples of organic farming including integrated fish farming can develop (Little and Muir, 1987; IIRR and ICLARM, 1992; Symoens and Micha, 1995; Mathias *et al.*, 1997).

The development of balanced, productive and environmentally sound forms of tropical smallholder agriculture may well lie somewhere in between these two extremes. Integrated farming, or integrated natural resources management, where modest amounts of external inputs are used to supplement the (re)use of internal resources could be a solution for many tropical smallholders (Costa-Pierce *et al.*, 1991; Edwards 1993; Lightfoot *et al.*, 1993a; Prein *et al.*, 1995). Neither the route of agrochemical- and capital-intensive agriculture, nor that of resource underutilization, appears feasible. The alternative then, could be a middle way. This study presents a comparison of different rice-based farming systems using a mass-balance analytical framework to assess their comparative ecological and economic performance characteristics.

SEMI-INTENSIVE INTEGRATED AGRICULTURE–AQUACULTURE

One potential avenue towards ecologically balanced farming is the development of semi-intensive, integrated, agriculture–aquaculture (IAA) systems. Where the environment (e.g. water availability, soil texture, topography), tradition (waste reuse, fish consumption), experience, economic circumstances (e.g. declining farm productivity), and new opportunities (e.g.

access to markets) present fish farming as an option, IAA can emerge successfully (IIRR and ICLARM, 1992; Lightfoot *et al.*, 1993a; Brummett and Noble, 1995; Edwards and Little, 1995; Lightfoot and Pullin, 1995; Pullin and Prein, 1995; Prein *et al.*, 1996a, b). Some examples include the following:

- In Ghana and Malawi, farmers have established fish ponds in suitable locations in lowlands such as small inland valleys and depressions and operated these during the months following the rainy season, simultaneously growing an array of crops and vegetables (Prein, 1993; Ofori *et al.*, 1993; Brummett and Noble, 1995; Noble, 1996).
- In Vietnam, smallholder farmers have linked pig rearing, rice, vegetable and fruit growing with fish and freshwater prawn farming to become a profitable and highly productive system in the Mekong River and Red River deltas (Tran and Demaine, 1996; FAO-RAP, 1996; WES, 1997; Rothuis *et al.*, 1998a, b; D.K. Chung, H. Demaine, V.T. Pham, Q.D. Nguyen and T.H. Bui, 1999, unpublished observations).
- In Thailand, profitable fish farming ventures have developed utilizing chicken and other livestock manures and chicken slaughterhouse wastes purchased from other commercial farms (Edwards and Little, 1995). Yet these off-farm integration systems tend towards greater intensity due to their often peri-urban setting and ensuing constraints of required water quality and quantity (Edwards *et al.*, 1983; Engle and Skladany, 1992; Edwards, 1993; Little *et al.*, 1994).
- In China, rice–fish farming covered an area of 800,000 ha by 1988 with an average fish production of 180 kg ha^{-1}. The integration of fish culture in rice fields entails an increase in rice production by at least 10% which is attributed to weed removal, bioturbation and fertilization by the fish (MacKay, 1995; Mathias *et al.*, 1997).

Smallholder IAA is defined here as diversification of agriculture in the sense that aquaculture is developed as a subsystem on a farm with existing crops, trees or livestock subsystems, or a combination. An output from one subsystem in an integrated farming system which otherwise might have been wasted becomes an input into another subsystem resulting in a greater efficiency of output of desired products from the land/water area controlled by a farmer (Little and Muir, 1987; Edwards *et al.*, 1988). IAA systems in general are labelled *semi-intensive* as opposed to *extensive* systems relying exclusively on natural feed produced without intentional inputs; the *intensive* system depending on nutritionally complete feeds (and fertilizers), with farmed organisms deriving little or no nutrition from natural feed produced *in situ* (Edwards, 1993).

Semi-intensive fish farming has been a feature of the smallholder farmscape for centuries, particularly in parts of Asia, where the development potential for IAA is considerable (Ruddle and Zhong, 1983; Yan and Yao, 1989; Lightfoot *et al.*, 1992; Edwards, 1993; Edwards *et al.*, 1996; Roger, 1996; Mathias *et al.*, 1997). One of the secrets to the success of IAA lies in the development of a fine-tuned balance between the plant, livestock, fish and human subsystems, facilitating intensive (re)use and integration of resources across trophic levels (Schaber, 1997).

On a larger village or community scale, the IAA system is successfully practiced in China in situations of high population density (e.g. 1500 persons km^{-1}). Studies of these systems based on energy and nutrient flow modelling have shown that the amount of external nutrient inputs in the form of feeds and fertilizers can be halved through internal recycling and increase of primary production (e.g. grass or phytoplankton) on existing areas (see Bossel, 1987; Ruddle and Christensen, 1993; Guo and Bradshaw, 1993). Still, in spite of considerable efforts, these large-scale high-production systems derive approximately 80–90% of their nutrient needs from outside the farmed area in the form of imported feeds and fertilizers including all of their considerable fossil fuel and electricity needs.

RICE FLOODWATER ECOLOGY

The rice floodwater ecosystem is by nature a very productive and stable system. The flooding favours soil fertility and rice production by: (i) bringing soil pH to near neutral; (ii) increasing availability of nutrients; (iii) retarding soil organic matter decomposition and thus maintaining soil N fertility; (iv) favouring N-fixation; (v) suppressing outbreaks of soil-borne diseases; (vi) supplying nutrients from irrigation water; (vii) depressing weed growth; and (viii) preventing water percolation and soil erosion (Roger, 1996). Much of the natural fertility of rice wetlands can be attributed to cyanobacteria (blue-green algae), the major indigenous N-fixing agent in ricefield floodwater. Balance studies have indicated that this biological fixation alone contributes 15–50 kg N per crop ha^{-1} in unfertilized fields (Koyama and App, 1979).

Ecological studies on the submerged soils of lowland ricefields are scarce, however. As a result, our quantitative understanding of the nutrient pathways through this agroecological system under field and farm conditions is limited. Although individual N contributions via different agents of biological N-fixation (BNF) can be estimated more or less accurately, total BNF in a ricefield has not yet been estimated by measuring simultaneously the activities of the various components *in situ* (Roger and Ladha, 1992).

A review of the literature (App *et al.*, 1984; Roger and Ladha, 1992; Lightfoot *et al.*, 1993b; Roger, 1996) provides the following approximate values of component N fluxes into and out of an inorganically fertilized rice agroecosystem (Table 7.1). Individual estimates vary substantially, for example from a few to 80 kg N (27 kg N on average) in the case of photo-dependent fixation by cyanobacteria, depending on management and site conditions (Roger, 1996). Inorganic fertilizer application reduces BNF. Roger and Ladha (1992) present BNF figures of only 8 kg ha^{-1} per crop in

Table 7.1. Published values of component N fluxes into and out of inorganically fertilized rice agroecosystems. See text for sources of published data.

	N flux
In-fluxes (gains):	
Dry and wet atmospheric deposition	~1.5 kg N ha^{-1} $year^{-1}$
Run-on/deposition with irrigation water	~10 kg N ha^{-1} $crop^{-1}$
BNF:	
Associative fixation in the rice rhizosphere	~4 kg N ha^{-1} $crop^{-1}$
Heterotrophic fixation associated with rice straw	~2–4 kg N t^{-1} straw
Heterotrophic fixation in flooded planted soil associated with organic debris	~10–30 kg N ha^{-1} $crop^{-1}$
Photodependent fixation by blue-green algae (cyanobacteria)	~27 kg N ha^{-1} $crop^{-1}$
Out-fluxes (losses):	
~50–75% of biologically fixed N lost through ammonia volatilization and denitrification	
Erosion and runoff (negligible)	
Leaching/deep percolation (negligible)	

plots with broadcast urea and 12 kg with deep placed urea, as opposed to 20 kg in no-N plots. Besides having a depressive effect on BNF, inorganic fertilizer efficiency is, in itself, low in wetland ricefields. Only 20–40% of applied N is recovered by the crop depending on N source, management and agroecological conditions (Lightfoot *et al.*, 1993b). The remaining 60–80% is essentially lost from the rice production system in gaseous form. Long-term fertility plot studies have produced little evidence to suggest that N, P or potassium (K) fertilization affects total soil N content over time (App *et al.*, 1984). Losses through erosion/runoff and leaching/deep percolation are generally ignored or assumed to be negligible in lowland rice farming on fine-textured, heavy soils.

Fish (and other aquatic organisms such as frogs, snails, bivalves and crustaceans) are a natural, although increasingly scarce, ingredient of the rice floodwater agroecosystem and have been an important contributor to the nutrition of traditional rice farming households in Asia. Fish culture in ricefields has been observed to have several beneficial effects, including: (i) reduced N losses from the floodwater due to ammonia (NH_3) volatilization; (ii) improved physico-chemical properties of the soil (soil fertility); (iii) increased nutrient cycling and availability; and (iv) increased rice yield and N uptake (Roger, 1996). Many of these potentially beneficial effects of fish on rice, however, remain unquantified.

Fish grazing on aquatic biomass contribute through their faeces to increased nutrient cycling and availability to rice. In Hunan Province, China, organic matter, N, available P and K were all higher in rice/fish fields than in rice-only fields (Hunan Research Team, 1987, cited in Roger, 1996). Increases in N concentration in rice grain by 5% and N uptake by 10% were observed in fields where fish were introduced (Pandá *et al.*, 1987, cited in Roger, 1996). The same study also reported that increased P uptake in the presence of fish was observed in some experiments (the underlying circumstances are not clear) as well as higher iron uptake in rice–fish culture than in rice alone. The presence of fish may thus benefit rice yield in both quantitative and qualitative terms.

Fish grazing on algal biomass reduces water turbidity. As high algal density is associated with high pH values through carbon dioxide (CO_2) consumption, algal reduction helps lower the pH towards neutral, which in turn reduces N loss through NH_3 volatilization in the earlier stages of crop growth (Roger, 1996). Other beneficial effects of fish on rice include direct consumption of rice pests and weeds by fish. Detrimental effects of fish on rice are primarily associated with uprooting of seedlings by herbivorous fish (e.g. carp) when stocked too early.

ECOPATH MASS-BALANCE MODELS

In a preliminary study of the trophic ecological interactions and N flows in the rice floodwater ecosystem, Lightfoot *et al.* (1993b) compared two systems: rice monoculture and rice–fish integration. The integration of fish in rice paddies increased rice yield compared with control plots by up to 30% (10–15% on average), while at the same time producing up to 500 kg fish ha^{-1}. It is hypothesized that the greater efficiency in rice production is related to an increased production of detritus due to the presence of fish through their bioturbation activity and their production of excreta, contributing to the replenishment of soil microbial biomass – the most important actor in the ecosystem in terms of N cycling.

Initially developed for the modelling and analysis of aquatic ecosystems (Christensen and Pauly, 1992), the ECOPATH approach and software is now also being applied to agroecosystems. The software is available from ICLARM. This mass-balance framework was employed by Lightfoot *et al.* (1993b) as it provides a good basis for exploring the characteristics of nutrient flows and budgets in rice agroecosystems. Figures 7.1 and 7.2 convey a visual impression of how the structure of a trophic network within a rice-based agroecosystem changes as a monoculture rice farm is transformed into a 'fully-fledged' more diversified IAA farm combining rice, fish, livestock and trees. ECOPATH diagrams individual farm components as boxes and indicates their biomass, production and consumption parameter values and linkages to other components, including detritus which denotes the soil resource base. See Christensen and Pauly (1992) and Dalsgaard and Oficial (1998) for more details on how to generate, analyse and interpret flow networks within the ECOPATH framework.

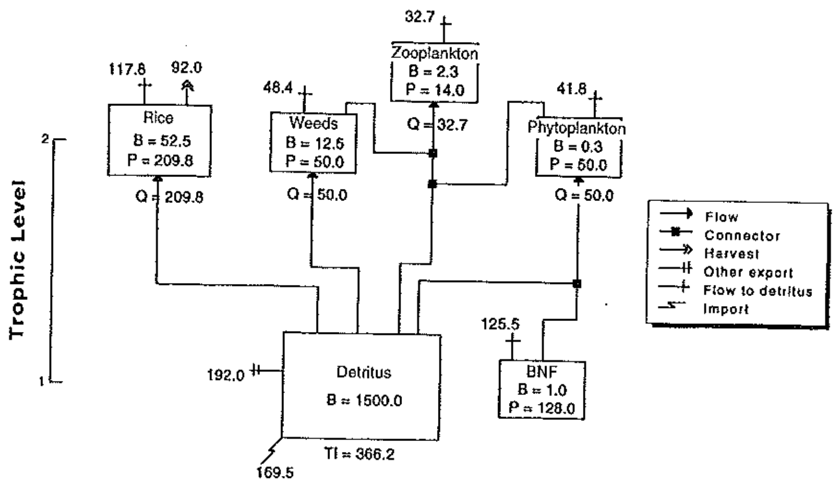

Fig. 7.1. ECOPATH flow diagram of a theoretical 1.0 ha monoculture rice farm (values in kg N ha^{-1} $year^{-1}$). B, average standing biomass; P, production; Q, consumption; TI, total input into detritus; BNF, bacterial nitrogen fixation.

In a comparative on-farm study of integrated and non-integrated rice farming, Dalsgaard and Oficial (1997) investigated N flows in four Philippine smallholder agroecosystems, including monoculture riçe, diversified rice cultivation, and rice farming integrated with trees, livestock and aquaculture. The farms were monitored during one annual cycle and data collected on imports, recycled biomaterials, and harvested products for all compartments (rice, weeds, vegetables, fruit and multipurpose trees, bamboo, ruminants, poultry, pigs and fish). Table 7.2 lists important quantitative agroecological performance indicators for the four farms. The bioresource flow diagram in Fig. 7.3 illustrates the reuse of wastes and by-products within one of the integrated farms (Farm D). The N budget for the same farm is shown in Fig. 7.4.

This on-farm investigation showed that through integrated natural resources management, economically attractive, productive and (near) balanced systems can be generated and maintained, without resorting to large nutrient imports. It also showed that high application rates of inorganic fertilizers are not necessarily associated with a positive nutrient balance, but rather with high flows through the rice-based agroecosystem and high losses to the environment. The comparative modelling and analysis of the four smallholder farms emphasized gaps in our quantitative understanding of N fluxes through the rice agroecosystem: a positive balance in the order of 72 kg N ha^{-1} $year^{-1}$ (Farm B, Table 7.2) suggests an impressive, but unlikely, build-up of soil N, supported neither by longer-term observations

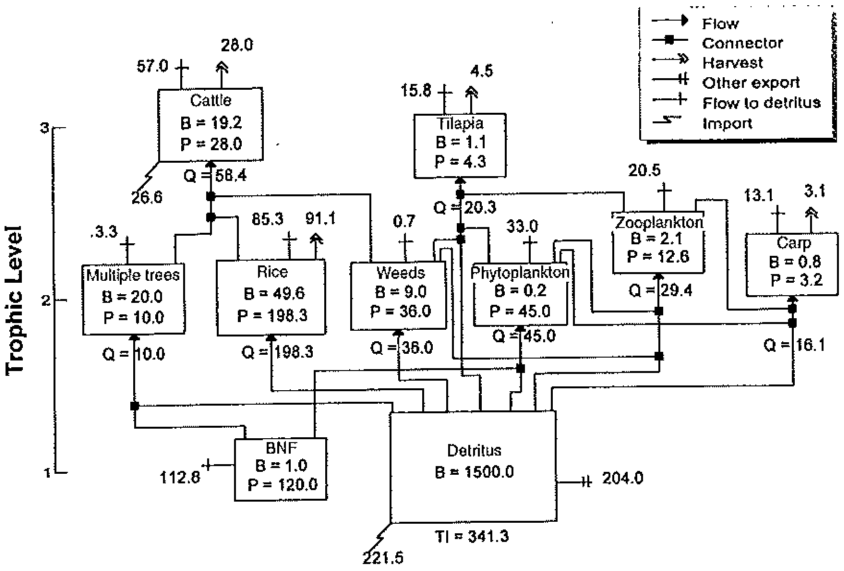

Fig. 7.2. ECOPATH flow diagram of a theoretical 1.0 ha integrated agriculture–aquaculture (IAA) farm system (values in kg N ha^{-1} year^{-1}). See Fig. 7.1 for details.

(App *et al.*, 1984) nor by long-term productivity trends (Cassman and Pingali, 1995); we are still very much in the dark as to the out-flows of nutrients through leaching and runoff. The former may be insignificant on waterlogged, well-puddled clay soils, whereas the latter will depend on water management and can be substantial where the surface water flow across a ricefield area is not carefully controlled after fertilizer applications.

DISCUSSION

The hypothetical models and actual case studies presented here indicate that one way to improve the balance, efficiency and impact of agricultural activities is through diversification and integration of farmed organisms across trophic levels. In our experience such integrated farming strategies benefit both the ecological and economic performance of smallholder farms, while reducing their off-site impact through better management and more intensive use of available soil and water resources.

Nitrogen is probably the most thoroughly researched macronutrient in the rice floodwater agroecosystem. Yet, our quantitative understanding of its inputs and outputs throughout this complex system remains fragmented.

Table 7.2. Agroecological performance indicators for four Philippine smallholder rice farm systems (from Dalsgaard and Oficial, 1997).

	Farm A High-fertilizer-input monoculture rice system	Farm B High-fertilizer-input diversified rice system	Farm C Low-fertilizer-input diversified and integrated rice system	Farm D Low-fertilizer-input diversified and integrated rice system
Surplus N (kg N ha^{-1} $year^{-1}$)[a]	190	152	58	62
N balance (kg N ha^{-1} $year^{-1}$)[b]	–2	72	1	–9
N efficiency[c]	0.19	0.17	0.40	0.38
N yield (kg N ha^{-1} $year^{-1}$)[d,e]	43 (22)	45 (26)	39	33
Gross margin (US$ N ha^{-1} $year^{-1}$)	~250	~750	~625	~600

[a]Lost from the farm system primarily in gas form (volatilized and denitrified N), and to a lesser extent through erosion/runoff.
[b]Expresses residual N not accounted for and thus assumed to be retained within the soil, as either available or unavailable N.
[c]Computed as the ratio of system N harvest over all N inputs (feeds, fertilizers, BNF, wet and dry atmospheric deposition, and run-on/sedimentation with incoming irrigation water).
[d]The productivity of the system expressed as total yield from all harvested products.
[e]Figures in brackets indicate yield with only one rice crop per year; on Farms C and D ricefields are left fallow during the dry season.

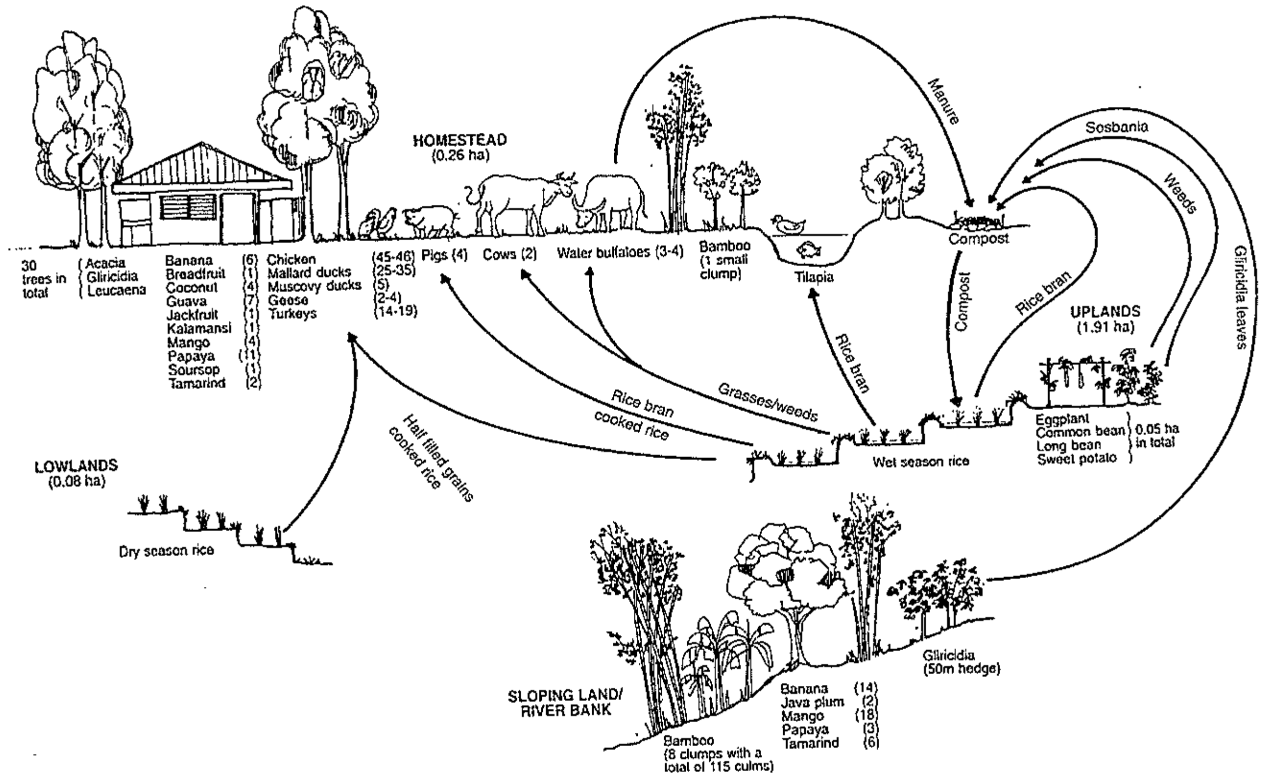

Fig. 7.3. Bioresource flow diagram of an integrated smallholder rice farm (Philippines). Values in parentheses next to enterprises are numbers of individuals (livestock or trees) unless otherwise specified (from Dalsgaard and Oficial, 1997).

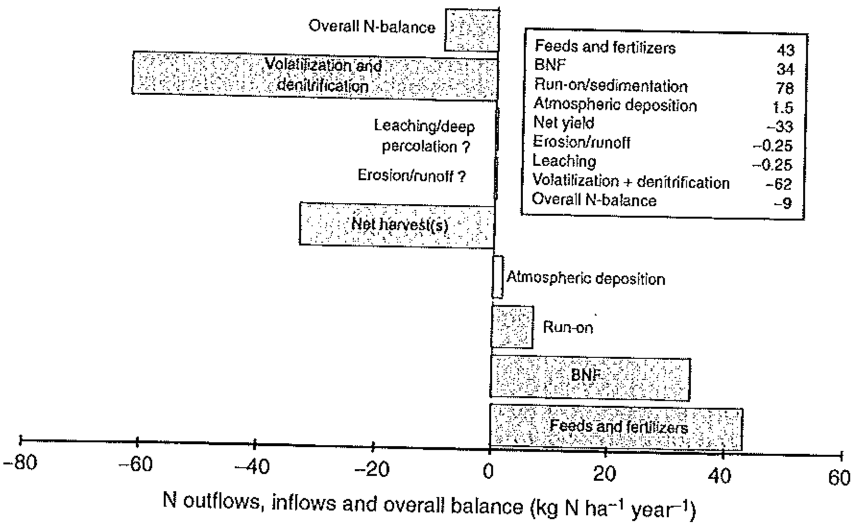

Fig. 7.4. Nitrogen budget for a smallholder rice farm with integrated agriculture–aquaculture (IAA) (Philippines); Farm D in Table 7.1.

This makes assessment and interpretation of nutrient budgets and flows at farm levels at best a difficult, and at worst a dubious, exercise.

A more complete understanding of N (and other nutrient) pathways through the rice floodwater agroecosystem requires complementary, *in situ* field studies at different spatial levels, below and above the farm scale. Plot studies can provide insights into the nutrient dynamics and availability within the soil-water resource base and nutrient exchanges across the soil-water interface. Catchment and water discharge studies give ideas of the magnitudes of nutrient loads in eroded soils, discharged water and sediments. Mass-balance studies can be developed as a first effort to identify the 'holes' in the systems – including gaps in our knowledge. More sophisticated (dynamic) modelling efforts will be needed to appreciate and quantify the physical and chemical processes behind the mass flows.

The overriding question remains, however, how to engineer the appropriate conditions for the evolution of such agroecosystems to occur on a wider scale. What are the technological, economic and/or social opportunities and constraints, which encourage or prevent farmers and farm communities from venturing into moderately intensive, integrated, nutrient balanced farming? Which tenure arrangements, market conditions, credit facilities and political incentives improve the acceptability and adoptability of IAA systems? What institutional mechanisms and communication channels within the researcher–adviser–farmer complex will further the development and spread of alternative, ecologically sound agricultural technologies and farming strategies? The transition towards IAA is knowledge and skill intensive and requires long-term commitment and entrepreneurially spirited farmers. IAA and learning to keep fish does not just mean handling a new, better variety under similar management conditions. Balanced, integrated natural resources management combines traditional and new knowledge systems and technologies to suit complex environments and find ways to utilize their heterogeneity and diversity in an ecologically sound manner.

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