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Nitrogen input, primary productivity and fish yield in fertilized freshwater ponds in Indonesia

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ABSTRACT

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Twelve 0.2-ha ponds in West Java were fertilized weekly with four levels of chicken manure (12.5, 25, 50, and 100 g dry weight/m^2 $week^{-1}$) during a 149-day growout experiment for Nile tilapia (*Oreochromis niloticus*) production. Laboratory leaching experiments for measuring dissolved inorganic nitrogen (DIN) release from chicken manure showed that nitrogen was released as ammonia-N, which was rapidly lost from the manure and leveled off at about 6 mg NH_4-N/g dry weight chicken manure after 4–5 days. Allochthonous DIN input from both chicken manure fertilization and almost daily source-water additions ranged from 0.055 to 0.142 g N/m^2 day^{-1}. Source water contributed more nitrogen than manure in all but the highest fertilization treatment.

Pond averages of net primary productivity (NP) ranged from 0.54 to 2.00 g C/m^2 day^{-1}, while gross fish yield at harvest ranged from 4.9 to 15.7 kg fresh weight/ha day^{-1}. Net fish yield (NFY) was linearly correlated to both the dry weight sum of NP and chicken manure fertilization ($r^2=0.97$) and allochthonous DIN input ($r^2=0.96$). Results suggest that Nile tilapia obtained organic carbon from both primary productivity and manure-derived detritus.

DIN availability limited algal productivity at a chicken manure fertilization rate of 100 g dry weight/m^2 $week^{-1}$ when microbial decomposition of manure supplied sufficient CO_2. Incorporation of allochthonous DIN input into NFY increased significantly from 15.0% at the three lower fertilization rates to 25.4% at the highest loading rate. Using organic fertilizers proportionally rich in phosphorus and carbon relative to nitrogen may maintain this element's limitation of algal productivity. Efficient utilization of DIN input also may minimize total and un-ionized ammonia concentrations. In the absence of deleterious ammonia effects on survival and growth, fish yields can be readily predicted from measurements of nitrogen inputs.

INTRODUCTION

Economically feasible aquaculture requires efficient utilization of nutrient inputs. Phytoplankton requires nitrogen and phosphorus at a ratio of approx-

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imately 7:1 by weight (Redfield et al., 1963; Round, 1973). Unlike temperate freshwaters where phosphorus generally is considered limiting (Vollenweider, 1968; Vallentyne, 1974), nitrogen alone or in combination with phosphorus often limits primary productivity in many tropical freshwater lakes (Moss, 1969; Zaret et al., 1981; Melack et al., 1982; Setaro and Melack, 1984).

Organic fertilizers often are added to ponds to boost fish yields by increasing primary productivity through released inorganic nutrients, or by providing organic carbon through heterotrophic pathways. Depending on the species, fish will feed directly on attached or planktonic algae, detrital/fungal flocs, or smaller animals such as zooplankton and snails which feed on algae and detritus (Colman and Edwards, 1987).

Fertilization programs should take into account algal requirements as well as pond sediment and water quality. Excess nitrogen input can cause high unionized ammonia concentrations, which may reduce fish growth or cause mortality (Colt and Armstrong, 1981; Ruffier et al., 1981; Meade, 1985). When nitrogen loading is proportionally less than other essential algal nutrients, ammonia concentrations can be kept low through efficient utilization by phytoplankton (Batterson et al., 1988). Carefully controlled inputs that keep available nitrogen close to limiting conditions lead to efficient nitrogen utilization and favorable water quality. For the farmer, efficient fertilizer utilization is also monetarily important.

Although the relationship between nutrient loading and algal production is well documented (Vollenweider, 1968; Dillon and Rigler, 1974), previous efforts to relate primary productivity to total fish yield have given linear (McConnell et al., 1977), log-linear (Melack, 1976; Liang et al., 1981), and quadratic (Almazan and Boyd, 1978) relationships. These models are often inadequate (Noriega-Curtis, 1979) and variable partly because of diversity among systems, nature of nutrient inputs, and differences among fish species (McConnell et al., 1977). One of our research objectives was to improve understanding of nutrient dynamics to optimize pond fertilization efficiency for Nile tilapia (*Oreochromis niloticus*) production. The analysis presented here better defines the relationships between nitrogen input, primary productivity, and tilapia yield in ponds fertilized with chicken manure.

MATERIALS AND METHODS

A 149-day growout experiment took place in 0.020-ha earthen ponds during the rainy season from 14 October 1986 to 12 March 1987 at the Institut Pertanian Bogor (IPB) Babakan Fisheries Station, Bogor, West Java, Indonesia. A description of the site is given in Egna et al. (1987). Ponds were filled to approximately 0.9 m with surface runoff collected in irrigation ditches. Pond sides were made of concrete for bank stability; bottoms were soil. Daily water input was necessary to maintain original pond depths due to rapid seepage (≈ 10 cm/day) through the porous volcanic sediments. Ponds were randomly selected to receive four treatments. Triplicate ponds were fertilized weekly with four levels of fresh layer chicken manure at rates of 12.5, 25, 50, and 100 g dry wt/m^2 $week^{-1}$. Hand-sexed male fingerlings, each weighing about 40 g, were stocked at one fish/m^2.

A laboratory leaching experiment was conducted to better understand nitrogen release from chicken manure. Loss rates of inorganic nitrogen were determined in 2-l amber glass bottles containing pond water to better simulate natural conditions, and distilled water to examine leaching with reduced biological effects. Pond water was pre-filtered through a 25-μm mesh net to eliminate zooplankton whose excretions may affect ammonia concentrations. Bottles were stored in the dark to prevent ammonia removal through algal uptake. Environmental temperatures ranged from 24 to 27°C. Coarsely ground, fresh layer chicken manure was added to six pond water samples and three distilled water samples in amounts ranging from 50 to 500 mg dry weight manure/l. These amounts approximated on a volume basis amounts used weekly to fertilize ponds. Triplicate controls for pond water and distilled water without manure were used to correct for ammonia and nitrate production not associated with manure decomposition. The chicken manure leaching experiment lasted 8 days. Total ammonia-N (indophenol method; Solorzano, 1969) and nitrate-nitrite-N concentrations (hydrazine reduction method; Kamphake et al., 1978) were measured on Days 0, 1, 2, 3, 4, and 6. Ten chicken manure samples were analyzed for total nitrogen by the IPB Soils Laboratory.

In addition to routine weekly water quality monitoring described in Egna et al. (1987), dissolved inorganic nitrogen (DIN=ammonia−N+nitrate-N+nitrite-N) concentrations in pond and inlet water were measured daily during Week 13 to monitor DIN depletion following fertilization. Integrated pond-water samples were collected between 08.00 and 09.00 h by vertically lowering and capping a prerinsed 1.0-m pvc tube. Samples were filtered through Whatman GF/F glassfibre filters and immediately analysed for total ammonia-N (NH_4-N) and nitrate-nitrite-N (NO_3-NO_2-N). Diel changes in ammonia and nitrate–nitrite concentrations were determined in all ponds on several occasions on Days 3 and 4 after fertilization. Twenty-four-h estimates of internal ammonia input to the water column were calculated by doubling the 12-h ammonia-N increase from 18.00 to 06.00 h.

Source-water DIN loading was estimated by multiplying average NH_4-N and NO_3-NO_2-N concentrations ($n=16$) by average daily water input, which was calculated by changes in pond water stage height. DIN loss through seepage was approximated using mean water-column DIN concentrations and assuming a pond seepage rate of 10 cm/m^2 day^{-1}.

Net primary productivity (NP) was estimated from diel changes in CO_2 calculated from pH and alkalinity measurements (after Harvey, 1955; Park, 1969). This method eliminates bottle effects which may underestimate productivity rates (McConnell et al., 1977; Oláh et al., 1978). Gross primary productivities (GP) were estimated using NP data and pond respiration (g O_2/m^2 day^{-1}) obtained from diel oxygen measurements (Batterson et al., 1988). The empirically derived production relationship of (g C)/(g O_2) = 0.317 for a tropical lake (Lewis, 1974) was applied to convert respiration data to units of carbon.

ANOVA, Student's *t*-test, and regression analyses presented here were done according to Steel and Torrie (1980). Means are given with ±1 standard error (s.e.) in parentheses.

RESULTS

The primary inputs of allochthonous nitrogen to the ponds were weekly fertilizations with chicken manure and almost daily additions of source water. Loss rates of inorganic nitrogen from chicken manure were not significantly different ($P < 0.05$) in pond water or distilled water. When chicken manure was leached in pond water, approximately 6 mg DIN were released per g dry weight chicken manure by Day 6 (Fig. 1). About two-thirds of the DIN leached out within the first 2 days; >90% was ammonia-N. Day 6 DIN concentrations represented about 40% of total chicken manure nitrogen. The manure had a mean of 14 mg (±1.3 mg) total N/g dry weight. As chicken manure fertilization rates were 12.5, 25, 50, and 100 g dry weight/m^2 week^{-1}, or 1.8, 3.6, 7.1, and 14.3 g/m^2 day^{-1} respectively, the original treatments had organic fertilizer loading ratios of 1:2:4:8. Based on leaching experiment data, these loading rates represented 0.011, 0.021, 0.043, and 0.086 g DIN/m^2 day^{-1} (Table 1).

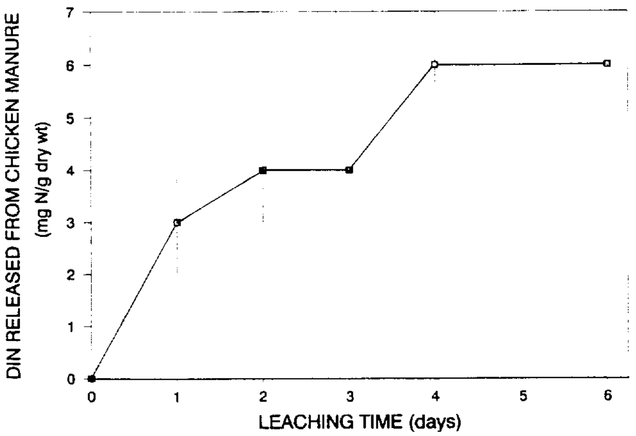

Fig. 1. Average dissolved inorganic nitrogen (DIN) losses (±1s.e.) from chicken manure in pond water.

TABLE 1

Estimated dissolved inorganic nitrogen (DIN) inputs from chicken manure (CM) and source-water additions, net primary productivity (NP), and net fish yields (NFY) for *Oreochromis niloticus* after 149-day growout period. All units in g/m^2 day^{-1}

Pond no.	Allochthonous				NP as C	NP as N[b]	NFY fresh wt.
	CM as dry wt.	CM as N[a]	Water DIN	Total DIN			
C3	1.8	0.011	0.044	0.055	0.77	0.135	0.32
C8	1.8	0.011	0.054	0.064	0.54	0.095	0.23
E4	1.8	0.011	0.049	0.060	1.10	0.193	0.22
C1	3.6	0.021	0.044	0.066	0.71	0.124	0.37
C6	3.6	0.021	0.051	0.072	0.99	0.175	0.43
E1	3.6	0.021	0.056	0.078	0.88	0.154	0.35
C2	7.1	0.043	0.047	0.089	1.14	0.198	0.59
C5	7.1	0.043	0.028	0.071	1.37	0.240	0.52
C7	7.1	0.043	0.049	0.091	1.37	0.236	0.71
C4	14.3	0.086	0.054	0.139	1.74	0.306	1.30
E2	14.3	0.086	0.050	0.136	1.83	0.320	0.26
E3	14.3	0.086	0.056	0.142	2.00	0.350	1.25

[a] Based on Day 6 chicken manure leaching data.
[b] Based on 40:7 C:N ratio (Redfield et al., 1963; Round, 1973).

Source-water concentrations of both NH_4-N and NO_3-NO_2-N averaged 0.25 mg/l with ranges of 0.09-0.47 mg/l and 0.12-0.52 mg/l, respectively. Daily DIN input from source water ranged from 0.028 to 0.056 g/m^2, and exceeded fertilization input in all treatments except at the highest fertilization rate (Table 1). Variable seepage rates between ponds resulted in differences in water input required to maintain depth, and therefore nitrogen loading. Most ponds lost about 10% total volume per day; pond C5, however, required considerably less water input than other ponds. As a result, total allochthonous DIN input was less in C5 than in ponds C6 and E1, which received chicken manure at a lower fertilization rate (Table 1). By including daily nitrogen input from source water, actual allochthonous DIN input ranged from 0.055 to 0.142 g/m^2 day^{-1} (Table 1) and treatment ratios were approximately 1:1.2:1.4:2.3.

Rapid nitrogen release from chicken manure was evident in all fertilizer treatments. With all treatments, mean DIN concentrations peaked on Day 2 after fertilization (Fig. 2). With the exception of ponds receiving 25 g dry weight manure/m^2 week^{-1}, DIN concentrations declined through Days 3 to 6. By Day 6, ponds receiving 50 and 100 g dry weight manure/m^2 week^{-1} had

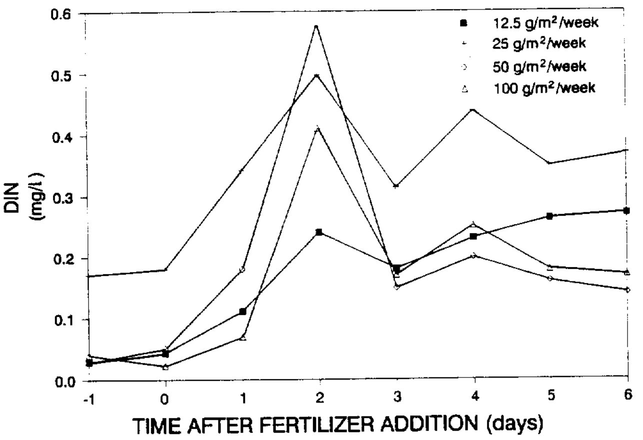

Fig. 2. Average daily pond-water dissolved inorganic nitrogen (DIN) concentrations following chicken manure fertilization on Day 0.

TABLE 2

Differences between observed mean pond water DIN concentrations (in mg/l) at different chicken manure fertilization rates and expected values based on leaching experiment data

Chicken manure input (g dry weight/m^2 week^{-1})	DIN: Observed – Expected			
	Day 1	Day 2	Day 4	Day 6
12.5	0.00	0.13	0.11	0.15
25	0.05	0.22	0.11	0.00
50	−0.08	0.33	−0.14*	−0.28*
100	−0.39*	−0.09*	−0.42*	−0.65*

*Observed significantly different from expected ($P<0.05$).

DIN concentrations about one half (< 0.20 mg/l) of those observed in ponds receiving 12.5 and 25 g dry weight manure/m^2 week^{-1}.

Table 2 shows differences between measured DIN concentrations compared to expected values based on chicken manure leaching results (Fig. 1), daily water additions, and estimated DIN losses through seepage. In ponds fertilized at 12.5 g dry weight/m^2 week^{-1}, measured DIN concentrations were not significantly different from expected values from Day 1 through Day 6 after manure input. Ponds receiving 25 g dry weight/m^2 week^{-1} also showed no significant difference between expected and observed DIN concentrations, but DIN removal was indicated by the decrease from −0.22 mg/l to 0.00 mg/l from Day 2 to Day 6. Differences became significant ($P<0.05$) by Day 4 in ponds fertilized at 50 g dry weight/m^2 week^{-1}, decreasing from +0.33 mg/l on Day 2 to −0.28 mg/l on Day 6. Ponds receiving 100 g dry weight/m^2 $week^{-1}$ showed significant DIN removal on all days except on Day 2. The difference between observed and expected concentrations increased to -0.09 mg/l on Day 2 corresponding to maximum DIN leaching from manure, but decreased to -0.65 mg/l on Day 6.

Estimates of internal nitrogen loading to the water column yielded an average rate of 0.47 g NH_4-N/m^2 day^{-1} (± 0.05) for all treatments.

Net primary productivity (NP) ranged from 0.54 to 2.00 g C/m^2 day^{-1} in experimental ponds (Table 1) and rose with increasing fertilization. Gross primary productivity (GP) was estimated to be about twice the NP value, and ranged from 1.2 to 4.7 g C/m^2 day^{-1}.

Hand-sexing juvenile *O. niloticus* at stocking resulted in accidental introduction of females. Subsequent reproduction resulted in fry representing 11.3% (± 2.8), 10.3% (± 2.7), 12.8% (± 4.6), and 38.6% (± 1.5) of the total harvest weight in ponds receiving chicken manure at rates of 12.5, 25, 50, and 100 g dry weight/m^2 $week^{-1}$, respectively. Relatively greater fry production in ponds with the highest fertilization rate may have caused the observed levelling out of adult growth rate through resource competition. Gross fish yield (GFY), including both adults and fry, increased with fertilization input and ranged from 4.9 to 15.7 kg fresh weight/ha day^{-1}. Daily net fish yield (NFY) was considerably less than GFY due to the relatively large stocking weight (about 40 g/fish), and ranged from 2.2 to 13.0 kg fresh weight/ha, or 0.22 to 1.30 g fresh weight/m^2 (Table 1).

DISCUSSION

Nitrogen input

The layer chicken manure used in this study had a mean nitrogen content of 1.4% N by dry weight (14 mg total N/g dry weight). This value was lower than the 5.2% N measured in the USA and the United Kingdom (Smith, 1974), but approximated concentrations found in chicken manure from Thailand (PD/A CRSP, unpublished data) and Honduras (Green et al., 1989). The 40% DIN loss of total chicken manure nitrogen (6 mg total N/g dry weight) after 6 days of leaching was similar to the value (approximately 30%) reported by Sims (1986).

Daily DIN input from source water was greater than DIN input from chicken manure in all treatments except at the highest fertilization rate (Table 1). Canal water used to fill ponds was also used upstream for domestic and agricultural purposes, which probably contributed to its nutrient content of about 0.5 mg/l DIN and 0.2 mg/l total phosphorus. Coarse, volcanic soils are common in many areas of the world, and characteristic of West Java. Due to their high porosity, earthen ponds in volcanic sediments require frequent filling. As long as rainfall is abundant, surface drainage enriched from human activity may provide an important source of algal nutrients. Based on the leaching study, the approximately 10 cm/day water input needed to maintain pond depth added DIN at an average of 0.048 (±0.002) g/m^2 day^{-1}, or at a rate equivalent to weekly fertilizations of 560 kg dry weight chicken manure/ha.

Precipitation and nitrogen fixation can be important contributors of inorganic nitrogen to natural aquatic systems, but probably not to fertilized ponds. Precipitation chemistry data from tropical watersheds have yielded total DIN loadings of <4 kg/ha year^{-1} or <0.002 g/m^2 day^{-1} (Lewis, 1981; Kellman et al., 1982). These rates are one to two orders of magnitude less than the fertilizer and source-water inputs in this study (Table 1). Investigations in fertilized fish ponds (El Samra and Oláh, 1979) and at eutrophic Clear Lake, California (Horne and Goldman, 1972; Horne, 1979) found fixation rates of <0.005 g N/m^2 day^{-1}. Lin et al. (1988), however, reported rates from 0.006 to 0.057 g N/m^2 day^{-1} in fertilized ponds in Thailand.

DIN depletion in ponds

Table 2 suggests that the algal requirement for nitrogen was met at lower fertilization rates; at 50 and 100 g dry weight/m^2 week^{-1}, nitrogen became increasingly more important, indicating an apparent switch in nutrient limitation to nitrogen.

Previous work in IPB ponds (Batterson et al., 1988) suggested that source water low in alkalinity (20–30 mg/l $CaCO_3$) caused dissolved inorganic carbon (DIC) limitation of NP at low chicken-manure fertilization rates (12.5 and 25 g dry weight/m^2 week^{-1}). At higher fertilization rates, manure decomposition supplied sufficient DIC relative to the input of other nutrients, and carbon no longer limited phytoplankton growth. In a separate experiment, manured ponds filled with alkalinity-enriched water (passed through a limestone filter) resulted in primary productivities and *O. niloticus* yields nearly double that found in ponds receiving untreated water, with NH_4-N and NO_3-N concentrations often below 0.03 mg/l (McNabb et al., 1990). Urea fertilization (0.12 g N/m^2 day^{-1}) of ponds filled with untreated water resulted in NH_4-N and NO_3-NO_2-N concentrations of around 0.5 mg/l, supporting the hypothesis that nitrogen inputs were inefficiently utilized when DIC was limiting (McNabb et al., 1985).

Lower DIN concentrations (Fig. 2) and significant DIN depletion (Table 2) at higher fertilization rates further indicated the replacement of inorganic carbon by nitrogen as the limiting nutrient for phytoplankton production in IPB ponds fertilized with chicken manure. Phosphorus limitation was not feasible because the N:P ratios of 1:2 in chicken manure and 3:1 in canal water resulted in soluble reactive phosphorus concentrations of three to ten times greater than required for primary productivity in all ponds (Batterson et al., 1988). The fact that DIN concentrations in these ponds only occasionally fell below 0.15 mg/l was probably due to nocturnal ammonia input from decomposition and daily nitrogen input from source water.

Relationship between DIN input and primary productivity

Allochthonous inputs for all treatments provided 44% (±3%) of the nitrogen necessary to sustain measured NP rates, assuming a cellular C:N ratio of 40:7 by weight (Redfield et al., 1963; Round, 1973). In addition to allochthonous inputs, regenerated ammonia and urea can be important nitrogen sources for primary productivity (Sugiyama and Kawai, 1979; Horrigan and McCarthy, 1982; La Roche, 1983). For all treatments in this study, 24-h estimates of ammonia production based on diel ammonia data were 0.47 mg/m^2 day^{-1} ammonia-N, or about 80% (±2%) of total DIN contributed to the water column. This compares to approximately 70% of daily total nitrogen input to the water column of fertilized Israeli fish ponds (calculated from Schroeder, 1987).

The linear relationship between NP and the sum of allochthonous and estimated regenerated ammonia inputs was insignificant ($r^2=0.13$), probably because nitrogen limitation was indicated only at the highest fertilization rate. The significant linear relationship ($r^2=0.81$, $P<0.05$) between NP and allochthonous nitrogen input only (Fig. 3), however, suggests rapid uptake of externally derived DIN, even under non-limiting conditions. The apparent linearity between NP and allochthonous DIN loading should break down at higher algal productivities when self-shading or some mechanism other than nutrients limit NP.

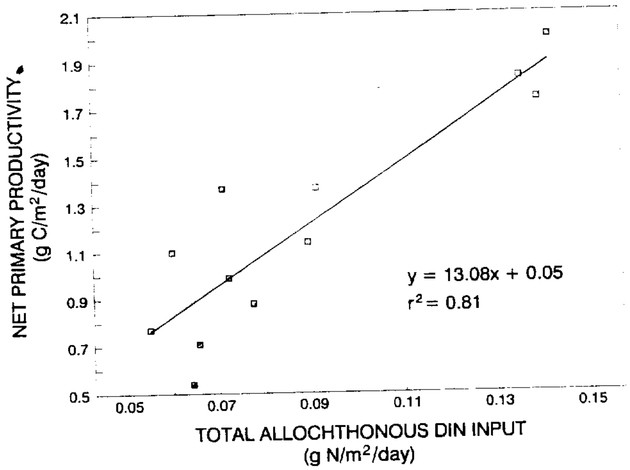

Fig. 3. Relationship between daily net primary productivity (NP) and daily allochthonous dissolved inorganic nitrogen (DIN) loading.

Relationship between primary productivity and fish yield

Ratios of net fish yield (NFY) to gross photosynthetic productivity (GP) increased from about 4.9% to 10.3% with increasing manure loading rates (Table 3). These values are higher than the 2% reported for carp (Hepher, 1962) and tilapia (McConnell et al., 1977), but close to the 11.9% and 12.8% found for common carp, silver carp, and tilapia hybrid polyculture (Noriega-Curtis, 1979). McConnell et al. (1977) suggested degree of herbivory, stocking density, harvest efficiency, and production of vascular and attached plants as major causes for FY/GP variability among systems. Because none of these factors varied in this study, the observed rise in NFY/GP as the ratio of dry weight manure loading to net phytoplankton production increased from about 1:1 to 4:1 (Table 3) suggests a more significant role of chicken manure/detritus in the diet of *O. niloticus* with increasing availability. Linear regression analysis revealed that net fish yield was better predicted by the dry weight sum of NP and chicken manure input ($r^2=0.97$, $P<0.01$, Fig. 4), than by NP alone ($r^2=0.85, P<0.01$).

These results support earlier investigations (Noriega-Curtis, 1979; Oláh et al., 1986; Schroeder, 1987; Coleman and Edwards, 1987; Green et al., 1989) which concluded that organic supplements contributed to fish yield by supplying inorganic phosphorus, nitrogen and carbon (through respiration) for algal growth, and organic carbon for detrital production and heterotrophic utilization. Schroeder and Buck (1987), however, deduced from naturally occurring stable C isotope ratios ($^{13}C/^{12}C=\delta C$) that algae and algae-based detritus were the main source of carbon for a *O. niloticus* × *O. aureus* hybrid raised in ponds fertilized with inorganic nutrients, chicken manure, or dried leaves/corn stalks. This conclusion may not be valid, however, because the δCs from live algal cells and chicken manure differed by only 3%, and contributions to fish growth from either source could not be differentiated.

Conversion efficiencies of NP nitrogen and carbon into net fish production were calculated by relating NP measurements (Table 1) to estimates of g N and C incorporated/m^2 day^{-1} assuming fresh tilapia were 70.5% moisture,

TABLE 3

Relationships (± 1s.e.) between chicken manure input (CM, g dry weight/m^2 day^{-1}), net primary productivity (NP_{dw}, g dry weight phytoplankton/m^2 day^{-1}, with 1 g C = 1.98 g dry weight phytoplankton (Lind, 1979)), gross primary productivity (GP, g O_2/m^2 day^{-1}), and net fish yield (NFY, g fresh weight/m^2 day^{-1})

CM	NP_{dw}	CM:NP_{dw}	NFY/GP as a %
1.8	1.59 ± 0.32	1.1:1	4.9 ± 1.0
3.6	1.70 ± 0.16	2.1:1	6.6 ± 0.5
7.1	2.56 ± 0.15	2.8:1	7.3 ± 0.7
14.3	3.68 ± 0.14	3.9:1	10.3 ± 0.5

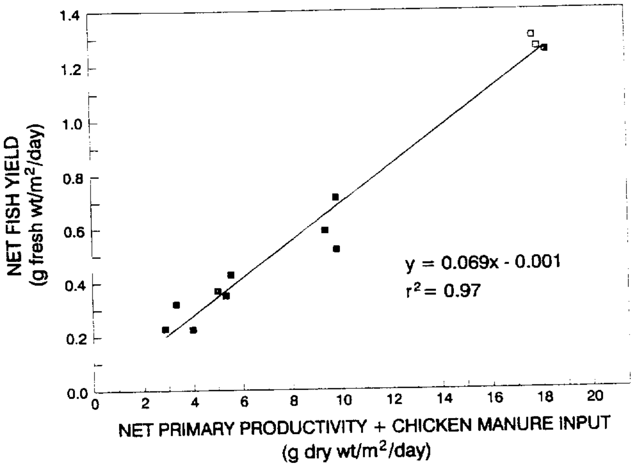

Fig. 4. Relationship between daily net fish yield (NFY) and the combined dry weight sum of daily net primary productivity (NP) and chicken manure input (CM).

9.5% N dry weight, and 48% organic carbon dry weight (Edwards et al., unpublished data). Algal nitrogen incorporation into fish production averaged 6.7% (±0.5%) at the three lower fertilization rates. At the highest fertilization rate, where nitrogen limitation was indicated, nitrogen assimilation increased to 11.0% (±0.6). As the linear relationship between allochthonous nitrogen input and NP was highly significant (Fig. 3), the observed increase in nitrogen assimilation may reflect more efficient utilization of regenerated nitrogen under nitrogen-limiting conditions.

Percent carbon recovered in fish from available NP carbon exhibited a similar pattern, increasing from 5.9% (±0.5%) at the highest fertilization rate. Liang et al. (1981) also found greater carbon transfer efficiencies with more intensive management in 18 shallow eutrophic ponds in China. Their values ranged from 1% to 11% based on GP measurements.

Relationship between allochthonous DIN input and fish yield

The linear relationship between fish yield and allochthonous DIN input from chicken manure and source water (Fig. 5) was highly significant ($r^2=0.96, P<0.01$). Increased nitrogen conversion efficiency noted for phytoplankton production at the highest chicken-manure loading rate was also observed for net fish yield. Daily incorporation of allochthonous DIN input increased significantly ($P<0.01$) from 15.8% (±1.4%) for the first three fertilization rates, to 25.7% (±0.4%) under nitrogen-limiting conditions established with the highest treatment. Greater nitrogen assimilation efficiencies observed for both algal and fish production at the highest fertilization rate reflected the importance of phytoplankton as a source of nitrogen for *O. niloticus*.

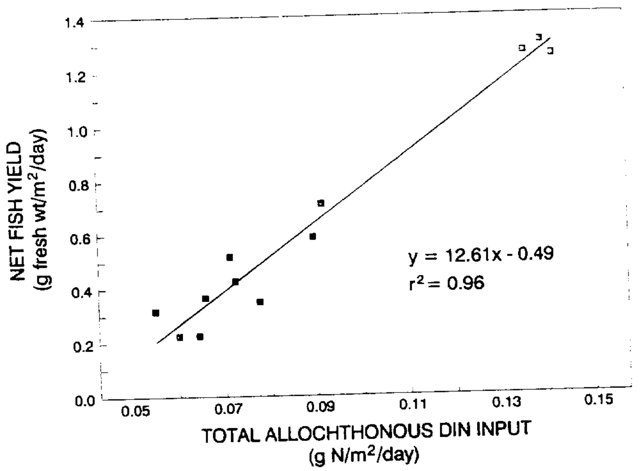

Fig. 5. Relationship between daily net fish yield (NFY) and daily allochthonous dissolved inorganic nitrogen (DIN) input.

Nitrogen conversion efficiencies should decrease and the DIN loading versus NFY curve for tilapia should plateau when light availability from self-shading rather than nitrogen limits algal productivity. Maximum nitrogen fertilization efficiency and predictable fish yields may be obtained by promoting nitrogen limitation through the addition of other algal nutrients above non-limiting levels. Maintaining nitrogen limitation also eliminates the risk of potentially lethal concentrations of un-ionized ammonia.

Tropical ponds, often naturally nitrogen limited, can be made more so by the addition of organic manures relatively rich in phosphorus. With sufficient DIC, the 1:2 N:P ratio in chicken manure should result in nitrogen limitation of algal productivity. Organic manures could be used to provide phosphorus and carbon, while the nitrogen requirement may be met by adding a nitrogen-rich fertilizer such as urea (46.7% N). In Indonesia, layer chicken manure (in 1987, Rp 25/kg wet weight; Rp 1650=US$1) and urea (in 1987, Rp 125/kg) are readily available. As a source of nitrogen, Rp 0.4/g urea DIN is about 20 times less expensive than 8 Rp/g DIN for chicken manure (6 g DIN/kg dry weight). Besides providing nitrogen more cost efficiently, urea would exert a lesser biochemical oxygen demand than chicken manure.

Maintaining nitrogen limitation may be more difficult in ponds located in temperate climates where P limitation is common. Boyd and Sowles (1978) were unable to increase bluegill production in Alabama with the addition of 8.9 kg N/ha per 21 days ($=0.04$ g N/m^2 day^{-1}) to ponds fertilized with 9.0 kg P_2O_5/ha per 21 days ($=0.02$ g P/m^2 day^{-1}). DIN concentrations were about 0.2 mg/l in ponds without the additional nitrogen input. As ponds were apparently still P limited even with P fertilization, nitrogen fertilization did not further stimulate primary productivity. When P fertilization exceeds algal requirements, additional nitrogen input can increase fish yields (Boyd, 1976). Determining optimal fertilization rates and N:P input ratios will be system specific, as internal nutrient loading is affected by such factors as pond substrate, pond history, mean depth, and water exchange/mixing characteristics.

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