Comparative analysis of material flows in low input carp and poultry farming: an overview of concepts and methodology

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ABSTRACT

An overview is given of existing approaches and applications to account for the flow of materials within and in association with low input farming of fish and livestock, notably of carp and poultry. Statistical methods describe or quantify the effect of environmental and management factors on fish growth and yield, and the interactions between these variables. Other methods are bioresource-flow accounting ("resource-flow diagrams"), energy and nutrient flow budgeting, mass balance modelling and dynamic simulation modeling. Some of these tools were specifically designated to assess sustainability, notably of integrated agriculture-aquaculture farming systems, others to enable a wide range of system-analytical functions and purposes.

INTRODUCTION

Common forms of low input aquaculture and livestock production systems are usually classified as "mixed" farming systems, i.e. in association with other enterprises on the same farm, usually with some degree of integration. Few types exist as "extensive/grazing" systems (zero input category). Farming operations in the "intensive" category require high levels of inputs, notably feed, electricity and/or fuel energy, capital, infrastructure, and know-how. The latter two categories of production systems, by definition, are not included within the scope of this paper, but may be studied with the described methods.

In developing countries, low input farming of carp and poultry are conducted outside the formal economy, with the major focus of the household on staple crop production and on cash crops. Livestock and fish are partly managed for home consumption, but usually are kept for cash generation. However, rural farmers often perceive these high-value enterprises in a "living cash bank" function, to be marketed in times of need of greater cash amounts (costs for medical treatment, weddings, funerals, etc.). From

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their perspective, low input rearing and maintenance of these enterprises is adequate. Therefore, many farmers in rural areas are not motivated to provide higher inputs for faster growth and shorter production cycles in quick succession (which are technically feasible given adequate resources and knowledge). Enterprise level improvements are weighed against costs at the farm level and in respect to social obligations.

Low input carp culture

Carp cultivation in low input systems in developing countries is conducted mostly in polyculture to exploit available natural food niches for higher production (Figure 1). Leading countries are China (Huang, Xu and Qiao, 2001), India (Nandeesha and Rao, 1989), Vietnam and Bangladesh (Gupta *et al.,* 1999).

Low input poultry farming

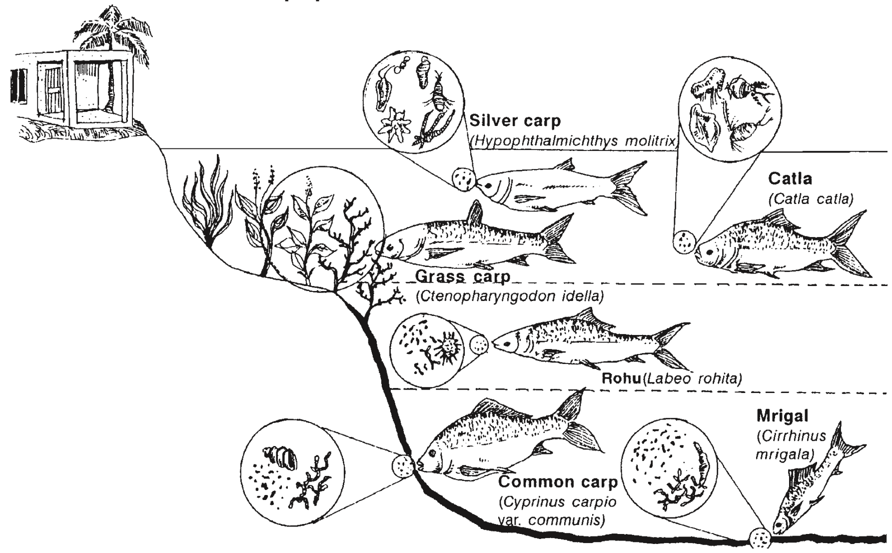
Poultry in rural smallholder farms are usually free roaming with possible night time confinement to pens. Food is usually scavenged as well as provided from the household in form of kitchen wastes or specific grain provisions. Spilling of feed around the farm homestead is common. Random manure droppings are characteristic during daytime when not confined in pens with no opportunity to collect these for recycling.

Collection of manure in pens shows that nitrogen in poultry wastes declines with the level of restricted feed given from 1.28 g N/duck/day, for birds fed ad libitum to 0.55 g N/duck/day for ducks restricted to 50 percent of *ad libitum* feeding levels (Little and Satapornvanit 1997). With higher density and numbers of farming, required feed inputs increase drastically, in the case of ducks and geese feed in-take is supplemented by flock grazing on harvested fields and open areas, if enabled by the farmers.

Integrated poultry-fish farming systems

In low input systems, carp and poultry enterprises are often linked, either vertically on the same farm, or horizontally between farms and small businesses. The main purpose of integration is the reuse and recycling of otherwise unused wastes, either on-farm or near-farm, always within affordable means of transport. Therefore in this paper, the main focus is on integrated agriculture-aquaculture (IAA) systems (Pullin and Shehadeh, 1980; Little and Muir 1987; Edwards, Pullin and Gartner, 1988; NACA

FIGURE 1
Qualitative representation of trophic niches exploited through polyculture of Chinese and Indian carp species (from IIRR and ICLARM, 1992)



1989; IIRR and ICLARM, 1992; Edwards, 1993; Little, 1995; Edwards *et al.,* 1996; Mathias, Charles and Hu, 1998; FAO, 2000; FAO, IIRR and ICLARM, 2001; IIRR *et al.,* 2001; Edwards, Little and Demaine, 2002; Little and Edwards, 2003).

The pivotal role of farm ponds as a nodal nutrient storage point, digester of organic material and sediment trap has a long history (Pullin and Prein, 1995). The beneficial function of IAA in Natural Resource Management (NRM) through benign nutrient use and reduced environmental impact was conceived as an additional reason for its promotion in the context of rural development. The rationale was to minimize the effects of necessary production increases through land use intensification for agriculture based development (Lightfoot, Pingali and Harrington, 1993; Pullin, Rosenthal and Maclean, 1993; Pullin, 1998).

These systems increase the overall food production of a given farm, and can replenish nutrient fertility in depleted crop fields to where nutrients are recycled back from the pond, compost and manure pits, thereby decelerating the rate of productivity decline observed in many farming areas, notably in Africa. However, IAA systems are labor demanding for the transport of these material flows to the sites to be fertilized. Therefore, mainly homestead gardens, inner crop fields and homestead ponds are recipients of recycled materials, while outer crop fields and remotely located ponds do not receive nutrient inputs due to the high labor requirement.

To date, the expansion and adoption of IAA has been most successful in Asia, mainly based on a combination of carp polyculture receiving poultry manures, as well as other wastes and inputs such as pig manure, grains and grasses; increasing in recent years has been the addition of formulated feeds (Little and Edwards, 2003; Prein, 2002),

Environmental effects of low-input livestock-fish systems, particularly in manure fed ponds are usually very low due to the usually small scale on actual smallholder farms, the low intensity and high diversity, the high level of recycling of nutrients within the system, as well as the high contribution of primary production to overall system productivity (Little and Edwards, 2003; Kwei Lin *et al.,* 1997; Edwards, 1993; Colman and Edwards, 1987). On the contrary, integrated farming with manure utilization is deemed to have less environmental impact than non-integrated farms (Lightfoot and Pullin, 1995).

Rice-fish

Concurrent fish-in-rice paddy culture is based on a long tradition in Asia, mainly stocking carp species and animal manures as inputs (Lu and Li, 2006; Halwart and Gupta, 2004; FAO, IIRR and ICLARM, 2001; Liu and Cai, 1998; Halwart, 1998; Gupta *et al.,* 1998; Cagauan, 1995; dela Cruz, 1994; dela Cruz, 1992). The system has to operate under a balanced management between the rice and fish components with respective requirements, and economic conditions: e.g. scheduling and quantity of inorganic fertilizer dosage is reduced and specifically tuned to avoid effects on fish; pesticide use is excluded; water management is arranged for adequate water heights (which also assists in weed suppression) and flood duration after the rice crop is harvested (to achieve a longer fish culture period, and to benefit from remaining food sources in the field.)

Alternating rice-fish culture, i.e. rotating high yielding rice culture in the dry season (often with irrigation) and fish culture (during the annual flood season) is spreading in river floodplain areas of annual rice field inundation, such as in south and southeast Asia (Dey and Prein, 2005; Dey, and Prein, 2005; Prein and Dey, 2006). Carp-dominated polycultures thrive together with naturally occurring small species behind larger fence-enclosed floodplain areas managed by communities. Usually no nutrients are applied as the system benefits from residual nutrients in the fields from the preceding rice cultivation cycle, as well as from new nutrients brought in by the river's floodwaters. It has been observed that rice farmers reduced their fertilizer applications in these systems. Occasionally, rice bran is fed to the fish in the final weeks before harvest when waters have receded and fish have aggregated in a smaller area of the enclosed floodplain.

Sewage-fed and biogas slurry-fed systems

Wastewaters from biogas production and sewage are also considered low-input systems growing mainly carp species, often in polyculture (Edwards, 1985, 1992; Edwards and Pullin, 1990; Prein, 1990; Mukherjee, M. 2003; Preston, 2005). These systems were established to utilize nutrients that would otherwise be released into the environment, untreated, and therefore have an improving effect on the environment.

OVERVIEW OF METHODS FOR COMPARISON OF MATERIAL FLUXES IN IAA SYSTEMS

A range of tools exist that have been applied for the assessment of effects of low-input aquaculture systems on the environment, either within the ponds themselves, or the natural environment external to the ponds.

Statistical analyses

Cause-and effect relationships resulting from material inputs (aside from other inputs) have been conducted on low-input integrated carp polyculture systems, such as analysis of variance, multiple regression, path analysis, canonical correlation analysis, principal component analysis and factor analysis (Milstein, Wahab and Rahman, 2002; Milstein *et al.*, 2003; Prein, Hulata and Pauly, 1993). Analyses essentially considered inorganic and organic fertilization dosage and fish crowding effects from the fish production activity within the ponds. Some statistical methods can also have graphical representations of results, such as for path analysis (Figure 2) and canonical correlation analysis (Figure 3), which assist in interpretation and visualization of the studied

FIGURE 2

Path diagram of nine variables controlling fish growth in length (L-GRO) with interactions between environmental (uncontrollable) variables RAD (solar radiation), WIND (wind speed), CLOUD (cloud cover), WATEM (water temperature) and management (controllable) variables MANU (manure loading rate), OXY (early morning dissolved oxygen), POND (pond size), DENS (fish stocking density), ML (mean length of fish) in experiments in the Philippines. Straight lined one-headed arrows denote direct causal effects where numbers on these arrows are standardized regression coefficients describing the amount of variation in the predicted (dependent) variable explained by the predictor (independent) variable. Curved two-headed arrows represent correlations between two independent variables and numbers on these are correlation coefficients (r^2) between them. See Prein (1993) for detailed descriptions. More explanation needed on the figures

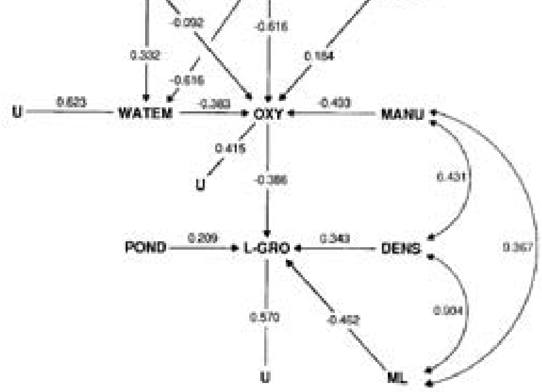
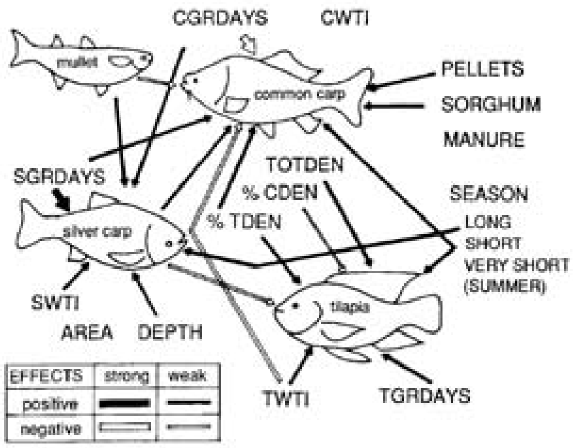


FIGURE 3

Relationships affecting fish growth as graphical representation of results from canonical correlation analyses of commercial carp polyculture farms in Israel, with positive and negative effects of environmental and management variables, as well as between-species interactions (from Milstein & Hulata 1993). Species: common carp (*Cyprinus carpio*), silver carp (*Hypophthalmichthys molitrix*), tilapia (Israeli strain hybrid of *Oreochromis niloticus x O. aureus*), grey mullet (*Mugil* sp.). CGRDAYS = common carp culture period (days), CWTI = common carp initial stocking weight, SGRDAYS = silver carp culture period (days), SWTI = silver carp initial stocking weight, AREA = pond area, DEPTH = average pond depth, TOTDEN = total stocking density of polyculture, CDEN = common carp stocking density, tilapia stocking density, PELLETS = cumulative total of pellet weight fed, SORGHUM = amount of sorghum fed, MANURE = amount of chicken manure added to pond as fertilizer, SEASON = duration of culture period, ranging from March until November



relationships and interactions between independent and dependent variables. These methods have been chiefly applied to analyses of growth and production as a result of environmental and management factors within the production systems themselves.

Budget analysis / material flows analysis

Budget analyses of Chinese integrated agriculture-aquaculture systems focusing on the operational enterprises were conducted by Ruddle and Zhong (1989); Zhong (1995) and Zhong, Wang and Wu (1997). Pond production is driven by plant residues (grass, vegetable leaves), animal manure (silkworm droppings, pig manure), grains and formulated fish feeds. A large area around the ponds is required to grow mulberry leaves to feed the silkworms. Most nutrients added to the pond end up in the pond mud as detritus, and are recycled to the dikes for fertilization of the mulberry bushes, elephant grass and vegetables, requiring considerable amounts of labor and energy, yet leading to high rates of nutrient use efficiency. Losses to the environment are minimal.

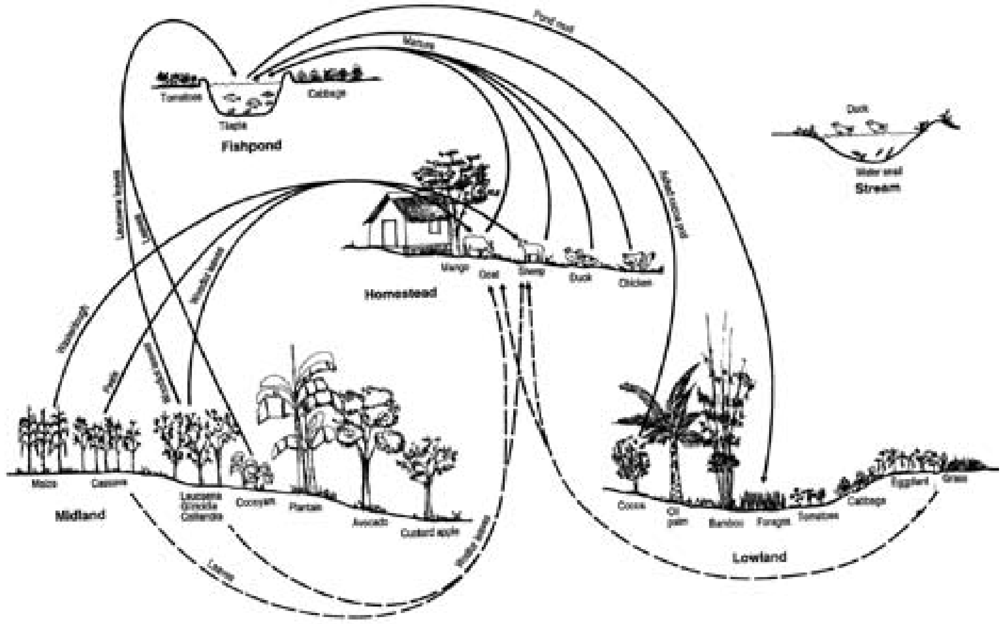
Material flow analysis based on nitrogen flows was conducted to study environmental sanitation aspects of the VAC integrated system in Vietnam which consist of three main agricultural production components: food gardening, fish rearing and animal husbandry (Montangero and Thai, 2005). Domestic sewage is utilized for manuring of crops and ponds, however the majority of nutrient inputs stems from mineral fertilizers. The study found that 80percent of the nitrogen reaching the households as food is released to the farm components as nutrients and to the off-farm environment resulting in pollution.

Resource flow diagrams (RFD)

This method was originally designed (Noble, Lightfoot and Bage, 1991; Lightfoot, Noble and Morales, 1991; Lightfoot *et al.*, 1993c) as a pictorial tool for farmer participatory diagnosis and planning of changes (e.g. new recycling flows between

FIGURE 4

Resource flow diagram of IAA farm in Ghana, before (hatched arrows) and after (solid line arrows) integration of a fish pond. Not increase in recycling flows including use of livestock manure and plant wastes as input to fish pond, but also recycling of nutrients in pond mud to crops



existing enterprises) and new technology adoption by the farmer (e.g. new enterprises, such as fish culture in rice fields or ponds, enabling additional flows). Subsequently, the tool has become an integral component of a farmer participatory whole-farm diagnosis, intervention planning, monitoring and evaluation procedure named RESTORE (see below, and Lightfoot, Noble and Morales, 1991; Lightfoot, Prein and Lopez, 1994; Lightfoot, Prein and Ofori, 1996).

The RFDs focus on *internal flows,* i.e. of on-farm nutrients from wastes and byproducts and auto-consumed products (Figure 4). In previous applications, *external inflows* (i.e. near-farm as well as from further away, such as in the case of inorganic fertilizers) and *external outflows* (i.e. products for sale as well as discharged wastes that leave the managed farm area to markets or through streams or into ground water) were not considered within the concept. However, in the course of varied applications it was found that tracking and accounting for these flows was vital for the understanding and budgeting of whole farm nutrient flows (see below).

The utility of relatively simple resource flow diagrams (RFDs) as an approximation to farm-level material flow analysis is established from applictions to mixed farming systems studied in a research-for-development context in Asia (Lightfoot *et al.,* 1993a, 1993c; Prein *et al.,* 1999, 2002) and Africa (Lightfoot and Noble, 1993; Ofori and Prein, 1996).

Whole farm natural resource management, monitoring and evaluation tool

Low input carp and poultry farming are usually one of several components of mixed farms, and even occur together on the same farm. Therefore, given the diversity, complexity and variability of mixed farms in developing countries, their assessment as discrete components in partial analyses is not useful when the purpose is to assess their utility in enhancing the livelihood of farm households when all other household resources (including land and labor) need to be considered together. Consequently, a whole farm analysis (and material budgeting) was developed as a tool package to enable comparative analyses between farms, and over time (Lightfoot *et al.,* 1993a, 1993b; Lightfoot and Pullin, 1995).

RESTORE (Research Tool for Natural Resource Management, Monitoring and Evaluation) is a whole-farm monitoring and evaluation tool for assessing all on-farm and off-arm natural resources accessed and utilized by a particular household, and for measuring and economically valuing material flows in terms of biomass (Lightfoot, 1993a, 1993b; Lightfoot and Noble, 1993). It consists of a specifically compiled package of farmer participatory field-based appraisal and data collection techniques, as well as an analytical software package (Lightfoot *et al.*, 1996). The outputs of the software analyses are financial budgets for the whole-farm as well as its management sub-units (termed 'natural resource types') and sustainability indicators (see below).

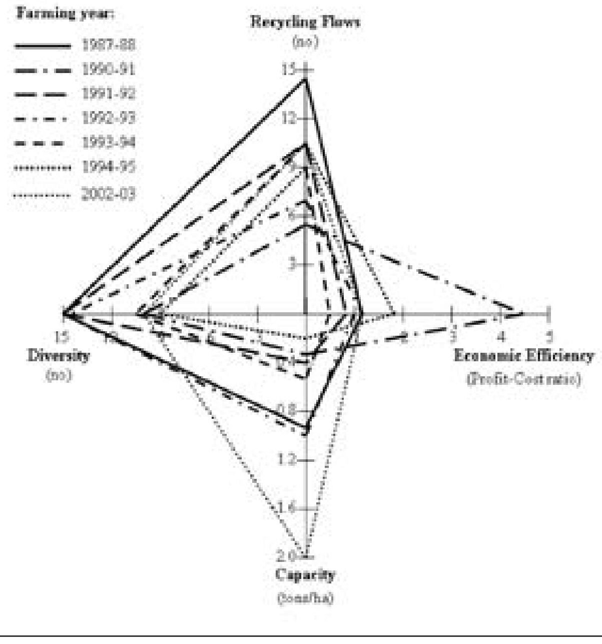
As a first step, *a priori* assessments (usually on an annual basis) of a range of farms are made before an intervention occurs (e.g. adoption of aquaculture or a major technological improvement to existing enterprises). Subsequently, these farms are monitored over a few years in the same manner and analyzed with the same protocols, enabling the impact assessment of the intervention over time, usually in annual steps. The above mentioned RFDs likewise are one contributing component of the analyses. The approach includes the derivation of sustainability indicators (see below) which enable comparisons across farms and over time.

Sustainability indicators

The indicators are (Lightfoot *et al.*, 1996): 1) *Diversity*: number of enterprises, approximating stocks; 2) *Recycling:* number of actively managed material flows, including a material description (quality); origin/source and target enterprise/flow direction; biomass (usually in kg); frequency of flow; value of material flow; 3) *Capacity:* total biomass of material products from the farm (usually in t/ha); 4) *Economic efficiency*: profit-cost ratio (approximating "outputs vs. inputs"). These effects can be displayed in sustainability indicator diagrams (see Figure 5).

FIGURE 5

Diagram of sustainability indicators for IAA farm in Malawi over seven production years showing effect of variations in environmental (e.g. drought in 1994-1995) and managerial factors (diversity in farm enterprises, recycling flows in number and volume), in response to market opportunities, leading to inter-annual variability in economic performance (data from D. Jamu, pers. comm.; see Dey *et al.* 2006, 2007 for details). "no" = number of species (diversity) or number of managed nutrient flows (recycling)



The approaches focus only on the farms themselves within their agroecological and socioeconomic context, and mainly measure the ability of the farm with its enterprises to provide food and income. However, the measurement of the maintenance of an acceptable environment is an inductive process of the application of the tools over time, namely under the assumption that overall production and component productivities should only reduce over a multi-year trend if the environment is negatively affected. Here other additional assessments are necessary, i.e. of additional parameters on the farm and of impacts beyond the farm (e.g. nutrients, agrochemicals and water quality and quantity).

Negative effects of farm management on the environment are considered to lead to negative feedback on farm productivity and, with monitoring over time, be detectable in a farm's sustainability indicators (Lightfoot *et al.,* 1996; Bimbao and Prein, 1999).

Steady state models of trophic flows: ECOPATH

For analyses at the ecosystem level, and applying a steady state assumption, a modeling software tool is now widely used to study trophic relationships based on material flows between the main component groups of an ecosystem's food web, and to derive comparative indicators that characterize key attributes of the ecosystem (Christensen and Pauly 1993, see also www.ecopath.org). The 'internal currency' of the approach is commonly nitrogen content of the components' biomasses and material flows, but also energy content and other nutrients have been used.

ECOPATH analyses of low-input IAA systems

Chinese integrated farms based on carp polyculture systems were modeled with ECOPATH by Ruddle and Christensen (1993) (Figure 6). Tilapia polyculture systems on smallholder farms in Malawi were modeled by van Dam *et al.* (1993).

ECOPATH analyses of rice-fish systems

Nutrient flow models using ECOPATH on fish-in-rice paddy culture were established for irrigated systems in the Philippines (Dalsgaard, 1995, 1997; Dalsgaard and Oficial, 1995, 1997, 1998; Dalsgaard and Christensen, 1997; Dalsgaard, Lightfoot and Christensen, 1995; Dalsgaard and Prein, 1999; van Dam, Lopez and Prein, 2002). These all concluded that nitrogen flows are higher in IAA systems compared to non-IAA farming (Figure 7).

FIGURE 6

Quantified material flows resulting from ECOPATH analysis of low-input integrated systems in China, with carp polyculture receiving pig manure, silk worm dung, elephant grass and vegetable leaves aside from commercial feed as inputs. Note that greatest biomass results in detritus deposits in pond bottom (from Ruddle and Chistensen, 1993). Numbers on flow arrows and in tabular listing are in tons/ha/y

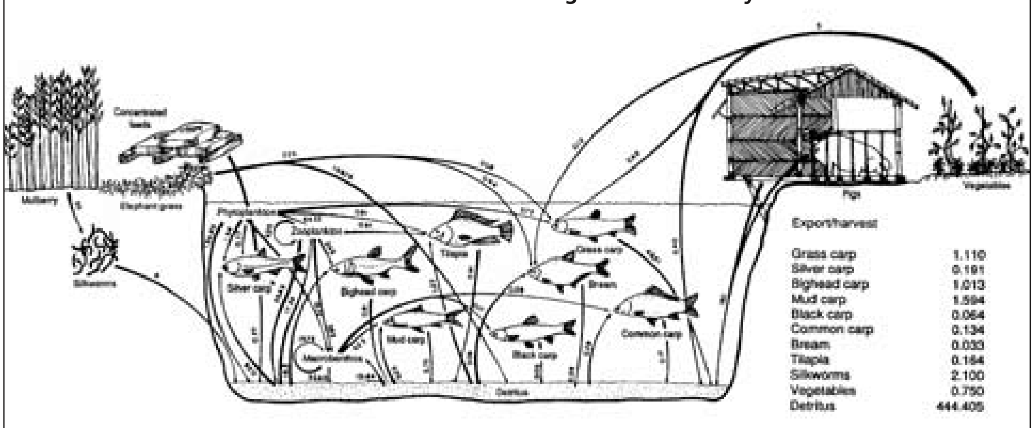
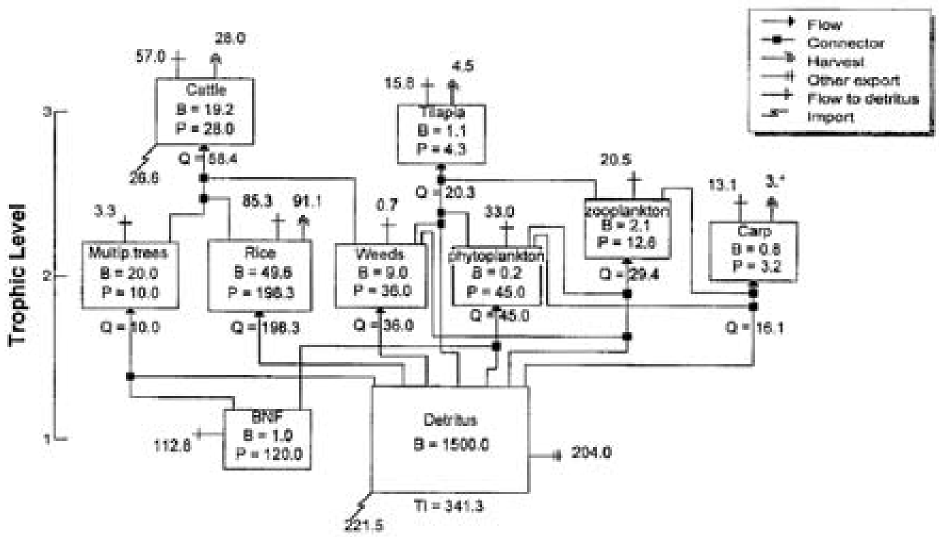


FIGURE 7
ECOPATH diagram of nitrogen flows arranged in trophic levels (ordinate) of hypothetical rice-based IAA farming system in the Philippines. Values in kgN/ha/y on 1ha total area (from Dalsgaard and Prein 1999). B = biomass, P = production



Dynamic simulation models

Zweig (1992) established ecological-economic dynamic simulation models for the design and analysis of IAA systems, leading to reliably predicted estimates of nutrient flows in Chinese integrated systems. A dynamic model for the simulation of yields, nutrient cycling and resource flows on Philippine small-scale farming systems (FARMSIM) was developed by Schaber (1997). Nutrient flow efficiency in ponds based on nitrogen flows on Malawian integrated farms were developed by Jamu and Piedrahita (2002a, 2002b).

The most widely known simulation software for pond aquaculture systems is the POND software tool (Bolte and Nath, http://biosys.bre.orst.edu/pond/pond.htm). POND is a computer program that has been developed to guide decision making processes relevant to warm-water pond aquaculture systems, intended to function as decision support systems. POND was written to provide educators, extension agents, managers, planners and researchers with a tool for rapidly analyzing aquaculture systems under different management regimes, and to assist in the development of optimal management strategies, including nutrient inputs and flows. POND can simulate input and output processes but with a focus on the pond environment.

Environmental costs associated with low input carp and poultry farming

Nutrient outputs to the environment from low input carp and poultry farming are generally low (Table 1). Water use is essentially non-consumptive and losses involve evaporation and seepage from the pond. Nitrogen, phosphorus and potassium are retained and accumulated in fish and in pond sediments. Impacts from nutrient losses are from leaching to the groundwater below the pond through leaky pond bottoms and during water discharge for draining, in which sediment particles and nutrients are released.

Other inputs are occasional vitamin mixes and antibiotics, now seen on many smallholder farms in developing countries. Poultry chicks may be vaccinated. Agrochemicals such as herbicides, pesticides, hormones, and other growth promoters are not used, or are minimized in low-input carp-poultry systems. Not considered here are factors such as solar radiation and evaporative transpiration of water.

TABLE 1
Types of material flows (carriers of N, P, K, organic carbon, or energy) in low input carp and poultry farming systems

Inflows	Amount	Outflows	Amount
Water: rainfed, irrigation	++	Evaporation, seepage, draining	++
Fertilizer, organic	++	Excreta from fish, poultry	+
Fertilizer, inorganic	+	Detritus from pond bottom (draining, removal for recycling)	++
Feed, plant residues	+	Seepage to sediments and groundwater	++
N-fixation	++	Volatilization	+
Off-farm manure sources	+	(recycling)	
Fingerlings / chicks	+	Eggs; consumable / marketable fish, birds; feathers; bones	+

DISCUSSION

In general, low input carp and poultry systems are semi-intensive operations with diversification of enterprises enabling integration, greater resource use efficiency, and higher profits to farmers (Bosma *et al.,* 2005). In rice-fish systems based on low input carp culture organic matter, total nitrogen and phosphorus content of the rice field soil increase by 15.6 to 38.5 percent (Lu and Li, 2006). Nitrogen and organic carbon in ponds accumulate when these are fertilized with higher amounts of pig manure than in ponds with low amounts of manure (Nhan *et al.,* 2005), i.e. added manure is stored in the pond, not lost to the environment. Nitrogen and phosphorus accumulation is higher in manure-fed pond systems, with losses to the environment higher when formulated feed is given to the same carp polyculture system (Rahman, 2005).

In general, there is a wide portfolio of powerful methods for analysis of material flows in low input IAA systems. However, with increasing analytical performance these methods require detailed, regularly collected data which are sometimes very tedious and costly to collect. Some methods permit the use of proxies (e.g. ECOPATH) as first approximations. Although the general understanding is that IAA systems are more beneficial environmentally than existing monoculture systems (e.g. IAA systems recycle nutrients internally 4-20 times more than monoculture systems, Dalsgaard and Oficial 1997, 1998; Dalsgaard and Prein 1999), the increasing diversity of IAA systems and their establishment in new farming systems and environments (e.g. Africa, Latin America, the Pacific, parts of Asia) requires that these coming developments be comparatively studied with standardized methods such as those outlined above.

ACKNOWLEDGEMENTS

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