Preliminary Steady-State Nitrogen Models of a Wetland Ricefield Ecosystem With and Without Fish*

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Abstract

Rice and fish are the most important food sources in Asian diets. Up to now the supplies of rice and fish have come from different sources. The traditional practice of catching wild fish in ricefields is insignificant today. Recent investigations indicate, however, that integrated rice-fish systems offer possibilities of increasing rice yields by as much as 15% and at the same time harvesting fish up to 500 kg·ha^{-1} every rice crop.

Modern rice production has become heavily dependent on insecticides. Through the integration of fish in rice paddies the possibility exists for reducing insecticide use. Similarly, chemical fertilizers could be partially substituted with farm by-products fed to the fish.

To improve our understanding of ecological interactions in rice-fish systems, we have used ECOPATH II to construct initial models of rice systems, one with and one without fish. While these preliminary models were constructed from limited field data, they do provide indicators for critical field measurements and experimentation. Future models will assist in the development of guidelines for optimum management of rice-fish integrated systems.

Introduction

By the year 2000, Asian farms must provide food for 3.6 billion people. A prerequisite will be higher production of rice and fish, the mainstays of Asian diets. Asian farming systems are predominantly rice-based and depend upon, among other things, water control. Thus they could theoretically at least produce large quantities of high-value fish. Integrating the production of rice and fish in the same water on the same land can help to achieve high food production requirements. Even modest adoption of such integration could dramatically increase fish production (Lightfoot et al. 1990). More than one hundred and fifty fold increases in fish production (500 to 79,000 t) could be achieved in Vietnam, for example, if 300 kg·ha^{-1}·year^{-1} of fish were harvested from only 5% of its riceland. India and Thailand, with current productivity levels of 450 and 1,044 kg·ha^{-1}, respectively, could increase their fish production by similar orders of magnitude. On 5% of their ricelands, the Philippines and Bangladesh could theoretically produce 45,000 and 140,000 t of fish, respectively. Rice-fish integration may also

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provide incentives for farmers to reduce levels of pesticide use and fertilizer application without reducing rice production.

Adoption of rice-fish farming will depend greatly on what happens to rice yields. An analysis of rice-fish data from research stations and farms in several Asian countries by Lightfoot et al. (1989) showed that even though some negative effects on rice yields were reported, positive effects in the order of 5 to 30% were typical. They concluded that "from these data it is not unreasonable to assume a 10-15% increase in rice yield when fish are present." Little empirical evidence exists and even less is known about the underlying ecological processes of the synergistic effects in rice-fish farming.

Fish may consume rice pests including weeds. Work conducted in Indonesia showed ricefield weed biomasses to be significantly reduced by grazing of carps and tilapia (Moody 1988). Chinese studies report similar findings (Xu and Guo 1988). Rice pest predation by fish has been observed in China. Rice stemborer egg masses, leaf folders and plant hopper populations have been reduced by fish (Spiller 1985; Yuan 1988).

Fish may contribute to soil fertility. Differences in soil nitrogen, phosphorus, potassium and organic matter have been detected between paddy soils where rice was grown with and without fish (Li 1988; Xu and Guo 1988). The nitrogen cycle to be presented below helps explain how nitrogen accumulation might occur.

Fish not only contribute to nitrogen accumulation through their feces, but they may also reduce nitrogen losses. In irrigated rice-fish culture, a continuous flooding of the field is expected and therefore high losses by denitrification observed in fields subjected to alternate dessication and submergence are not expected to occur.

Fish may reduce the strong nitrogen losses by ammonia volatilization in rice monoculture system. The high level of fertilizer directly applied in the floodwater causes pH increases. Ionized NH_4^+ increasingly converts to unionized NH_3 which may escape from the water as a gas. Major factors affecting ammonia loss by volatilization are pH and ammonia concentration and wind speed at the floodwater surface (De Datta 1981). Aquatic photosynthetic organisms, especially microalgae, have a key role in NH_3 volatilization by causing diurnal changes in floodwater pH, by 1-2.5 units. Large populations of algae are not required to increase floodwater pH to levels that support rapid N losses (Fillery et al. 1986). Losses by NH_3 volatilization range from 2 to 60% of N applied. Most losses occur at the beginning of the crop cycle, when there is almost no canopy and the resulting high light availability permits microalgae to develop while their biomass is not large enough to limit N losses through immobilization.

The introduction of the plankton feeder Nile tilapia (*Oreochromis niloticus*) with rice at the beginning of the culture period may decrease ammonia volatilization by reducing the biomass of microalgae that increase floodwater pH. The bottom feeding action of common carp (*Cyprinus carpio*) could cause turbidity that would limit light available for photosynthetic activity of phytoplankton. Therefore, with fish in the ricefields it is expected that nitrogen loss through ammonia volatilization is reduced.

Ecological processes involved in irrigated rice monoculture differ from that of rice-fish culture. This paper attempts to use ecological models constructed using the ECOPATH II software of Christensen and Pauly (1992) to compare these different systems.

Methodology

Quantitative data were obtained from measurements performed in irrigated ricefields without fish on the International Rice Research Institute (IRRI) research farm in Los Baños, Philippines. Input parameters for the rice-fish model other than the fish biomass and diet were estimated from data collected in irrigated ricefields. Fish biomass and diet data are average values of available data from rice-fish experiments conducted at the Freshwater Aquaculture Center, Central Luzon State University research station in the Philippines. Other data and nitrogen conversions were based on Jφrgensen (1979). The input parameters for the models are given in Table 1. Details of data sources for each component in both models follow. Due to the paucity of data, especially on fish and biological productivity, this model must be considered preliminary.

Fish Component

While reported fish yields from irrigated rice-fish systems in China, Indonesia, the Philippines and Thailand ranged from 100 to 1,800 $kg \cdot ha^{-1} \cdot crop^{-1}$ (dela Cruz et al. 1988), we have selected a very conservative figure of 300 $kg \cdot ha^{-1}$ for our model, of which 180 $kg \cdot ha^{-1}$ is Nile tilapia (*Oreochromis niloticus*) and 120 $kg \cdot ha^{-1}$ is common carp (*Cyprinus carpio*). Nile tilapia, an omnivorous plankton feeder, contributes more to total production as it is a better food converter than common carp, an omnivorous benthic feeder. Fish flesh nitrogen content is equivalent to 13% of dry matter (Cagauan 1990). Based on this, a whole fish is assumed to have 7% N and a dry matter of 20%; therefore, fish N equivalents are 2.5 $kg N \cdot ha^{-1} \cdot crop^{-1}$ for tilapia and 1.7 $kg N \cdot ha^{-1} \cdot crop^{-1}$ for common carp.

Table 1. Input parameters and consumption of static nitrogen models in irrigated ricefields with and without fish. Values in parenthesis are estimated by ECOPATH II.

	Production		Consumption	
	Rice (kg N·ha⁻¹·crop⁻¹)	Rice-fish (kg N·ha⁻¹·crop⁻¹)	Rice (kg N·ha⁻¹·crop⁻¹)	Rice-fish (kg N·ha⁻¹·crop⁻¹)
Phytoplankton	25.0	25.0	27.8	27.8
Weeds	8.0	6.4	8.9	7.1
Rice	(104.9)	(114.6)	(116.5)	(127.3)
Aquatic macrophytes	17.0	17.0	18.9	18.9
Snails	4.0	4.0	13.3	13.3
Benthos	8.0	4.0	26.6	13.3
Zooplankton	7.0	7.0	16.3	16.3
Insects	0.9	0.7	3.0	2.4
Microbial biomass	(130.0)	(114.9)	(162.5)	(143.7)
Tilapia	-	(2.6)	-	12.5
Carp	-	(1.8)	-	9.0
BNF	12.0	12.0	0.0	0.0

Rice

Nitrogen exported by rice was estimated on the basis of 1.5% N in grain, 0.8% N in straw and on a harvest index of 1, based on a six-crop experiment at IRRI with five modern varieties of rice. On the basis of the quantity of N fertilizer offered, we used an average 4 t grain yield in the rice model equivalent to 92 kg N exported when straw is not incorporated. An analysis of rice-fish data by Lightfoot et al. (1989) shows rice yield increase ranging from 5 to 30% in rice-fish systems. We assumed a conservative average increase of 10%.

Fertilizer

INORGANIC N FERTILIZER

In wetland ricefields, the efficiency of fertilizer is low. Twenty to 40% N applied is recovered by the crop, depending on the N source, management, and agroecological conditions. In thirty-eight ^{15}N balance experiments with 20-80 kg $N \cdot ha^{-1}$, N losses ranged from 10 to 65% of N applied (average: 37%), N recovery in the soil ranged from 12 to 76% (average: 35%), and N recovery in the plant ranged from 1 to 54% (average: 28%) (Fillery and Vlek 1986).

ORGANIC MANURE

No information is available on the fate of N applied as chicken manure and pig manure. Part of the N in chicken/pig manure is already in a humified form and is not available for rice. It is unknown how much is eaten by fish, added to detritus as unavailable N, and immobilized in the photosynthetic aquatic biomass (PAB). When applied into the water, probably a significant part of the N is rapidly ammonified and lost by ammonia volatilization. We assumed that 37% of the 74 kg N applied as inorganic fertilizer in both models was lost.

In the rice-fish system the additional N input due to the application of 3 $t \cdot ha^{-1}$ of chicken manure (1.7% N) and 2 $t \cdot ha^{-1}$ pig manure (1.3% N) was estimated to be 49 kg $N \cdot ha^{-1}$ after losses by volatilization (28 kg $N \cdot ha^{-1}$) were subtracted.

Biological Nitrogen Fixation

With regard to the high level of nitrogen fertilizer applied in both systems, the contribution of biological nitrogen fixation (BNF) was expected not to be high. Using average values summarized by Roger and Ladha (1990) we assumed a contribution of 12 kg ha^{-1}, with photodependent BNF contributing about 5 kg ha^{-1} and heterotrophic BNF contributing 7 kg $N \cdot ha^{-1} \cdot crop^{-1}$. We assumed the same N contribution by BNF in both models.

Gross Primary Production in Floodwater

In wetland ricefields, phytoplankton and aquatic macrophytes are responsible for primary production in floodwater. Phytoplankton is dominant during the first part of the crop cycle, then macrophytic algae and submerged macrophytes become dominant. Planktonic algae generally have lower productivity than macrophytes (Roger and Watanabe 1984) but a higher N content and probably a faster turnover. Estimates of productivity for the rice model were derived from data summarized by Roger et al. (1989). We assumed a total gross primary production of 600 kg $C \cdot ha^{-1} \cdot crop^{-1}$ split as 300 kg microalgal carbon and 300 kg of aquatic macrophyte carbon in the rice model. This would correspond to 25 kg N for micro- and filamentous algae (C/N of about 12) and 17 kg N from submerged aquatic weeds (C/N of about 18).

We assumed a lower standing phytoplankton biomass in the rice-fish system but a faster turnover because of a better recycling by fish, leading to the same phytoplankton productivity. We assumed that aquatic macrophyte biomass was not significantly affected by the presence of fish.

Weeds

Measurements conducted in 65 plots of the IRRI farm with various managements show a total N content in weeds harvested at two weedings that average about 8 kg $N \cdot ha^{-1} \cdot crop^{-1}$ (Roger et al. 1989).

This average value is used in the rice model. We assumed that fish reduced the standing weed biomass by 20%.

Invertebrates in Rice Canopy

No quantitative data are available for the biomass of arthropods in the rice canopy. A theoretical estimate was calculated assuming that the biomass of a single dominant species during a bloom or an outbreak is an estimate of the upper limit of the biomass of the balanced population of the corresponding group of organisms (e.g., zooplankton, phytoplankton, arthropods) in an ecological niche such as the floodwater or the rice canopy. That is, an estimate of the biomass of brown plant hopper (BPH) during an outbreak is an estimate of the upper limit of arthropod populations in rice canopy when such a population is balanced among consumers and predators. Using this BPH population as a proxy for all invertebrates is probably an underestimate.

The calculation considers populations of 1,000 BPH m^{-2}, 0.4 mg·dw each, 7% N, which is a total of 4 kg·ha^{-1} dw as standing biomass or 0.3 kg N·ha^{-1}. Assuming the standing biomass has a 3 times turnover, this leads to contribution of 0.9 kg N·ha^{-1} for the rice model.

We assumed that fish pressure on arthropods in rice canopy and the surface water reduced the standing biomass of arthropods by 20%.

Zooplankton

Standing biomasses of zooplankton were estimated from data summarized by Roger and Kurihara (1988) in wetland ricefields. These data mostly refer to ostracods and therefore we used the same type of calculation as for the invertebrates in rice canopy.

A maximum biomass of 150 kg·ha^{-1} ww was extrapolated for populations of 50,000 animals m^{-2}. Assuming three turnovers during the crop and an average biomass of half the peak biomass, this leads to an estimate of 2.3 kg N·ha^{-1} (.5 x 150 x 3 x 15% dw x 7% N) in the rice model.

Data on nitrogen excretion by zooplankton were obtained from the values presented by Roger and Kurihara (1988). We assumed that the productivity of zooplankton was primarily limited by that of phytoplankton and therefore was the same in the rice and in the rice-fish model.

Snails

Populations up to 1,000 m^{-2} (1.5 t·ha^{-1} ww) have been observed in Philippine ricefields (Roger and Kurihara 1988). Some large species (*Pila* spp., *Pomacea* spp., and *Ampullaria* spp.) may additionally develop biomass of a few hundred kg·ha^{-1} ww.

Snail biomass estimated by recent counts in the IRRI farm in plots where *Pomacea canaliculata* was dominant ranged from 0 to 1 t·ha^{-1} ww. Based on average biomasses of 400-500 kg·ww·ha^{-1} and assuming 80% water, 25% shell, 5.5% N, and one turnover this leads to a production estimate of 4 kg N·ha^{-1}·$crop^{-1}$.

Benthos: Oligochaetes and Nematodes

Surveys of oligochaete populations in experimental plots in the IRRI farm and 32 farmers' fields of Laguna Province (Philippines) showed that populations ranged from 0 to 630 kg·ha^{-1} ww. Relatively large populations of aquatic oligochaetes are expected to develop when large quantities of organic nutrients are added in the field.

In the rice model, we used a biomass of 300 kg·ha^{-1} ww for oligochaetes and the same value for saprophytic nematodes, which was calculated to the equivalent of 8 kg N·ha^{-1}·$crop^{-1}$ using 6.5% N content at 20% dry matter. Because of the benthic feeding habit of common carp, we estimated that soil meiofauna was reduced by half in the rice-fish model.

Microbial Biomass

Research on nitrogen nutrition of rice has shown that, whatever the quantity of N fertilizer applied, between 75 and 60% of the nitrogen absorbed by the plant usually originates from soil (Fig. 1). But only a small fraction of total soil N is available to the plant, and most of this available nitrogen originates from the turnover of the microbial biomass in soil which represents only a small per cent of total soil N (Watanabe et al. 1988). Crop residues, rhizosphere exudates and the photosynthetic aquatic biomass (algae and aquatic plants) contribute nutrients that allow the replenishment of microbial biomass. Crop residues are incorporated at the beginning of the crop while nutrients accumulating in PAB (including biologically fixed nitrogen) are continuously recycled and reincorporated into the deeper soil by zooplankton and soil fauna, which are therefore key components of the ricefield fertility (Roger et al. 1987).

Preliminary studies, under a restricted number of cultural conditions in the IRRI farm, indicated that microbial biomass might be about 50 kg N·ha^{-1} at the beginning of the crop and then decreases to reach a value of about 30 kg N·ha^{-1} at harvest. The turnover of this biomass has not been determined yet but should be 20-30 days (4 times) to ensure rice nutrition.

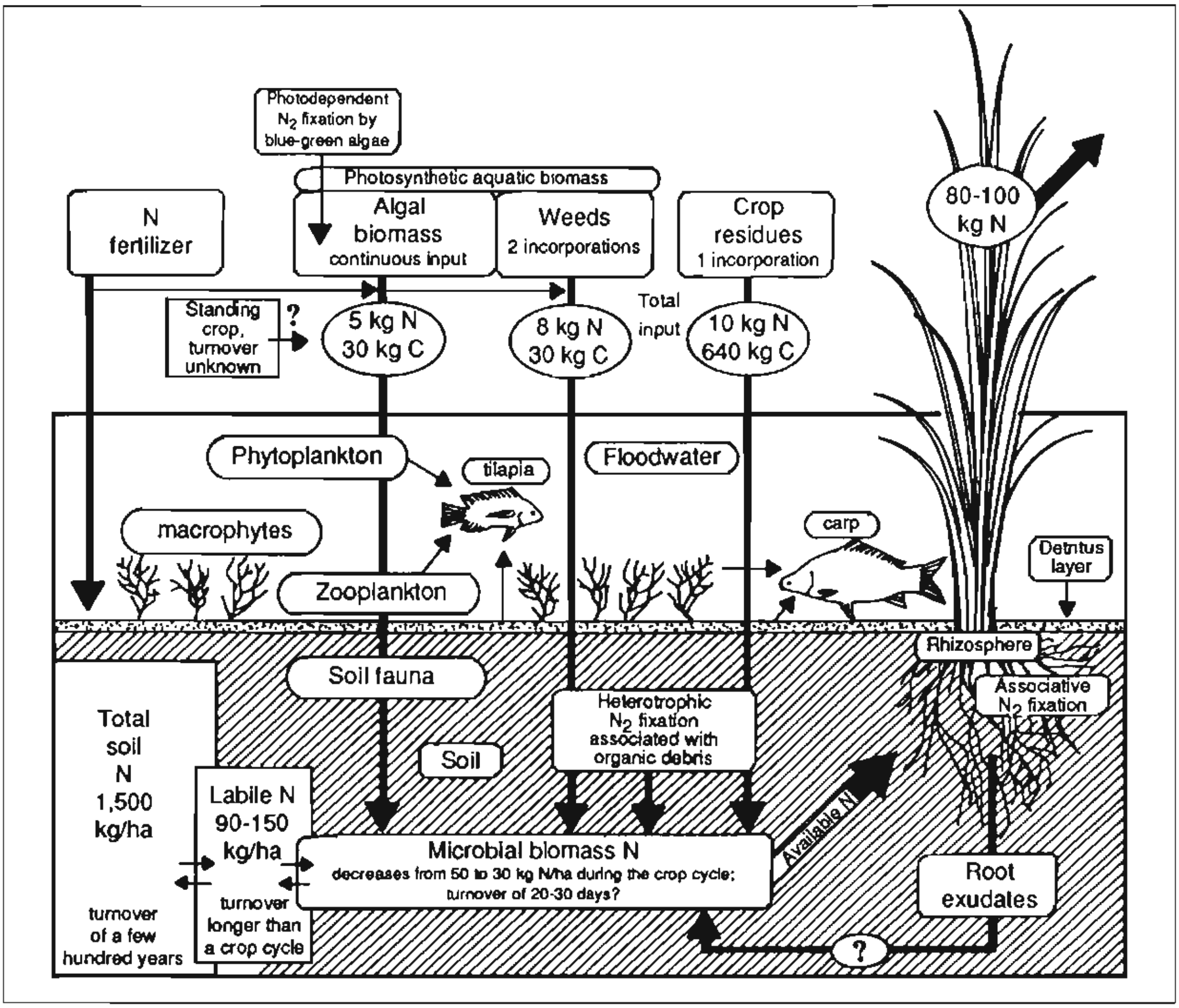

Fig. 1. Schematic representation of the rice-fish ecosystem with a conceptual representation of the origin of the nitrogen absorbed by rice, the role of the microbial biomass in providing available nitrogen to rice, and the pathways involved in the replenishment of the microbial biomass.

Results

Comparison of Box Models

The box models in Fig. 2 compare the two systems. The greater complexity of the system that includes fish is evident, both in terms of number of boxes and complexity of flows. Note that most boxes in the rice-fish model have more consumers or exit paths than they do in the rice model. Less evident is the reduction of weed, insect, and benthic fauna boxes and increase in the rice box by fish, as shown in the P values. Trophic levels of components are not different between systems. Noteworthy is that carp and tilapia both have lower trophic levels than the insects. As the "currency" for these models is a nutrient (N), the primary producers do not appear on trophic level I in the models as they do in energy-based models. Instead BNF is found together with detritus on trophic level I. This is apparent from Table 2, which shows how the relative flows by groups are distributed on discrete trophic levels. The dominance of pests at the highest trophic level (IV) in the rice model indicates a loss of

Table 2. Trophic transformation matrix for nitrogen models of wetland irrigated ricefields without and with cultured fish. The table shows how the relative flows of the groups in the systems are allocated to trophic levels.

Group	Relative flows by trophic level				
	I	II	III	IV	V
Insects	-	-	0.43	0.57	-
Tilapia[a]	-	0.15	0.48	0.32	0.06
Snails	-	0.25	0.63	0.12	-
Rice	-	0.40	0.60	-	-
Aquatic macrophytes	-	0.40	0.60	-	-
Carp[a]		0.67	0.17	0.13	0.03
Benthos	-	0.50	0.45	0.05	-
Weeds	-	0.50	0.50	-	-
Zooplankton	-	0.60	0.31	0.09	-
Phytoplankton	-	0.75	0.25	-	-
Microbial biomass	-	1.00	-	-	-
BNF	1.000	-	-	-	-
Detritus	1.000	-	-	-	-

[a]Included in rice-fish model only.

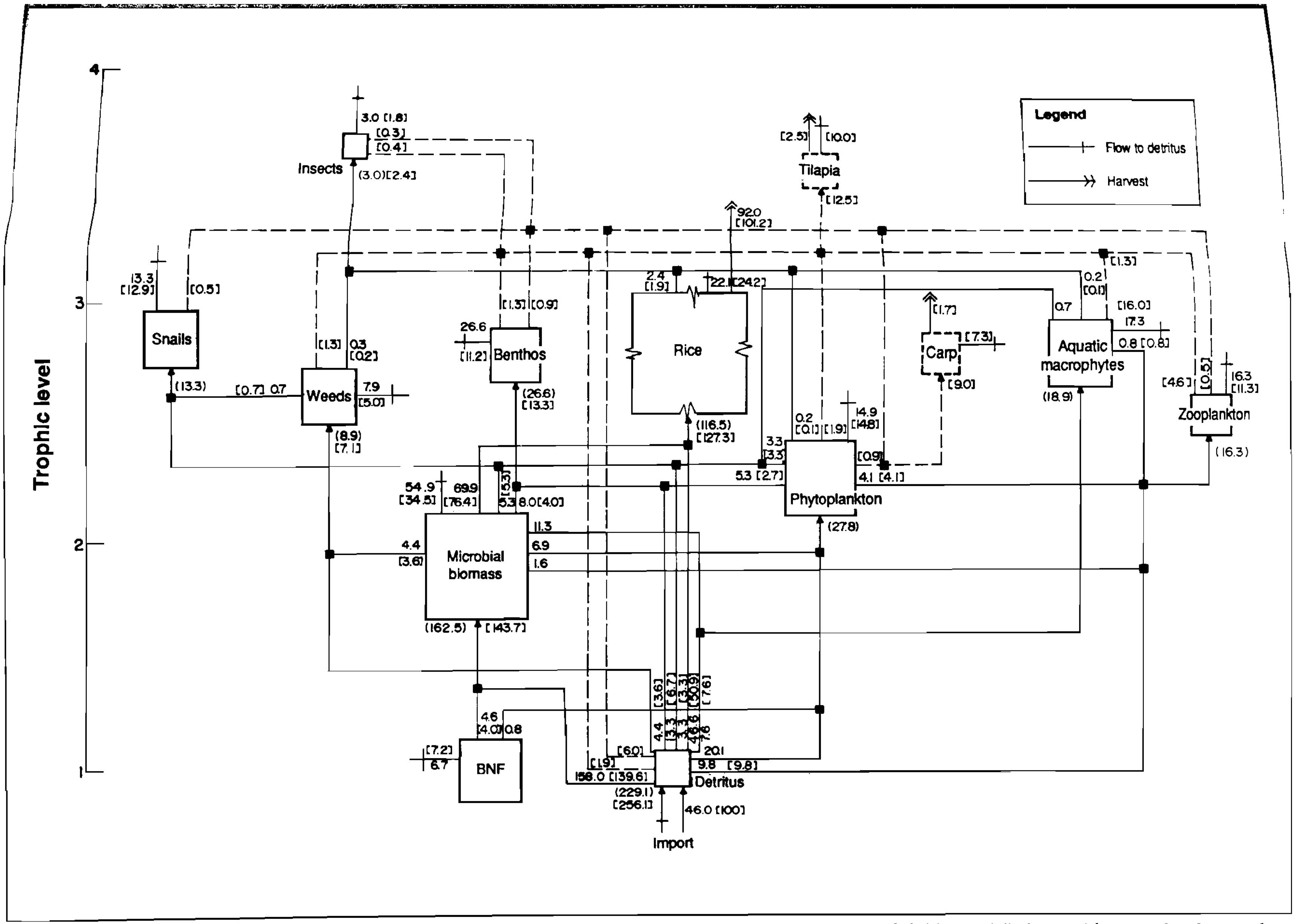

Fig. 2. Comparison of steady-state nitrogen models of a wetland ricefield ecosystem with (rice-fish-model) and without fish (rice-model). Rates with square brackets apply to the rice-fish model only, while other rates apply to the rice model and also to the rice-fish model where no rates in square brackets are given. Dotted lines show flows that are present in the rice-fish model only. All rates are in kg N ha^{-1} crop^{-1}.

high-value N. However, in systems with fish some of this high-value N is captured.

Based on the allocation of nutrient flows to trophic levels shown in Table 2, the trophic transfer efficiencies by discrete levels can be estimated as the percentage of flow entering a trophic level that is ultimately harvested or transferred to the next trophic level (Christensen and Pauly 1992). These transfer efficiencies for the two systems are given in Table 3. It can be seen that the transfer efficiencies in all trophic levels are highest for the system including fish which suggests that fish improve the utilization of nutrients within the systems.

The summary statistics of Table 4 suggest that rice-fish ecosystems hold more nitrogen in the system, put more nitrogen through the system and have a higher capacity than rice alone. This is possibly because rice-fish systems have more consumers and more flow paths. This suggests that fish may impart greater efficiency to rice production systems. However, less nitrogen is cycled in rice-fish systems, possibly because less nitrogen flows to the detritus. This is also shown by the mean path length which gives the number of groups an average nutrient unit passes through from entering the system until exiting.

Table 3. Trophic transfer efficiencies by trophic levels for two nitrogen models of rice systems without and with fish.

Model	Trophic level I	II	III	IV
Rice only	-	58%	51%	0.0%
Rice-fish	-	66%	57%	20%

Table 4. ECOPATH II summary statistics for nitrogen models of wetland irrigated ricefields with and without fish.

	Rice	Rice-fish	Unit
Total production	316.8	310.0	$kg\ N \cdot ha^{-1} \cdot crop^{-1}$
Total flow to detritus	229.1	256.0	$kg\ N \cdot ha^{-1} \cdot crop^{-1}$
Total throughput	714.9	759.6	$kg\ N \cdot ha^{-1} \cdot crop^{-1}$
Throughput cycled	304.7	244.8	$kg\ N \cdot ha^{-1} \cdot crop^{-1}$
Cycling index	42.6	32.2	%
Mean path length	7.8	6.8	-

Comparison of Ecotrophic Efficiencies

Ecotrophic efficiencies (i.e., proportion of production harvested or utilized for consumption in the system) among the components of the ecosystem most affected by the introduction of fish are zooplankton, benthic fauna, weeds and insects (Table 5). Efficiency has increased through the consumption of invertebrates (mostly grazers of PAB) by fish. There is a better utilization of weed biomass through tilapia grazing.

The trophic levels for all components (other than fish) are alike in the two models. As noted above, the trophic levels of carp and tilapia (2.53 and 3.28, respectively) are lower than that of insects (3.57).

The nutrient throughputs by groups are shown in Table 5. As expected, the largest throughput among the living groups involves the bacteria, which may even have a considerably higher throughput than conservatively estimated here.

Comparison of Mixed Trophic Impacts

Rice, being the largest biomass component of the ecosystem, has higher impacts than fish on other components. Impact values range from -0.50 to 0.47 for rice, from -0.25 to 0.02 for tilapia and from -0.07 to 0.01 for carp (Fig. 3). Besides an expected negative impact on itself, rice has a marked negative effect on soil microbial biomass (mainly due to competition for nitrogen resources). It may be that rice absorbs most of the available soil nitrogen, thus not allowing the replenishment of the microbial biomass. This is important as it indicates that intensification of rice production might lead to a decrease in soil microbial biomass and thus, possibly of soil-available N and of fertility. Such a hypothesis has indeed to be tested by *in-situ* measurement in long-term experiments. Increasing rice biomass also leads to a reduction of the biomasses of weeds and the components of the floodwater. This can be related with competition for nutrients and an expected decrease in floodwater productivity under a dense rice canopy. Rice has a positive effect on the accumulation of BNF (a larger rice root biomass and exudation is expected to

Table 5. ECOPATH II-generated values for efficiencies, trophic levels and nutrient throughput in irrigated ricefields with and without fish.

	Ecotrophic efficiency Rice	Ecotrophic efficiency Rice-fish	Gross efficiency	Trophic level	Nutrient throughput Rice	Nutrient throughput Rice-fish
Phytoplankton	0.52	0.52	0.90	2.25	27.8	27.8
Weeds	0.12	0.34	0.90	2.50	8.9	7.1
Rice	0.90	0.90	0.90	2.60	116.5	127.3
Aquatic macrophytes	0.10	0.17	0.90	2.60	18.9	18.9
Snails	0.00	0.11	0.30	2.87	13.3	13.3
Benthos	0.00	0.54	0.30	2.55	26.6	13.3
Zooplankton	0.00	0.73	0.43	2.49	16.3	16.3
Insects	0.00	0.90	0.30	3.57	3.0	2.4
Microbial biomass	0.83	0.95	0.80	2.00	162.5	143.7
Tilapia[a]	-	0.95	0.21	3.28	-	12.5
Carp[a]	-	0.95	0.20	2.53	-	9.0
BNF	0.44	0.40	-	1.00	12.0	12.0
Detritus	-	-	-	1.00	229.1	256.0
Import	-	-	-	-	46.0	100.0

[a]Included in rice-fish system only.

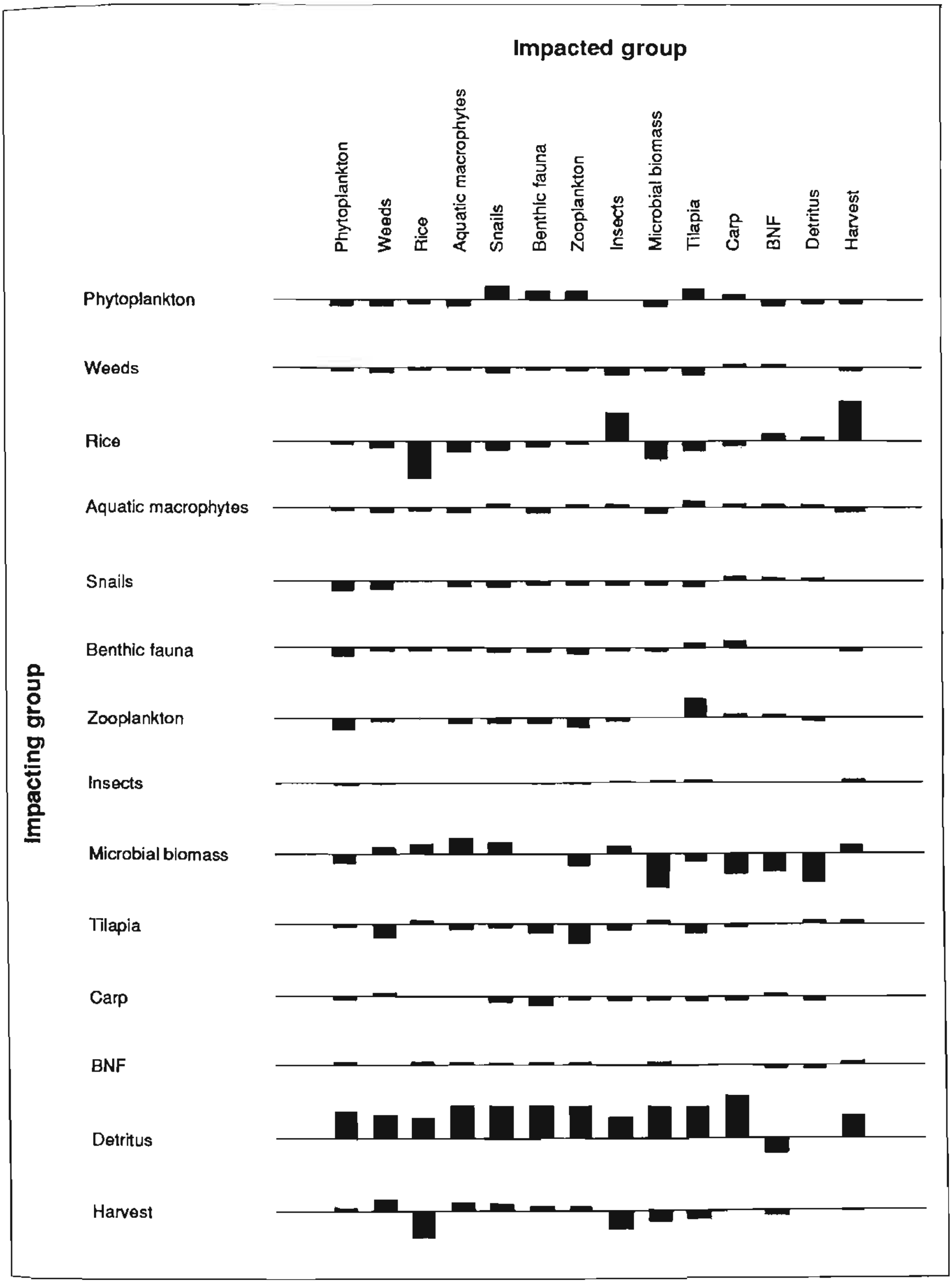

Fig. 3. Matrix of mixed trophic impacts of components in wetland irrigated ricefield ecosystem stocked with tilapia and carp. The histogram shows the relative response of the *impacted* groups resulting from an increase in the biomass of the *impacting* group.

increase heterotrophic BNF in the rhizosphere) and on insects living in the rice canopy.

Tilapia as an omnivorous fish has negative impacts on most of the living components of the ecosystem except rice and microbial biomass. The slight beneficial effect of tilapia on rice might be related to an increased production of detritus contributing to the replenishment of soil microbial biomass and a negative effect on insect pests and weeds. Carp has a very moderate effect on the other components of the ecosystem. The main negative effect is on benthic fauna which reflects the feeding habit of this fish. Carp has a negative impact on snails, benthos and zooplankton and hardly any effect on other groups.

The harvest is affected positively by the rice, detritus, and microbial biomass groups. Obviously, insects have a negative impact on the harvest, indicating potential for increasing the harvest through pest control.

Conclusion

ECOPATH II results raise the intriguing possibility that stocking ricefields with fish not only produces fish, but also leads to greater efficiency in rice production. Ricefields with fish hold more nitrogen, move more nitrogen through the ecosystem and are more efficient. Even more interesting is the suggestion that intensifying monocropped rice might lead to a decrease in microbial biomass and therefore soil fertility in the long term. Microbial biomass is the most important actor in the ecosystem in terms of N cycling.

We cannot conclude from these preliminary models that optimum management of ricefields as an ecosystem and as a production system may require the integration of fish. Our information has too many gaps and our rice-fish model is too hypothetical. Nevertheless, none of the results disagree with current knowledge of N cycling in ricefields. We conclude that the questions raised warrant more studies using ECOPATH II.

ECOPATH II deserves further trial not only because its results raise important questions about ricefield management, but also because they suggest critical long-term experiments and important parameters to study for better understanding of how these ecosystems work. Moreover, ECOPATH II allows environmental impact of rice-fish experiments using different field layouts, fish species, rice varieties, etc., to be compared. We believe that ecological models such as ECOPATH II could provide insights on sustainability in agricultural systems.

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