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Ideotyping integrated aquaculture systems to balance soil nutrients

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Abstract

Due to growing land scarcity and lack of nutrient inputs, African farmers switched from shifting cultivation to continuous cropping and extended crop area by bringing fragile lands such as river banks and hill slopes into production. This accelerated soil fertility decline caused by erosion, harvesting and insufficient nutrient replenishment. We explored the feasibility to reduce nutrient depletion by increasing nutrient utilization efficiencies, while diversifying and increasing food production through the development of integrated aquaculture – agriculture (IAA). Considering the climatic conditions prevailing in Kenyan highlands, aquaculture production scenarios were ideotyped per agro-ecological zone. These aquaculture production scenarios were integrated into existing NUTrient MONitoring (NUTMON) farm survey data for the area. The nutrient balances and flows of the resulting IAA-systems were compared to present land use. The effects of IAA development on nutrient depletion and total food production were evaluated. With the development of IAA systems, nutrient depletion rates dropped by 23–35%, agricultural production increased by 2–26% and overall farm food production increased by 22–70%. The study demonstrates that from a bio-physical point of view, the development of IAA-systems in Africa is technically possible and could raise soil fertility and total farm production. Further studies that evaluate the economic feasibility and impacts on the livelihood of farming households are recommended.

Keywords: soil fertility decline, IAA systems, African farming systems, nutrient balances

1 Introduction

Loss of soil fertility is a major setback in agricultural production in Africa (Stoorvogel *et al.*, 1993; Gruhn *et al.*, 2000). While on average nitrogen losses of 22 kg ha^{-1} year^{-1} have been estimated for sub-Saharan Africa (Stoorvogel *et al.*, 1993), up to 76 kg ha^{-1} year^{-1} of nitrogen losses have been reported for arable lands in various African countries (Shepherd *et al.*, 1995, 1996; Nandwa & Bekunda, 1998; Wortmann & Kaizzi, 1998; Shepherd & Soule, 1998; Baijukya & Steenhuijsen Piters, 1998; Defoer *et al.*, 1998; Mohamed-Saleem, 1998).

Nutrient losses to erosion, in combination with nutrient removal through cropping and insufficient nutrient inputs, have contributed to the observed decline of soil fertility (Kumwenda *et al.*, 1996; Mango, 1996; Gruhn *et al.*, 2000). Growing land scarcity has led to increased utilization of land for cultivation resulting in a decline in fallowing, previously used for soil nutrient replenishment (Mango, 2002). Grazing areas have also been cleared for cultivation leading to a decline in cattle population and less manure availability for soil nu-

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trient replenishment. Nutrient replenishment through application of inorganic fertilizers is constrained by high costs that make them unaffordable to most farmers (FAO, 1995; Nandwa & Bekunda, 1998; Gruhn *et al.*, 2000). With the land shortage and lack of nutrient inputs, farmers intensify crop production through reliance on continuous cropping and other inappropriate land use practices, such as cultivation on river banks and hill slopes, which increase susceptibility of the land to erosion (Thomas, 1988).

To reduce the ongoing nutrient depletion, research focus is shifting towards technologies that allow for more efficient recycling of available organic nutrient resources, and that result in conservation of existing soil nutrient resources, e.g., interception of erosion and leaching (Smaling & Janssen, 1993; Buresh *et al.*, 1997). Crop residues and other farm residues should be recycled on farm (Reijntjes *et al.*, 1992; Nandwa & Bekunda, 1998). Unfortunately, re-utilization of farm residues is constrained by a temporal mismatch between availability and application (Prein, 2002). Available residues can be stored through composting for later use. However, in the process of composting, high nutrient losses occur through gaseous losses (Karlsson & Jeppson, 1995; Eghball *et al.*, 1997) and nutrient leaching (Petersen *et al.*, 1998; Sommer, 2001). Nitrogen losses of 5–77% during composting have been reported (Martins & Dewes, 1992; Eghball *et al.*, 1997; Petersen *et al.*, 1998; Thomsen, 2000). Diversification of African farming systems and incorporation of additional farm activities may have a potential for higher efficiencies in nutrient recycling (Stoorvogel & Smaling, 1990; Buresh *et al.*, 1997).

In Asia, such diversification of farming systems have been practiced in integrated fish – livestock – crop systems. Crop, vegetable wastes, and livestock droppings are used as fish pond inputs and when silt gradually reduces the pond depth, it is removed and thrown on the surrounding dikes. Vegetables, crops, and fruits are successfully planted on these dikes. Nutrient dynamics and sustainability of such integrated systems are yet to be studied in more depth, but increased profits from fish, animal and crop production, due to reduced costs of feeds and chemical fertilizers, have been reported (Little & Muir, 1987; Prein, 2002).

In Africa, ponds are still a rare component of local farming systems. Development of integrated aquaculture-agriculture (IAA) systems in African farming could reduce the on-going nutrient depletion. If ponds are located in low lying areas of the farm, they can trap run-off water and sediments rich in nutrients and utilize crop and animal residues year-round. Pond sediments can subsequently be used at any time as an on-farm crop fertilizer and improve on-farm nutrient retention and utilization efficiencies. They would not only serve to combat nutrient depletion, but would also improve household nutrition and income by adding a new protein source to the diet which in addition is a potential cash crop.

This paper explores the feasibility of integrating fish ponds in African farming systems. Based on existing farm survey data sets available from extensive NUTrient MONitoring (NUTMON) studies in Africa (De Jager *et al.*, 1998; van den Bosch *et al.*, 1998b), and using Kenyan highlands as a case study, an aquaculture component (fish pond) was ideotyped within existing farming systems. Nutrient balances of the resultant ideotype IAA systems were calculated and in comparison with those of the existing farming systems, the effects of fish ponds integration on nutrient depletion and food production were evaluated and quantified. The study focused on nitrogen because it is the major critical element limiting productivity in both aquatic and terrestrial environments in Africa (Vitousek *et al.*, 1997; Shepherd & Soule, 1998), and is closely linked with the overall soil condition, including organic matter content (Sekhon & Meelu, 1994).

2 Materials and methods

2.1 Study area

In 1997, a NUTMON study was carried out in Embu district in the Eastern Province of Kenya (00° 8' Southern latitude and 00° 50' and 37° 3' and 37° 9' Eastern longitude) (van den Bosch *et al.*, 1998b). The district rises from about 515 m above sea level at the River Tana Basin in the east to 4,570 m on the top of Mt. Kenya in the North-West. It is characterised by hills and valleys to the northern and eastern parts and steep slopes at the foot of Mt. Kenya. Variations in altitude, rainfall and temperature between highlands and lowlands, coupled with differences in geology, result in varying agricultural potential. Average rainfall increases with altitude from 640 mm to 2000 mm per year. The upper highland areas are cool, wet and steep and forestry is the main land use while in the lower highlands, coffee and tea are grown. In the low lying areas, cash crops such as cotton and tobacco and food crops such as maize and millet are grown and livestock is kept. The district shows the typical agro-ecological profile of the windward side of

Table 1: *Characteristics of the 5 agro-ecological zones (AEZ)*

Characteristic	*Agro-ecological zones*				
	AEZ 1	*AEZ 2*	*AEZ 3*	*AEZ 4*	*AEZ 5*
Altitude (m.a.s.l.)	1770	1590	1320	980	830
Annual mean temp. (°C)	16.8	18.2	20.2	21.4	22.6
Annual average rainfall (mm)	1750	1400	1200	900	800
Main soil types	Andosol/Nitosol	Nitosol	Nitosol	Nitosol/Combisol	Arenosol

Mt. Kenya. Five agro-ecological zones were identified in previous studies (FURP, 1987) and the present study covers those five zones (Table 1).

2.2 NUTMON

The NUTMON toolbox was developed as a monitoring tool for soil nutrient balances. The toolbox (van den Bosch *et al.*, 1998a) allows for monitoring actual nutrient flows on the farm and to calculate soil nutrient balances. The balances are based on an accounting exercise in which the net balance equals the sum of the nutrient inputs minus the sum of the outputs. Table 2 provides an overview of the various inputs and outputs considered.

Table 2: *Nutrient inputs and outputs*

Nutrient inputs		*Nutrient outputs*	
IN 1	Mineral fertilizer	OUT 1	Crop product
IN 2	Organic fertilizer *	OUT 2	Crop residues †
IN 3	Atmospheric deposition	OUT 3	Leaching
IN 4	Nitrogen fixation	OUT 4	Denitrification
IN 5	Sedimentation	OUT 5	Erosion

* including feeds, organic fertilizer, external grazing, and imported food

† including crop residues but also manure from the SPU and grass through grazing

The farming system is subdivided into a number of compartments including:

a. the primary production units (PPU's) which include fields with crops or grassland,

b. the secondary production units (SPU's) which include the animals on the farm,

c. the household (HH) defined as the actual household with all the people that spend a significant amount of time on the farm,

d. the redistribution units (RU) which are locations within the farm where nutrients are collected or accumulated and from where nutrients are redistributed over the farm (including e.g., garbage heaps and stables),

e. the stock which allows for temporary storage of e.g., crop products and fertilizer on the farm.

During monitoring the various management-related nutrient flows were recorded. This includes IN 1, IN 2, OUT 1, and OUT 2 as indicated in Table 2. Other flows are not recorded and will have to be estimated in a later stage using simple transfer functions or models. The NUTMON-toolbox makes calculations for the various compartments and the sum of the various compartments yields the farm balance.

2.3 NUTMON data, Embu district, Kenya

The NUTMON study monitored 15 farms in Embu province during a two year survey. Each of the five agro-ecological zones (AEZ) included three farms of which one single farm with a representative cropping pattern and management was selected.

On a typical farm up to 14 different PPU's and five different SPU's were observed. For this explorative exercise the various PPU's were aggregated into a single overarching PPU. Similarly, the SPU's and RU's were aggregated. Given the long term evaluation, in this manuscript we assumed the stock and the HH to be constant. They were therefore excluded from the analysis. As a result, the farming systems were described by three compartments, the PPU, SPU and RU.

2.4 Data analysis

The NUTMON-toolbox has proven to be a valuable tool to evaluate farming systems under all kind of agro-ecological conditions. It allows people to determine where major losses of nutrients take place and get a better understanding of the farming system. However, the system does not include the required feedbacks that would allow for an evaluation of alternative interventions. As such, the existing NUTMON methodology does not serve the purposes of this manuscript to ideotype a farming system comprising a fish pond. To do so, feedbacks necessary to dynamically model the farming system were incorporated in NUTMON. Here, we report on the various adaptations that were made to the standard NUTMON methodology (De Jager *et al.*, 1998; van den Bosch *et al.*, 1998a).

For the aggregated PPU we derived a number of basic properties: the current productivity, the harvest index, average nitrogen concentration of inputs and outputs, and the level of inputs. Crop growth simulation is often described as the exponential relationship between nutrient availability (N_{avail}) and nutrient uptake (N_{uptake}). Nitrogen availability was calculated on the basis of soil nitrogen contents, bulk density, and estimated mineralization rates plus nitrogen supplied through the various inputs. Subsequently, we defined the following exponential model:

$$N_{uptake} = c_0 + c_1\, e^{-c_2\, N_{avail}}$$

The three constants were estimated using the observed nitrogen uptake in the system and an assumed 50 % nitrogen use efficiency for the current systems which corresponds to the results of a large fertilizer use recommendation program in Kenya (Smaling *et al.*, 1992).

The current efficiency of the various redistribution units is set at 30 % corresponding to the observed rates (ratio of nitrogen input and output) in various Kenyan studies (Rufino *et al.*, 2006).

While making changes in the farming system, the secondary production unit is maintained (in other words the number of animals is kept constant). Lack of food is compensated for by external feeding. A surplus of food enters the redistribution units and will leave as part of the farm yard manure. This is often observed in the extensively managed ‘bomas’ (animal stables) where crop residues are left on the ground and mix with manure. Note that feeding requirements have been defined in NUTMON and were kept the same.

Management decisions in terms of use of e.g., crop residues are derived from the initial datasets and flows are redefined in per cent terms. For example, part of the crop residues may be incorporated in the soil, another part may be fed to the animals, and finally a fraction may be sold. The fractions are calculated as observed in the system and kept constant even if the total production of residues increases or decreases.

2.5 Ideotyping fishponds

In idiotyping fish ponds for potential integration in the farming systems, the following further adaptations were made. (A) Immediate re-utilization (in fish ponds) of nutrients that accumulate in the RU is expected to result in reduced nutrient losses from the RU due to reduced storage period and improve the RU efficiency. As such, the efficiency of the RU was re-set at 60 % (Lekasi *et al.*, 2001; Woomer *et al.*, 1998; Kirchman *et al.*, 1985). (B) To increase nutrient use efficiency, 70 % of nutrients from RUs, currently applied to PPUs, were re-allocated to fish production assuming their compensation on re-utilization of enriched pond sediment on crop fields. (C) The sum of the nutrients that became available due to increased RU efficiencies and the 70 % re-allocated from PPUs was set as the quantity of nutrients available in the farm for aquacultural use. Based on a reported nitrogen application requirement rate of 4 kg ha^{-1} day^{-1} in tropical fish ponds (Knud-Hansen *et al.*, 1993), and assuming a 12 month culture period, the size of fish pond that can be supported with the available nutrients was determined. (D) Interception of nutrients contained in eroded sediments by the fishpond was set at 50 %, an average drawn from reported rates of 21–100 % sediment trap efficiency by small retention ponds constructed on drainage ways of cropped fields (Fiener *et al.*, 2005; Verstraeten & Poesen, 2001; Renwick *et al.*, 2005). (E) Annual atmospheric nitrogen deposition in ponds was calculated following the NUTMON calculation as $0.014 \times \sqrt{rainfall}$ (in mm/year) (Stoorvogel *et al.*, 1993).

Based on averages of pond nutrient flows for semi-intensive tropical ponds available in literature, pond nutrient balances were calculated as follows:

(i) Nitrogen fixation of 24 mg N m^{-2}day^{-1} (Acosta-Nasser *et al.*, 1994),

(ii) Fish retain 20 % of total nitrogen input (Green & Boyd, 1995; Acosta-Nasser *et al.*, 1994),

(iii) 65 % of total nitrogen inputs accumulate in pond sediments (Acosta-Nasser *et al.*, 1994),

(iv) 10 % of total nitrogen inputs are lost through denitrification, volatilization and leaching (Briggs & Funge-Smith, 1994; Lorenzen *et al.*, 1997; Gross *et al.*, 2000),

(v) Drainage water contains 5 % of the nitrogen input (Green & Boyd, 1995).

Table 3: *Nutrient balance in current farming systems in Embu district, Kenya*

	AEZ 1				*AEZ 2*				*AEZ 3*				*AEZ 4*				*AEZ 5*			
	PPU	*SPU*	*RU*	*FP*	*PPU*	*SPU*	*RU*	*FP*	*PPU*	*SPU*	*RU*	*FP*	*PPU*	*SPU*	*RU*	*FP*	*PPU*	*SPU*	*RU*	*FP*
Area (ha)	1.21	–	–	0	1.41	–	–	0	3.51	–	–	0	2.12	–	–	0	2.28	–	–	0
Inputs																				
Mineral fertilizer	139	0	0	0	111	0	0	0	25	0	0	0	131	0	0	0	0	0	0	0
Organic fertilizer/feed	46	133	113	0	56	211	179	0	42	129	109	0	65	162	138	0	66	168	184	0
Atmospheric deposition	8	0	0	0	9	0	0	0	22	0	0	0	12	0	0	0	11	0	0	0
Nitrogen fixation	6	0	0	0	7	0	0	0	18	0	0	0	11	0	0	0	12	0	0	0
Sedimentation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total IN	199	133	113	0	183	211	179	0	107	129	109	0	219	162	138	0	89	168	184	0
Outputs																				
Crop/animal products	58	13	0	0	19	21	0	0	57	13	0	0	56	16	0	0	66	17	0	0
Crop residues	145	113	34	0	44	179	54	0	73	109	33	0	127	138	41	0	10	142	55	0
Leaching	85	0	79	0	67	0	126	0	112	0	77	0	74	0	96	0	41	0	129	0
Denitrification	32	0		0	35	0		0	62	0		0	31	0		0	4	0		0
Erosion	13	0	0	0	182	0	0	0	154	0	0	0	18	0	0	0	134	0	0	0
Total OUT	333	126	113	0	346	200	179	0	458	122	109	0	306	154	138	0	255	159	184	0
Net balance	–134	7	0	0	–163	11	0	0	–351	6	0	0	–87	8	0	0	–166	8	0	0
Depletion rate (kg/ha/year)	111				116				100				41				73			

AEZ = agro-ecological zone, PPU = primary production unit, SPU = secondary production unit, RU = Redistribution unit and FP = fish pond

2.6 *Effects of fish pond integration*

With the integration of the fish pond, the farming system is now described by the PPU, SPU, RU, and Fish Pond (FP). It should be noted that NUTMON fishponds are often considered as redistribution units (Phong *et al.*, 2011). Given the specific focus of the fishponds in the manuscript, they were examined separately. Nutrient balances of the ideotyped IAA-systems were calculated considering the various inputs and out puts (Table 2), assuming that incorporation of pond sediment nutrients in PPUs (IN 5) is 100% and that the incorporation of nutrients contained in drainage water from ponds (for irrigation purposes) is 50% and is included in the PPU balance (combined with pond sediment) as IN 5 (sedimentation).

Nutrient depletion rates and overall food production in the ideotyped IAA-systems were compared with those in the existing farming systems and the differences were evaluated and quantified.

3 Results

3.1 *Nutrient balances of existing farming systems*

In the nutrient balances of existing farming systems, the major nutrient inputs to the PPUs are mineral and organic fertilizers, while crop products, crop residues, leaching and erosion are all major nutrient outputs (Table 3). There was a high variation in nutrition balances between farms.

The sources of the organic fertilizer input to the PPUs include the RUs and household wastes (organic fertilize input – RU crop residue output). The majority of the crop residues from the PPU are recycled as organic feeds to the SPUs and the remainder is incorporated into the fields or sold (as observed in the NUTMON flows). Organic feeds (crop residues from PPUs + external supplemental feeding) are the main input to the SPU. Of the total SPU inputs, 10 % is contained in harvested animal products and 85 % is excreted as manure. All excreted manure is stored in the RUs (main RU input) where 70 % of the nutrients are lost to leaching and denitrification and the remaining 30 % is recycled in the PPUs. At all zones, total nutrient outputs from the PPUs are higher than total inputs resulting in nutrient depletion rates ranging from 40 to 116 kg N/ha/year. Overall food production in the farms (crop products in PPU + in SPU) range from 40–83 kg N/farm/year.

3.2 *Nutrient balances of the ideotyped IAA-systems*

With the estimated reduction in N losses in RUs and the decrease of organic inputs in PPUs (section 2.5), 56 to 94 kg nitrogen per year became available for pond use. These quantities were sufficient to support ponds ranging between 400 and 700 m^2 in size (Table 4).

Table 4: *Ideotyped aquaculture units (fish pond) for integration in existing farming systems*

	AEZ 1	*AEZ 2*	*AEZ 3*	*AEZ 4*	*AEZ 5*
N available for use in pond (kg)					
From increased RU efficiency	34	54	33	41	55
Re-allocated from PPU inputs	24	38	23	29	39
Total	58	92	56	70	94
Possible pond size (m^2)	–	600	400	500	700

IAA-systems were not ideotyped for the farming system in AEZ 1 due to unavailability of information on nutrient utilization efficiencies in ponds at low temperatures (Table 1). The major pond nutrient inputs are organic fertilizer (manure from RU) and sediments (intercepted erosion). Compared to the existing farming systems (Table 3), nutrient depletion rates were lower, ranging between 30 and 89 kg N/ha/year in AEZ 2–5, and overall food production (products in PPU, SPU, and FP) was higher, ranging between 81 and 129 kg N/farm/year (Table 5).

3.3 Effects of fish ponds integration

Because a part of the land is converted into fish ponds, the PPU area in the ideotyped IAA-systems is 1–4 % smaller than in the original farms. On the other hand, the nutrient inflow to the PPU is 11–69 % higher in ideotyped IAA-systems due to additional input from pond sediments. Based on increased nutrient inputs, crop production in the PPU is 2–26 % higher in ideotyped IAA-systems than in the existing farming systems despite the reduction in PPU land area. Increased crop production plus new fish yields raise the overall food production in ideotyped IAA-systems by 22 to 70 % (Table 6). Mainly due to an increase in total PPU inputs, ideotyped IAA-systems nutrient depletion rates were 23–35 % lower than in existing farming systems (Table 6).

4 Discussion

The results have demonstrated that development of IAA-systems in African farming would improve nutrient use efficiencies and enable increased food production while reducing soil fertility losses (Table 5 and 6). These positive impacts are achieved because of the possibility of the aquaculture component to (i) utilize available farm residues (e.g., a variety of animal manures, crop residues, and household residues) as fish pond nutrient inputs, (ii) trap and retain nutrients in pond sediments and (iii) operate year round.

As a fish feed, terrestrial vegetation results in negligible fish growth due to its low palatability and digestibility (Castanares *et al.*, 1992). However, application of composted green manures resulted in net fish yields of up to 3 tons ha^{-1} $year^{-1}$ (Veverica *et al.*, 1990; Rurangwa *et al.*, 1990; Chikafumbwa *et al.*, 1993). A variety of animal manures such as chicken litter, cow dung, buffalo and pig manures have been used successfully to provide nutrients to tropical and sub-tropical ponds (Hopkins & Cruz, 1982; Green *et al.*, 1989) and 6–10 tons ha^{-1} $year^{-1}$ were produced (Wohlfarth & Schroeder, 1979; Schroeder, 1980; Schroeder *et al.*, 1990; Knud-Hansen *et al.*, 1993). Fish production in manure driven ponds is primarily phytoplankton based (Colman & Edwards, 1987; Knud-Hansen *et al.*, 1993). Manures decompose slowly releasing inorganic nutrients which stimulate algal production. Since on-land composting results in a net loss of carbon and nitrogen through leaching (Lin *et al.*, 1997), farmers (in e.g., Rwanda) have developed in-pond composting methods. Grass, kitchen waste and animal manure are added to enclosures built within the ponds where the decomposing wastes are regularly stirred to release nutrients (Veverica *et al.*, 1990). Although on-farm residues are high in carbon and consume large amounts of dissolved oxygen during decomposition (Lin *et al.*, 1997), careful management of application rates will alleviate this constraint (Veverica *et al.*, 1990). Besides tropical fish species such as Tilapia sp. tolerate large dial dissolved oxygen fluctuations (Popma & Lovshin, 1995)

The ability of aquaculture ponds to trap and retain nutrients in sediments has been demonstrated in numerous studies. On average, 20–30 % of the total nitrogen input to aquaculture ponds is retained in fish (Avnimelech & Lacher, 1979; Boyd, 1985; Krom *et al.*, 1985; Porter *et al.*, 1987; Green & Boyd, 1995) and up to 80 % is retained in the pond sediment (Avnimelech & Lacher, 1979; Schroeder, 1987; Myint *et al.*, 1990; Acosta-Nasser *et al.*, 1994; Briggs & Funge-Smith, 1994; Olah *et al.*, 1994). Besides the retention of a large proportion

Table 5: *Nutrient balance in current farming systems in Embu district, Kenya*

	AEZ 2				*AEZ 3*				*AEZ 4*				*AEZ 5*			
	PPU	*SPU*	*RU*	*FP*	*PPU*	*SPU*	*RU*	*FP*	*PPU*	*SPU*	*RU*	*FP*	*PPU*	*SPU*	*RU*	*FP*
Area (ha)	1.35	–	–	0.06	3.47	–	–	0.04	2.07	–	–	0.05	2.21	–	–	0.07
Inputs																
Mineral fertilizer	111	0	0	0	25	0	0	0	131	0	0	0	0	0	0	0
Organic fertilizer/feed	18	211	179	91	20	129	109	56	37	162	138	70	27	168	185	94
Atmospheric deposition	8	0	0	0.4	22	0	0	0.2	12	0	0	0.3	11	0	0	0.3
Nitrogen fixation	7	0	0	0.2	18	0	0	0.1	11	0	0	0.2	12	0	0	0.2
Sedimentation + irrigation	121	0	0	87	89	0	0	76	54	0	0	9	108	0	0	65
Total IN	265	211	179	179	173	129	109	132	244	162	138	79	158	168	185	160
Outputs																
Crop/animal products	24	21	0	36	64	13	0	26	57	16	0	16	80	17	0	32
Crop residues	56	179	108	0	82	109	66	0	128	138	83	0	12	143	111	0
Leaching/pond drainage	73	0	72	9	118	0	44	7	75	0	55	4	51	0	74	8
Denitrification	38	0	0	18	65	0	0	13	31	0	0	8	5	0	0	16
Erosion/pond sediment	174	0	0	116	152	0	0	86	18	0	0	52	131	0	0	104
Total OUT	366	200	179	179	481	122	109	132	309	154	138	79	278	160	185	160
Net balance	–101	11	0	0	–308	6	0	0	–65	8	0	0	–120	8	0	0
Depletion rate (kg/ha/year)	75				89				31				54			

AEZ = agro-ecological zone, PPU = primary production unit, SPU = secondary production unit, RU = Redistribution unit and FP = fish pond

Table 6: *A summary of the main differences in the nutrient balances of the existing farming systems (Table 3) and of the ideoyped IAA systems (Table 5) for Embu district, Kenya*

	AEZ 2			*AEZ 3*			*AEZ 4*			*AEZ 5*		
	Existing	IAA	% change	Existing	IAA	% change	Existing	IAA	% change	Existing	IAA	% change
PPU area (ha)	1.41	1.35	–4	3.51	3.47	–1	2.12	2.07	–2	2.28	2.21	–3
Total PPU input (kg)	183	265	45	107	173	62	219	244	11	89	158	69
PPU crop products	19	24	26	57	64	12	56	57	2	66	80	21
Depletion rate (PPU)	116	75	–35	100	89	–23	41	31	–23	73	54	–25
Overall food production	40	81	22	70	103	58	72	89	30	83	129	70

of nitrogen inputs in aquaculture ponds, small retention ponds constructed on spillways in hilly areas could trap 21–100 % of soil eroded from fields in the upper slopes (Fiener *et al.*, 2005; Verstraeten & Poesen, 2001; Renwick *et al.*, 2005).

Fish ponds need to be operational year-round to allow instant utilization of farm residues and to minimise nutrient losses during storage in the RUs. The tropical conditions in sub-Saharan Africa favour year-round pond aquaculture. However, in high altitude areas, temperature becomes sub optimal. Nile tilapia, the commonly cultured species in Africa, grows best at 25–28 °C and stops growing below 20 °C (Popma & Lovshin, 1995). In areas where temperatures drop below 20 °C, more cold tolerant species should be stocked. Various carp species thrive well at 17–37 °C (Coutant, 1977; Jhingran, 1982). When temperatures drop below 17 °C for extended periods of the year, trout which grows best in 12–18 °C waters could be farmed (Shelton, 1994). Thus, considering the temperature regimes in the various agro-ecological zones (Table 1) suitable culture species are: tilapia in AEZ 3–5, carp in AEZ 2 (but also possible in AEZ 3–5) and trout in AEZ 1.

Nutrient pond budget studies from low temperature areas comparable to AEZ 1 are not available. Available data on nutrient dynamics in tropical ponds is mainly based on fish culture within a temperature range of 20–40 °C. However, reported pond nutrient balances for carps under semi-intensive conditions in a temperate climate (Olah & Pekar, 1992) are within the same range. Therefore, the same balances were used to ideotype IAA systems in AEZ 2 – AEZ 5. Because of the lack of data, IAA-systems were not ideotyped for AEZ 1.

High water quality is essential to produce trout in ponds. The water should be below 18 °C, clear, dissolved oxygen levels should be 5–12 mg l^{-1} and pH levels 6.5–8.5 (Shelton, 1994). Grown purely on natural foods, trout yield are 100–150 kg ha^{-1} $year^{-1}$ and yields of 1000–2000 kg ha^{-1} $year^{-1}$ are achievable with feeding (Marriage *et al.*, 1971), which increases production costs by 60% (Sloene, 1994). Such characteristics make trout farming unsuitable for small-scale IAA-systems since organic wastes, but not formulate feeds, are the available nutrient inputs. Due to high respiratory demand of bacterial degradation of organic wastes, night and dawn oxygen levels below 5 mg l^{-1} are common in organically fertilized ponds (Popma & Lovshin, 1995), and pond waters are turbid, mainly due to high plankton concentrations. In addition, trout farming in small-scale ponds may not be economically feasible.

Carps and tilapia are omnivores (Jhingran, 1982; Popma & Lovshin, 1995), growing well in organic wastes driven ponds (Nandeesha, 1982). They are tolerant to high fluctuations in water quality, capable of tolerating low oxygen levels (Huet, 1972; Popma & Lovshin, 1995) and production of 3000–8000 kg ha^{-1} $year^{-1}$ were achieved in organically fertilized ponds (Popma & Lovshin, 1995; Pekar & Olah, 1991). These characteristics make them suitable culture species for small-scale IAA-systems where on-farm residues are the available pond nutrient sources.

Therefore, based on available literature, as demonstrated in the foregoing discussion, the required characteristics of the aquaculture component are possible in most of the agro-ecological zones. An important factor for successful integration of the various components of the IAA-systems is the utility of pond sediment to fertilize crops. Studies in Thailand, The Philippines and Japan showed that incorporating pond sediments in degraded rice fields increased productivity for several years (Mochizuki *et al.*, 2006). The pond sediments are commonly used to sustain rice productivity (Conklin, 1980; Furukawa, 1997) or to improve the chemical and physical properties of soils (Iwata *et al.*, 1973; Matsushima, 1980).

In conclusion, this explorative study shows that from a bio-physical point of view, the development of IAA-systems in Africa is technically possible and would results in improved soil fertility management and increased total farm production. In a further step, economic feasibility and on-farm conditions (e.g., availability of water, and soil characteristics) should be considered. A pilot study, monitoring IAA-system nutrient budgets, while recording economic feasibility and impacts on the livelihood of farming household, is recommended as the next step towards the development of IAA-systems in Africa.

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References

Acosta-Nasser, M. V., Morell, J. M. & Corredor, J. E. (1994). The nitrogen budget of a tropical semi-intensive freshwater fish culture pond. *Journal of the World Aquaculture Society*, 25, 261–269.

Avnimelech, Y. & Lacher, M. (1979). A tentative nutrient budget for intensive fish ponds. *Bamidgeh, the Israeli journal of aquaculture*, 31, 3–8.

Baijukya, F. P. & Steenhuijsen Piters, B. (1998). Nutrient balances and their consequences in the banana-based land use systems of Bukoba district, northwest Tanzania. *Agriculture, Ecosystems and Environment*, 71, 147–158.

van den Bosch, H. D., De Jager, A. & Vlaming, J. (1998a). Monitoring nutrient flows and economic performance in African farming systems (NUTMON): II. Tool development. *Agriculture, Ecosystems and Environment*, 71, 49–62.

van den Bosch, H. D., Gitari, J. N., Ogaro, V. N., Maobe, S. & Vlaming, J. (1998b). Monitoring nutrient flows and economic performance in African farming systems (NUTMON): III. Monitoring nutrient flows and balances in three districts in Kenya. *Agriculture, Ecosystems and Environment*, 71, 63–80.

Boyd, C. E. (1985). Chemical budgets for channel catfish ponds. *Transactions of the American Fisheries Society*, 114, 291–298.

Briggs, M. R. P. & Funge-Smith, S. J. (1994). A nutrient budget of some intensive marine shrimp ponds in Thailand. *Aquaculture and Fisheries Management*, 25 (8), 789–811.

Buresh, R. J., Sanchez, P. A. & Calhan, F. (1997). *Replenishing Soil Fertility in Africa*. SSSA Special Publication, Vol. 51, Madison, WI, USA.

Castanares, A., McCrae, S. I. & Wood, T. M. (1992). Purification and propertiesof feruloyl/e-ccoumaroryl esterase from the fungus Penicillium Pinophilum. *Enzyme & Microbial Technology*, 14, 875–884.

Chikafumbwa, F. J. K., Costa-Pierce, B. A., Jamu, D. M. & Kadongola, W. K. (1993). Investigations on the use of on-farm resources as pond inputs to culture *Tilapia rendalli* and *Oreochromis shiranus* on smallholder farms in rural Malawi. *Aquaculture*, 117, 261–271.

Colman, J. A. & Edwards, P. (1987). Feeding pathways and environmental constraints in waste-fed aquaculture: balance and optimization. In D. J. W. Moriarty, & R. S. V. Pullin (Eds.), *Detritus and Microbial Ecology in Aquaculture. ICLARM Conference Proceedings 14* (pp. 240–281). International Center for Living Aquatic Resources Management, Manila.

Conklin, H. C. (1980). *Ethnographic Atlas of Ifugao*. Yale Univ. Press, New Heaven.

Coutant, C. C. (1977). Compilation of temperature preferences data. *Journal of the Fisheries Research Board of Canada*, 34, 739–745.

De Jager, A., Nandwa, S. M. & Okoth, P. F. (1998). Monitoring nutrient flows and economic performance in African farming systems (NUTMON): I. Concepts and methodologies. *Agriculture, Ecosystems and Environment*, 71, 37–48.

Defoer, H., De Groote, H., Hilhorst, T., Kante, S. & Budelman, A. (1998). Increasing nutrient use efficiency in West-African agriculture: impact of microtopography on leaching from cattle and sheep manure. *Agriculture, Ecosystems and Environment*, 71, 217–230.

Eghball, B., Power, J. F., Gilley, J. E. & Doran, J. W. (1997). Nutrient, carbon, and mass loss during composting of beef cattle feedlot manure. *Journal of Environmental Quality*, 26, 189–193.

FAO (1995). *The state of food and agriculture*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Fiener, P., Auerswald, K. & Weigand, S. (2005). Managing erosion and water quality in agricultural watersheds by small detention ponds. *Agriculture, Ecosystems and Environment*, 110, 132–142.

FURP (1987). Final Report: Description of first priority trial sites. Nairobi. Fertilizer Use Recommendation Project, National Agricultural Research Laboratories. Nairobi, Kenya.

Furukawa, H. (1997). Rice terrace of Ifugao. In H. Furukawa, Y. Kaida, I. Yamada, & Y. Takaya (Eds.), *Encyclopedia of Southeast Asia* (p. 617). Center for Southeast Asian Studies, Kyoto University, Kyoto. (in Japanese).

Green, B. W. & Boyd, C. E. (1995). Chemical budgets for organically fertilized fish ponds in the dry tropics. *Journal of the World Aquaculture Society*, 26, 284–296.

Green, B. W., Phelps, R. P. & Alvarenga, H. R. (1989). The effect of manures and chemical fertilizers on the production of *Oreochromis niloticus* in earthen ponds. *Aquaculture*, 76, 37–42.

Gross, A., Boyd, C. E. & Wood, C. W. (2000). Nitrogen transformations and balance in channel catfish ponds. *Aquacultural Engineering*, 24, 1–14.

Gruhn, P., Goletti, F. & Yudelman, M. (2000). *Integrated nutrient management, soil fertility, and sustainable agriculture: current issues and future challenges*. International Food Policy Research Institute, 2033 K Street, N.W. Washington D.C. U.S.A. 31 pp.

Hopkins, K. D. & Cruz, E. M. (1982). The ICLARM-CLSU integrated animal-fish farming project: final report. ICLARM Technics! Reports 5. International Center for Living Aquatic Resources Management, Manila, and the Freshwater Aquaculture Center, Central Luzon State University, Nueva Ecija, Philippines. 96 pp.

Huet, M. (1972). *Text Book of Fish Culture-Breeding and Cultivation of Fish*. Fishing News (Books), London.

Iwata, T., Matsuura, K. & Hasegawa, T. (1973). Studies on the occurrence of “Tomehagare”, a newly found physiological disease of rice and its preventive measures. III. Preventive effect of soil ameliorating materials. *Proceedings of the Crop Science Society of Japan*, 42, 468–474.

Jhingran, V. G. (1982). *Fish and Fisheries of India*. Hindustan Publishing Corporation, Delhi, India.

Karlsson, S. & Jeppson, K.-H. (1995). Djupströbädd i stall och mellanlager. JTI Rapport 204, Swedish Institute of Agricultural Engineering, Ultuna Uppsala, Sweden.

Kirchman, D. L., K’Nees, E. & Hodson, R. (1985). Leucine incorporation and its potential as a measure of protein synthesis by bacteria in natural aquatic systems. *Applied and Environmental Microbiology*, 49, 599–607.

Knud-Hansen, C. F., Batterson, T. R. & McNabb, C. D. (1993). The role of chicken manure in the production of Nile tilapia *Oreochromis niloticus* (L.). *Aquaculture and Fisheries Management*, 24, 483–493.

Krom, M. D., Porter, C. & Gordin, H. (1985). Nutrient budget of a marine fish pond in Eilat, Israel. *Aquaculture*, 51, 65–80.

Kumwenda, J. D. T., Waddington, S. R., Snapp, S. S., Jones, R. B. & Blackie, M. J. (1996). Soil fertility management research for the maize cropping systems of small holders in southern Africa: A review. Natural Resources Group Paper 96-02. Mexico City: International Maize and Wheat Improvement Center (CIMMYT).

Lekasi, J. K., Tanner, J. C., Kimani, S. K. & Harris, P. J. C. (2001). Cattle manure quality in Maragua District, Central Kenya: Effect of management practices and development of simple methods of assessment. *Agriculture, Ecosystems and Environment*, 94, 289–298.

Lin, C. K., Teichert-Coddington, D. R., Green, B. W. & Veverica, K. L. (1997). Fertilizer regimes. In H. S. Egna, & C. E. Boyd (Eds.), *Dynamics of pond aquaculture*. CRC Press, New York, USA.

Little, D. & Muir, J. (1987). A guide to integrated warm water aquaculture. Institute of aquaculture publications, University of Stirling, Stirling. 238 pp.

Lorenzen, K., Struve, J. & Cowan, V. J. (1997). Impact of farming intensity and water management on nitrogen dynamics in intensive pond culture: a mathematical model applied to Thai commercial shrimp farms. *Aquaculture Research*, 28, 493–507.

Mango, N. A. R. (2002). *Husbanding the land: Agricultural development and socio-technical change in Luoland, Kenya*. Ph.D. thesis Wageningen University, Wageningen, The Netherlands.

Mango, N. R. (1996). *Farmers' response to the agrarian crisis in Siaya District, Kenya. An analysis of how farmers 'internalise' induced technology interventions in dairy farming*. Master's thesis Wageningen Agricultural University, The Netherlands.

Marriage, L. D., Borell, A. E. & Scheffer, P. M. (1971). Trout Ponds for recreation. U. S. Department of Agriculture, Farmers' bulletin No. 2246.

Martins, O. & Dewes, T. (1992). Loss of nitrogenous compounds during composting of animal wastes. *Bioresource Technology*, 42, 103–111.

Matsushima, S. (1980). *Rice Cultivation for the Million*. Japan Scientific Societies Press, Tokyo. 276 pp.

Mochizuki, A., Homma, K., Horie, T., Shiraiwa, T., Watatsu, E., Supapoj, N. & Thongthai, C. (2006). Increased productivity of rainfed lowland rice by incorporation of pond sediments in Northeast Thailand. *Field Crops Research*, 96, 422–427.

Mohamed-Saleem, M. A. (1998). Nutrient balance patterns in African livestock systems. *Agriculture, Ecosystems and Environment*, 71, 241–254.

Myint, Z. W., Chiba, K., Okamoto, K., Hino, A. & Wakabayashi, H. (1990). Nitrogen and phosphorous budget aspects of fertilized fish ponds. In R. Hirano, & I. Hanyu (Eds.), *The Second Asian Fisheries Forum* (pp. 173–176). Asian Fisheries Society, Manila, Philippines.

Nandwa, S. M. & Bekunda, M. A. (1998). Research on nutrient flows and balances in East and Southern Africa: state-of-the-art. *Agriculture, Ecosystems and Environment*, 71, 5–18.

Olah, J. & Pekar, F. (1992). *Nitrogen metabolism in fish-cum-livestock ecosystems*. Fisheries Research Institute, Szarvas, Hungary.

Olah, J., Pekar, F. & Szabo, P. (1994). Nitrogen cycling and retention in fish-cum-livestock ponds. *Journal of Applied Ichthyology*, 10, 341–348.

Pekar, F. & Olah, J. (1991). Carbon pathways, bioenergetic efficiencies and energy cost in fish-cum-livestock ecosystems. In *Proceedings, FAO/IPT International Workshop on Integrated Livestock-Fish Production Systems, Kuala Lumpur, Malaysia, December 16-20, 1991* (pp. 78–84). FAO/IPT.

Petersen, S. O., Lind, A. M. & Sommer, S. G. (1998). Nitrogen and organic matter loss during storage of cattle and pig manure. *Journal of Agricultural Science*, 130, 69–79.

Phong, L. T., Stoorvogel, J. J., Van Mensvoort, M. E. H. & Udo, H. M. J. (2011). Modeling the soil nutrient balance of integrated agriculture-aquaculture systems in the Mekong Delta, Vietnam. *Nutrient Cycling in Agro-ecosystems*, 90, 33–49.

Popma, T. J. & Lovshin, L. L. (1995). *Worldwide prospects for commercial production of tilapia*. International Center for Aquaculture and Aquatic Environments, Auburn University, Alabama, USA.

Porter, C., Krom, M. D., Robbins, M. D., Bricknell, M. G. & Davidson, A. (1987). Ammonia excretion and total N budget for filthead seabream (*Sparus aurata*) and its effect on water quality conditions. *Aquaculture*, 66, 287–289.

Prein, M. (2002). Integration of aquaculture into crop-animal systems in Asia. *Agricultural systems*, 71, 127–146.

Reijntjes, C., Haverkort, B. & Waters-Bayer, A. (1992). *Farming for the future. An introduction to low-external input and sustainable agriculture*. MacMillan, London.

Renwick, W. H., Smith, S. V., Bartley, J. D. & Buddemeier, R. W. (2005). The role of impoundments in the sediment budget of the conterminous United States. *Geomorphology*, 71, 99–111.

Rufino, M. C., Rowe, E. C., Delve, R. J. & Giller, K. E. (2006). Nitrogen cycling efficiencies through resource-poor African crop–livestock systems. *Agriculture, Ecosystems and Environment*, 112, 261–282.

Rurangwa, E., Verheust, L. & Veverica, K. (1990). Fertilizer input method influences productivity. In H. S. Egna, J. Bowman, & M. MacNamara (Eds.), *Collaborative Research Suppert Program Pond Dynamics/Aquaculture, Seventh Annual Administrative Report 1989*. Oregon State University, Corvalis.

Schroeder, G. L. (1980). Fish farming in manure-loaded ponds. In R. S. V. Pullin, & Z. H. Shehadeh (Eds.), *Integrated Agriculture-Aquaculture Farming Systems* (pp. 73–86). International Center for Living Aquatic Resources Management, Manila.

Schroeder, G. L. (1987). Carbon and nitrogen budgets in manured fish pondson Israel's coastal plain. *Aquaculture*, 62, 259–279.

Schroeder, G. L., Wohlfarth, G., Alkon, A., Halevy, A. & Krueger, H. (1990). The dominance of algal based food webs in fish ponds receiving chemical fertilizers plus organic manures. *Aquaculture*, 86, 219–229.

Sekhon, G. S. & Meelu, O. P. (1994). Organic matter management in relation to crop production in stressed rainfed systems. In S. M. Virmani, J. C. Katyal, H. Eswarn, & I. P. Abrol (Eds.), *Stressed ecosystems and sustainable agriculture*. New Delhi: Oxford University Press and IBH Publishing.

Shelton, J. L. (1994). *Trout production*. University of Georgia, Cooperative Extension Service, Athens, Ga.

Shepherd, K. D., Ohlsson, E., Okalebo, J. R. & Ndufa, J. K. (1996). Potential impact of agroforestry on soil nutrient balances at the farm scale in the east African highlands. *Fertilizer Research*, 44, 87–99.

Shepherd, K. D., Ohlsson, E., Okalebo, J. R., Ndufa, J. K. & David, S. (1995). A static model of nutrient flow on mixed farms in the highlands of western Kenya to explore the possible impact of improved management. In J. M. Powell, S. Fernandez-Rivera, T. O. Williams, & C. Renard (Eds.), *Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of sub-Saharan Africa* (pp. 524–538). International Livestock Research Institute, Addis Ababa.

Shepherd, K. D. & Soule, M. J. (1998). Soil fertility management in West Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. *Agriculture, Ecosystem and Environment*, 71, 133–147.

Sloene, M. B. (1994). Feeding guide for rainbow trout and catfish in New Mexico. New Mexico cooperative extension service, Guide L – 107.

Smaling, E. M. A. & Janssen, B. H. (1993). Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices. *Geoderma*, 59, 21–44.

Smaling, E. M. A., Nandwa, S. M., Prestele, H., Roetter, R. & Muchena, F. N. (1992). Yield response of maize to fertilizers and manure under different agro - ecological conditions in Kenya. *Agriculture, Ecosystems and Environment*, 41, 241–252.

Sommer, S. G. (2001). Effect of composting on nutrient loss and nitrogen availability of cattle deep litter. *European Journal of Agronomy*, 14, 123–133.

Stoorvogel, J. J. & Smaling, E. M. A. (1990). *Assessment of soil nutrient depletion in sub-Saharan Africa: 1983 - 2000. Report 28*. DLO Winand Staring Centre for Integrated Land, Soil andWater Research (SC-DLO), Wageningen, Netherlands.

Stoorvogel, J. J., Smaling, E. M. A. & Jansen, B. H. (1993). Calculating soil nutrient balances at different scales. I. Supra-national scale. *Fertilizer Research*, 35, 227–235.

Thomas, D. B. (1988). Conservation of cropland on steep slopes in Eastern Africa. In W. C. Moldenhauer, & N. W. Hudson (Eds.), *Conservation farming on steep lands* (pp. 140–150). Soil and Water Conservation Society of America, Ankey IA.

Thomsen, I. K. (2000). C and N transformations in 15N-cross labeled solid ruminant manure during anaerobic and aerobic storage. *Bioresource Technology*, 72, 267–274.

Verstraeten, G. & Poesen, J. (2001). The importance of sediment characteristics and trap efficiency in assessing sediment yield using retention ponds. *Physics and Chemistry of the Earth*, Part B 26, 83–87.

Veverica, K., Rurangwa, E., Verheust, L., Popma, T., Seim, W. & Tubb, R. (1990). Tilapia production in Rwandan ponds is influenced by composting methods. In H. S. Egna, J. Bowman, & M. MacNamara (Eds.), *Seventh Annual Administrative Report* (p. 24). Pond Dynamics/Aquaculture CRSP, Oregon State University, Corvalis.

Vitousek, P. M., Aber, J., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., Schlesinger, W. H. & Tilman, G. D. (1997). *Human alterations of the global nitrogen cycle: Causes and consequences. Issues in Ecology 1*. Ecological Society of America, Washington DC. P. 15.

Wohlfarth, G. W. & Schroeder, G. L. (1979). Use of manure in fish farming – a review. *Agricultural Wastes*, 1, 279–299.

Woomer, P. L., Bekunda, M. A., Karanja, N. K., Moorhouse, T. & Okalembo, J. R. (1998). Agricultural resource management by small holder farmers in East Africa. *Nature and Resources*, 34, 22–33.

Wortmann, C. S. & Kaizzi, C. K. (1998). Nutrient balances and expected effects of alternative practices in farming systems of Uganda. *Agriculture, Ecosystems and Environment*, 71, 115–129.