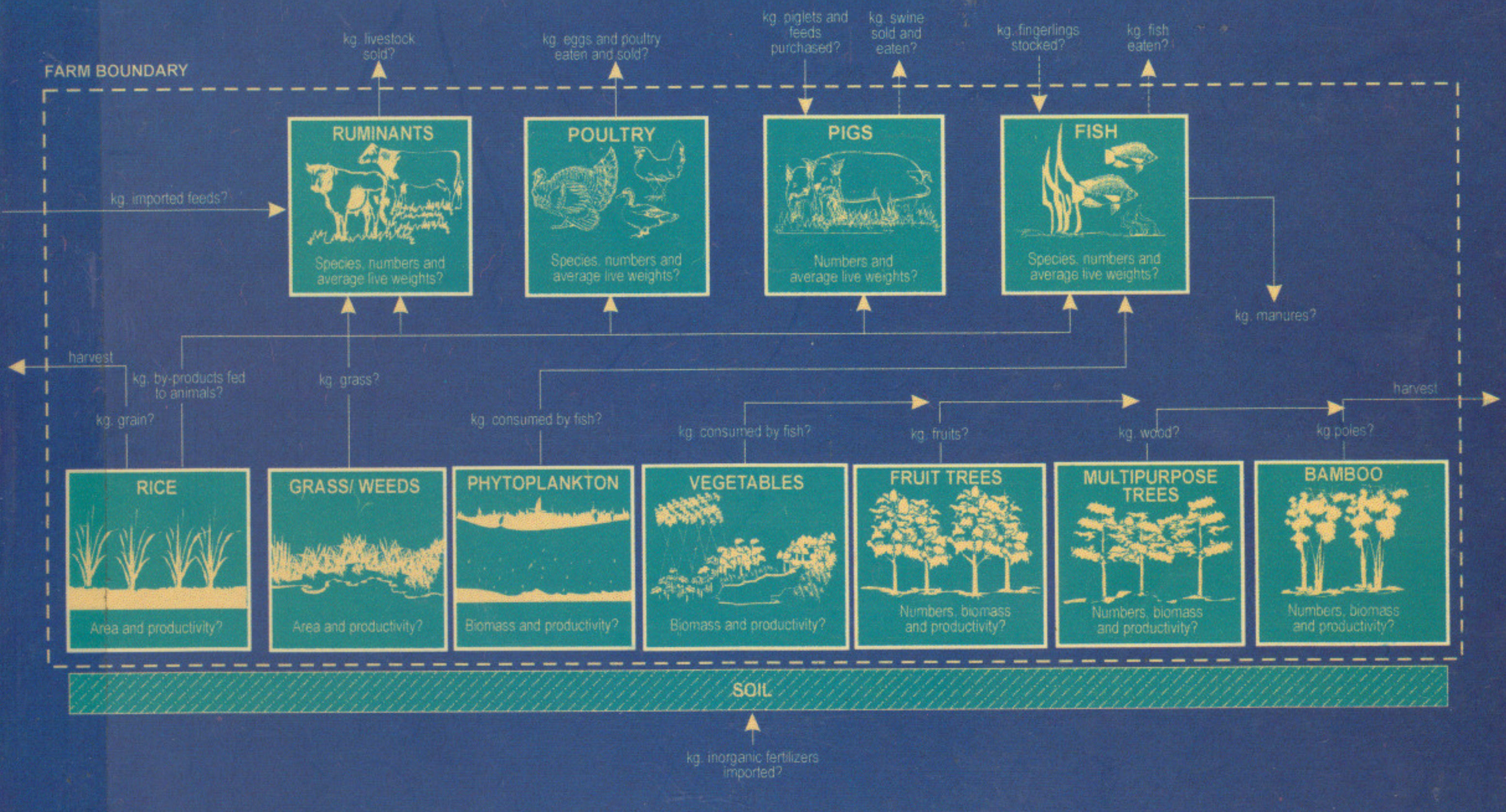
Modeling and Analyzing the Agroecological Performance of Farms with ECOPATH



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ICLARM
International Center for Living Aquatic Resources Management

Danida

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Foreword

Intensive and integrated resource management, where field crops, vegetables, trees, livestock and fish production are combined through efficient (re)use of wastes, residues, by-products and external inputs, offers a potential avenue towards a productive and ecologically balanced agriculture. Countless smallholder agriculture-aquaculture farms are found throughout Asia, Africa and South America. They include traditional systems which are centuries old, as well as new emerging systems designed by innovative farmers both with and without support from formal research and extension and modern technology.

Over several years the Integrated Aquaculture-Agriculture Systems Program of ICLARM has been conducting research on integrated resource management within farm communities in collaboration with National Agricultural Research Systems (NARS) in Asia and Africa, thereby fruitfully combining formal and informal knowledge systems.

An important output of this ongoing work is new research concepts, approaches and methodologies. This report details one such output. It is a result of the cross-fertilization that occurs when different disciplines–here farming systems research and aquatic ecosystem modeling–merge and explore new borders. The ECOPATH model software, developed within ICLARM's Fisheries Resources Assessment and Management Program, has provided important insights into the structure and function of global aquatic ecosystems. The application of the same concept and approach to terrestrial based culture systems exemplifies a tool which has the potential to improve communication and productivity within research by unifying fields as disparate as fisheries science, aquaculture, agroecology and farming systems research, while addressing the issue of sustainable natural resources management in a quantitative manner.

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Abstract

Understanding sustainable agriculture requires the application of quantitative and qualitative methods to determine the performance of agricultural systems. This report presents a pragmatic framework for monitoring, modeling, analyzing and evaluating the ecological characteristics of farms. Taking a natural resources management approach and applying mainstream descriptors from systems ecology, the report investigates the aggregate ecological properties of the whole farm agroecosystem including crops, trees, livestock, and fish. Productivity, efficiency, nutrient cycling, biomass, nutrient throughput, production/ biomass, biomass/throughput, species richness, agricultural diversity, nutrient balance and ecosystem goal functions (system overhead, ascendency, and exergy) form a preliminary list of quantifiable and measurable performance indicators.

The analytical framework is organized around the Windows-based ECOPATH software package. Developed to model and evaluate the state of aquatic ecosystems, ECOPATH is now also being applied to agroecological systems. A case study of a smallholder rice farm illustrates: the monitoring of agricultural activities and collection of field data in collaboration with farm households; the computation of the parameter sets required to build an ECOPATH mass-balance model, with nitrogen as the model currency; and the data entry and output routines used in the agroecosystem analysis and evaluation. A comparison of two farm scenarios further demonstrates the utility of the approach in assessing the performance of different farming strategies. The proposed framework can assist in the development and implementation of a healthy and sustainable agriculture. This report also serves as an introductory field guide and ECOPATH software manual for agriculture scientists.

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CHAPTER 1

Introduction

1.1 Ecologically Sound and Productive Farming

There is a widespread, ongoing search for a sustainable agriculture[1] (Douglass 1984; Conway 1985a; Gliessman 1990; Harrington 1991; Munasinghe and Shearer 1995). Both low-external-input farming on marginal lands and high-external-input farming on prime lands can lead to widespread natural resource degradation (Reijntjes et al. 1992; Kessler and Moolhuijzen 1994; Pretty 1995). Alongside a demand for environmentally sound farming goes the need for analytical methods of impact and performance assessment. We have ideas and opinions on what constitutes good natural resource management. However, we still lack quantitative methods to help verify these perceptions and operationalize sustainable farming.

It is not feasible to attempt to measure, model and document all components and processes within an agricultural system. Its complexities — ecological, economic, and social — are overwhelming. Yet we need not understand every detail about a complex organic system to gauge its state and measure its performance. Aggregate system properties are being used to describe the evolution, development, health, and integrity of natural ecosystems (Odum 1969, 1971; Ulanowicz 1986; Constanza et al. 1992; Jørgensen 1992; Woodley et al. 1993; Kay and Schneider 1994; Nielsen 1994). Applying ecosystem concepts and performance indicators to agroecosystems presents an opportunity for assessing their ecological state quantitatively and systematically.

The evaluation of (smallholder) farms on which crops and animals combine to form an operational unit can benefit from a systems perspective. Measuring, for instance, the appropriateness of aquaculture technology often requires that the entire farm system, both internally and within the context of the local market, be evaluated to ensure that the proposed solutions address the real situation (Brummett and Noble 1995). A farmpond rarely operates as a stand-alone enterprise serving only a single purpose. Fish is just one of several potential outputs and services. Other important pond functions may include: a source of water and nutrient enriched mud for vegetable cultivation; a production site for edible aquatic weeds; a reservoir for livestock watering; a refuge and feeding ground for poultry; and a productive sink and disposal site for farm wastes. Just as ponds are integrated into the surrounding agroecological system, so are many other enterprises including crops, trees and livestock.

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[1] Here the term agriculture covers natural resource management systems which are crop- and livestock-based, but may contain aquaculture and forestry components, as is the case on many smallholder farms.

1.2 Understanding Agroecological Systems

Analyses of agricultural ecosystems (Lowrance et al. 1984), agroecosystems (Douglass 1984; Conway 1985a, 1985b, 1987, 1991) and agroecological systems (Altieri et al. 1984; Gliessman 1990, 1992; Altieri 1995) in the broad sense address biological, economic, and social issues. Agroecology, in the narrow sense adopted in this report, focuses on the system's biophysical and ecological performance.

The systems perspective gained momentum during the 1970s-1980s with the emergence of cropping systems research (Trenbath 1974; Willey 1981; Zandstra et al. 1981; Francis 1986) and farming systems research (Spedding 1979; Shaner et al. 1982; Norman and Collinson 1985; Biggs 1995). The perception of the farm was gradually broadened from that of a unit of individual, independent enterprises to one of farms as sites of multiple, interdependent biophysical, economic and social components. Research and researchers moved closer to farms and farmers, initiating a change in the view of the farming community from a passive receptor of technology and formalized knowledge to an indispensable partner in research, extension, and development (Rhoades and Booth 1982; Chambers et al. 1989; Scoones and Thompson 1994). As a result, traditional and emerging, diverse, integrated crop-animal-tree farms are now receiving more attention when issues of productive performance and environmental impact are being addressed (Gliessman et al. 1981; Gliessman 1982; Ruddle and Zhong 1983; Nair 1984; Yan and Yao 1989; Soemarwoto and Conway 1991; Edwards 1993; Guo and Bradshaw 1993; Lightfoot et al. 1993a, 1993b; and Brummett and Noble 1995).

The recognition that the productive performance of mixed crops may be superior to monocrop cultivation helped give concrete evidence and justification for systems-oriented research. Complementarity was demonstrated on-station in mixed crops with land equivalent ratios greater than one, i.e., two or more crops produce a higher overall yield when grown together rather than separately on the same land area. Overyielding (Cox 1984) and synergy, became terms associated with interactions of plants-plants or plants-animals in polycultures on which farmers could capitalize. Integrated rice-fish farming (Capistrano-Doren and Luna 1992; Dela Cruz et al. 1992) provides a classic example of potential synergistic biological interactions. The system produces not only two different outputs, but is generally thought to improve the performance of the rice crop through a variety of mechanisms: some fish feed on harmful insects or snails and serve as biological pest controllers thus reducing the need for biocides; other bottom-feeding fish species stir up the mud, an activity thought to release additional nutrients for plant growth; some fish feed on aquatic macrophytes, i.e., on weeds that otherwise compete with the rice crop, and; the presence of fish usually leads to a general improvement in ricefield water management.

With polyculture systems, however, hard evidence to verify whether they are superior to more simplified systems has generally been lacking. Many integrated farming systems have evolved over extensive periods of time and are not (easily) amenable to replication, mapping, analysis and testing under controlled conditions. Quantitative research is not that straightforward when it comes to complex, polyculture farming.

1.3 Modeling with ECOPATH

One way to gain insights into the state and performance of agricultural systems is to model them as systems (Van Dyne and Abramsky 1975; Rykiel 1984; Jørgensen 1994). Systems modeling and analysis are not a panacea for fragmented and inadequate understanding or for inappropriate management of biological systems, but offer an important and useful complement to the more traditional scientific approach.

The ECOPATH software package (Christensen and Pauly 1992a, 1992b, 1993, 1995; Jørgensen 1994; Pauly and Christensen 1995) was developed for aquatic ecosystems modeling and quantitative trophic network analysis. It is now also finding use in the modeling and performance assessment of agricultural systems.

Based on a system of coupled linear equations and the principles of mass balance and mass conservation, the software calculates a range of summary statistics used to evaluate the state and performance of an (agro)ecosystem. Quantified properties include such attributes as system productivity (yield), efficiency, biomass, throughput, and cycling. These attributes allow us to put numbers on the ecological characteristics of a given system. Once we have the numbers we have the starting point for quantitative analyses and comparative performance evaluations. Examples of the application of ECOPATH to field and farm level agroecosystems can be found in Cagauan et al. (1993), Lightfoot et al. (1993c), Ruddle and Christensen (1993), Van Dam et al. (1993), Dalsgaard (1995), Dalsgaard et al. (1995), Dalsgaard and Oficial (1995), Dalsgaard (1997), Dalsgaard and Christensen (1997), and Dalsgaard and Oficial (1997). The approach helps us probe into issues like: is integrated nutrient management and a high recycling index synonymous with a low(ered) system productivity; can one maintain a high standing biomass to buffer the agroecosystem and a high net productivity at the same time; is mimicking the properties of natural ecosystems in the pursuit of an ecologically healthy agriculture incompatible with extractive farming and high yields; what are the trade-offs between sound ecology and other objectives such as productivity; and do there have to be trade-offs?

The data inputs into an ECOPATH model are simple. What is required is a balanced system model of boxes and arrows (Fig. 1.1). Boxes represent stocks, including soil, crops, vegetables, trees, livestock and fish. Arrows signify biomaterials flowing into, out of and between boxes. A model must be balanced in that all component stocks, stock changes, inputs and outputs must be accounted for. Stocks and flows can be quantified and expressed in either energy or nutrient terms.

Information on the parameters shown in Fig. 1.1 is not sufficient by itself to permit the construction of complete nutrient balance models. In the case of nitrogen (N), which is the model currency used in the smallholder rice farm example presented in the following chapters, it enters and leaves the farm through a range of processes and mechanisms. Feeds and fertilizers, dry and wet deposition, sedimentation, irrigation water and various forms of biological nitrogen (N_2) fixation, all represent potential input sources. Rice wetlands constitute a very suitable environment for the growth of all groups of N_2 fixing organisms (Roger and Ladha 1992; Ladha and

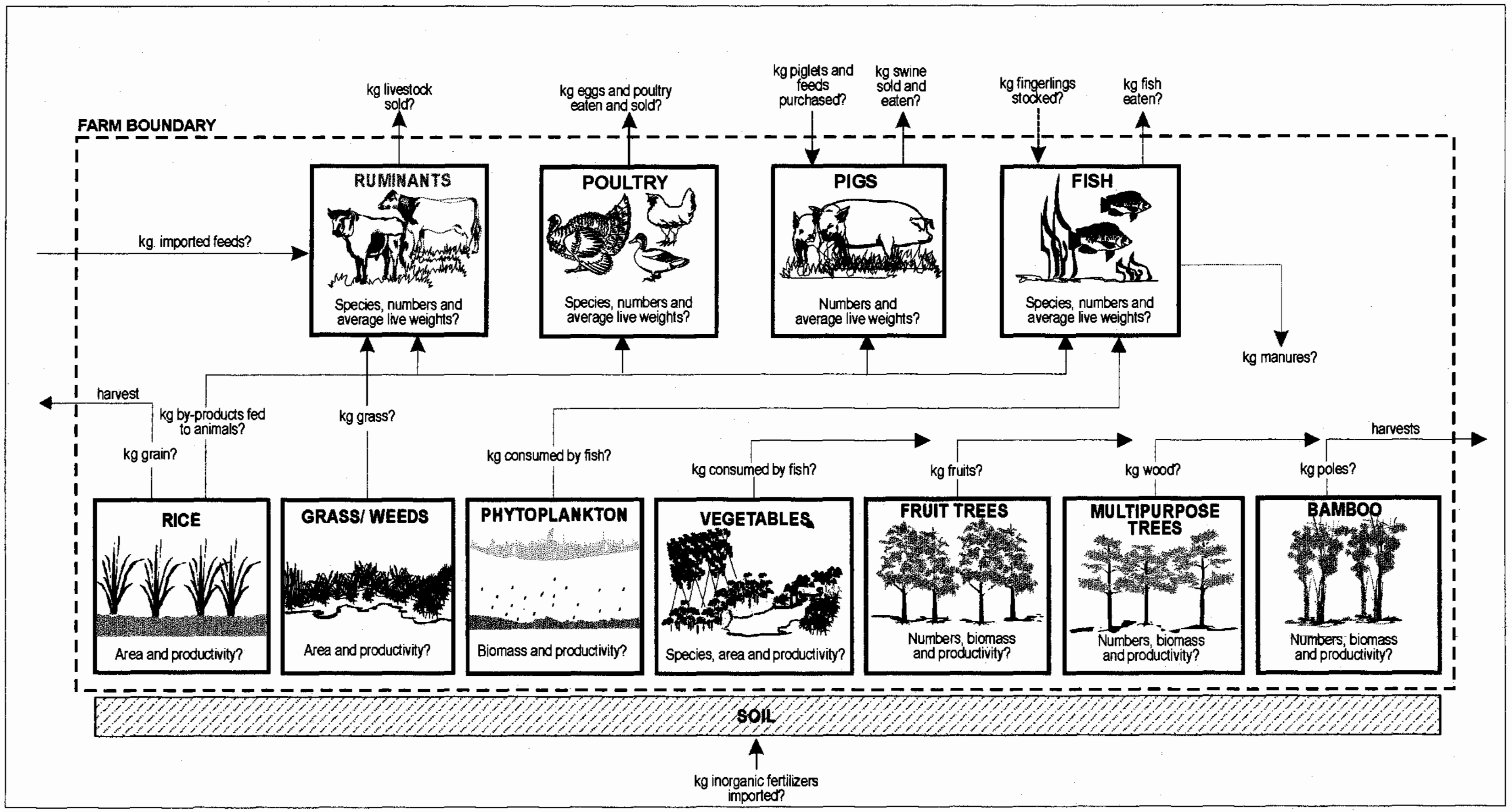

Fig. 1.1. A conceptual stocks and flows model of the case study farm.

Peoples 1995), which is one of the reasons that rice wetlands are so productive. Harvests, leaching, drainage, volatilization, denitrification, run-off and erosion all represent pathways of possible N loss. Accurate data on feed and fertilizer inputs and harvested outputs can be obtained via farm record keeping, whereas most of the natural fluxes are difficult to quantify.

1.4 Practical and Conceptual Model Constraints

Putting numbers on the boxes and flows within a farm agroecosystem is not always straightforward. The smallholder farm environment is not uniform, predictable or controllable. It varies in terms of climate, resource endowments and management, i.e., in terms of all major forcing functions. Smallholder farms are (surprisingly) diverse, complex and heterogeneous.

This makes it difficult to operate in a rigid research mode and adhere to systematic monitoring and sampling schemes. We (scientists) are trained to think in terms of rigid experimental designs and setups, with treatments and replicates, and comparative plant and animal performance evaluations based on statistical analyses and criteria of significance. Observing and interpreting what happens in a complex system, *in situ*, where the farmer and not the researcher is the experimenter, requires a different approach. Where established monitoring, recording, interviewing, assessment and sampling techniques exist, these should be applied. Often data collection schemes have to be improvized in cooperation with the farm household. Imagine arriving at a farm ready to sample and collect, only to find that the main crop has already been harvested prematurely due to labor (un)availability or an impending pest attack; that free-ranging animals have grazed the plots which had been identified for monitoring plant growth; that the trees selected for biomass assessments fell in the last typhoon; or that most of the newly stocked fish escaped into an irrigation canal during a heavy overnight downpour and pond overflow. Enterprises succeed or fail for one unexpected reason or another and activity schedules and farm management plans are sometimes literally changed overnight.

The Socioeconomic Dimensions of Agroecosystems

The ecological analysis presented here can only provide a partial assessment of an agroecosystem. Economic, social and political aspects are equally important for a comprehensive and complete performance and sustainability evaluation, but are not covered in this report. Very often the crucial question is not which practices are sustainable, but rather which conditions cause people to conserve their resources and which conditions favor destruction or overexploitation (Brookfield and Padoch 1994). It is our experience that, when conditions permit, farmers are concerned with both the productive performance and the well-being of the farm's resource base and see the two as being closely linked. For all practical purposes, an ecological assessment is thus a useful starting point for addressing the concept of agricultural sustainability.

The Farm Perspective

The individual household or farm, although generally identified as a preferred unit of analysis, has its limitations. Demarcating a farm is not easy where physical boundaries shift, as when open access and common property resources are (periodically) utilized. The comfortable idea of a fixed assembly of resources being managed by a household unit often does not apply in reality.

Upstream and downstream impacts mean that analyzing individual farms in isolation misses an important part of the story. "One sustainable farm situated in a landscape of high input, resource-degrading farms may produce environmental goods which are undermined or diminished by the lack of support from neighboring farms. A necessary condition for sustainable agriculture is, therefore, the motivation of large numbers of farming households for coordinated resource management" (Pretty 1995). The farm remains, nevertheless, the standard operational unit and, as such, provides a useful point of departure for a first model and analysis.

1.5 Report Outline

Fig. 1.1 provides an overview of the biomass stocks and biomaterial flows that one may find on a smallholder integrated rice farm. Throughout the remainder of the report we refer to this specific case study in order to illustrate the proposed analytical framework. Chapter 2 covers field methods and techniques employed in farm monitoring and data collection. Chapter 3 describes how to derive the parameter sets required to build a mass-balanced agroecological farm model. Chapter 4 introduces data entry into and analytical outputs from ECOPATH. Chapter 5 compares the case study farm with another rice farm scenario and discusses the use of quantitative indicators in comparing the ecological performance of different agroecological management systems.

CHAPTER 2

Monitoring Farm Agroecosystems and Collecting Data on Bioresource Stocks and Flows

2.1 'Agricultural Guilds'

In this chapter we suggest simple, practical field methods for collecting data on the boxes and flows of Fig. 1.1. Boxes include the following groups of plants and animals: rice, vegetables, fruit trees, multipurpose trees, bamboo, grasses/weeds, large ruminants, pigs, poultry, fish, and phytoplankton. These are groups of organisms that are distinguished by their function and life form, and which form distinct management entities and convenient units of monitoring, modeling, and analysis.

Within ecology, the guild concept refers to functionally similar species (Pianka 1988; Begon et al. 1990). The classification of farm components suggested here could be labeled 'agricultural guilds' — groups of species which, from a resource management point of view, perform similar functions. The number and types of groups identified in any particular model will differ according to the environmental context and management scenario. There will be cases where it makes sense and benefits the modeling and analysis to disaggregate groups that we have lumped, and vice versa. The variation that one encounters in the presence, selection, and management of plants and animals makes it impossible to construct a finite, fixed list of groups. What is suggested here only serves as a guide.

The extent to which boxes are further broken down or aggregated depends on the purpose and level of modeling. Two or more fish species may be cultured in the same body of water and to analyze them separately will require separate quantification of diet and harvested output. Whereas the latter can quite comfortably be obtained, e.g., through harvest records, the former would entail a level of detail probably not required to evaluate the performance of the agroecosystem at the whole farm level. Likewise, poultry is conveniently defined as one group although it may consist of several species, including ducks, chicken, geese, turkeys, etc. To separate feed inputs on a species basis becomes very cumbersome where the fowl are free-ranging and occasionally fed by-products, such as rice bran and other wastes, as is often the case in smallholder rice farming. Estimates of the total amount of feed given to the group of birds as a whole can be obtained via farm records and regular sampling and weighing of feed. The same applies to groups of large ruminants, in this case water buffaloes and cows herded and fed together. Pigs are treated separately, being housed and fattened primarily on imported commercial feed. Rice constitutes the main crop in our system. Vegetables are often cultivated in the dry season when the rice area lies fallow, and often managed as one unit in mixtures/intercrops. Trees are separated into fruit and multipurpose trees because of the rather different roles they fulfill within the farm. Bamboo, grasses/weeds and phytoplankton constitute the remaining distinct, functional groups within this rice-based system.

2.2 Biomass Above and Below Ground

We only consider the biomass that exists above ground. Above ground net production is (at present) the best basis for analysis and comparisons because it constitutes the usual database in ecology and, if not directly measured, can be obtained from secondary yield data with reliable cultivar-specific constants (Mitchell 1984), at least for major crops. The role of root biomass in nutrient recycling and storage is by no means insignificant. In leguminous trees, root biomass may account for up to 50% or more of tree N after pruning (Sanginga et al. 1995). Net primary production including roots is nearly always an extrapolation from above ground net production based on assumed constant proportions between the two. Data reviews, however, do not show a significant correlation between the above and below ground portions and there is no reliable basis for extrapolating total net primary production from above ground measurements alone (Mitchell 1984).

2.3 On-farm Monitoring: Practical Suggestions

An extensive literature exists on rationales, methods and protocols for conducting research on farms with farmers (see for instance Mikkelsen 1995). The scheme presented here requires the combination of different techniques and methods, including farm mapping, bioresource flow modeling, record keeping, semi-structured interviews, field measurements and sampling. To help implement the proposed framework, a few practical hints are given below.

It is recommended that researchers initially familiarize themselves with the nature and structure of the farm, for example, by asking the household to help draw a map or transect of the whole system (Lightfoot et al. 1991a, 1991b; 1994). A qualitative bioresource flow diagram (Fig. 2.1) can be generated based on the household's knowledge of the natural resource characteristics, and can provide an excellent overview of and focal point for discussing past, present, and planned activities. The diagram can also constitute the basis for a first rough resource inventory and serve as an entry point for planning the entire monitoring and data recording scheme. A farm map with field locations and natural resource types, or "land management units" (upland, lowland, homestead, forest land, etc.), can further assist in planning and designing monitoring and sampling schemes (Figs. 2.2 and 2.3).

When monitoring the growth of plants and animals in the field, one should adhere to standard measurement techniques and sampling methods. Fig. 2.2 shows an example of a layout for the sampling of ricefield bundweeds on the case study farm. A transect design is incorporated, with variations in the natural resource base adequately represented. Farms are not always square, uniform or even contiguous, and the sampling transect seldom ends up forming a neat, 'ideal' straight line across the farm. Farmers are usually capable of identifying different land management units as distinguished by soil type, topography and moisture regime, i.e., land units

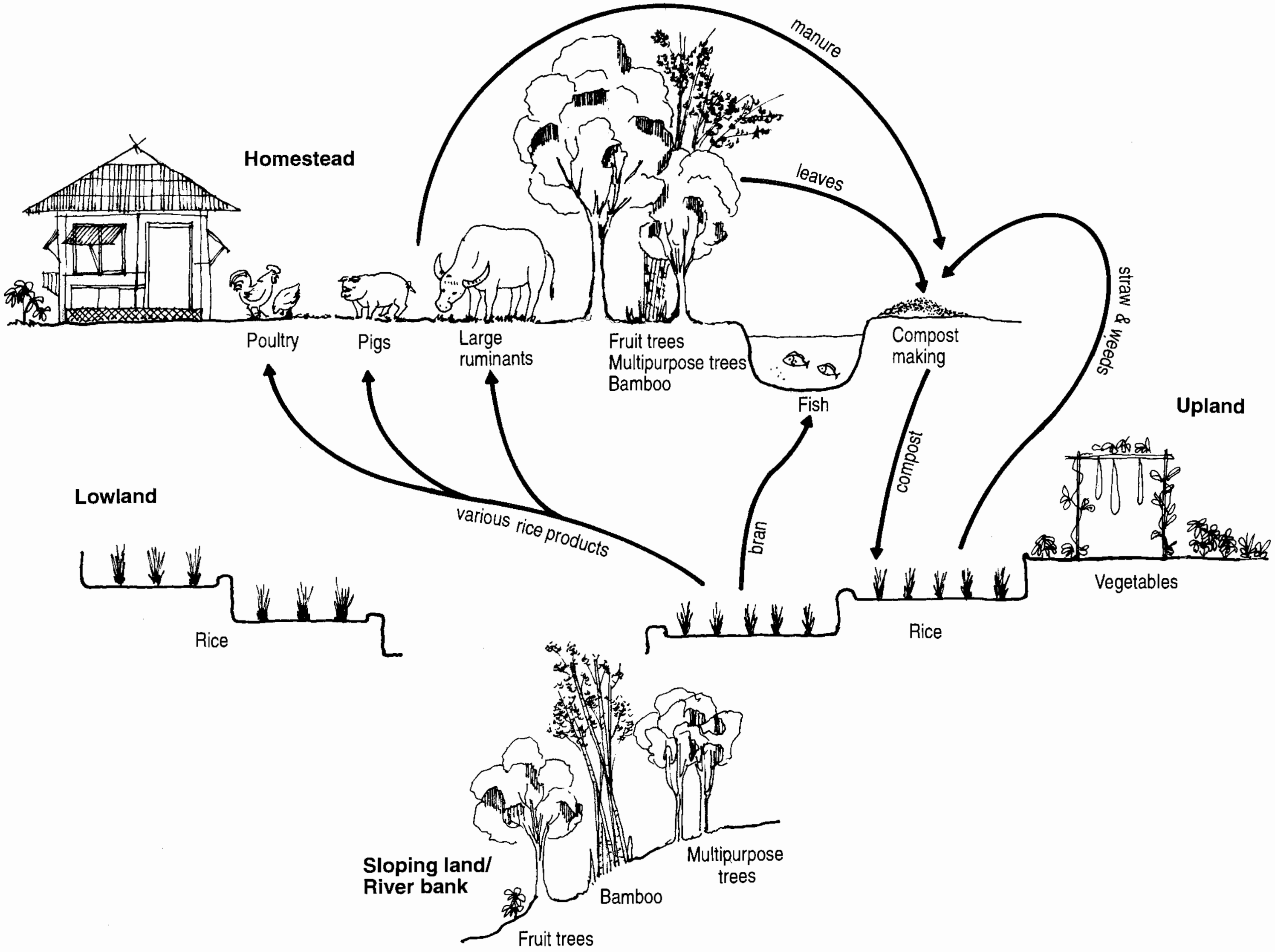

Fig. 2.1. A qualitative bioresource flow diagram of the case study farm drawn with the household at the outset of the monitoring scheme.

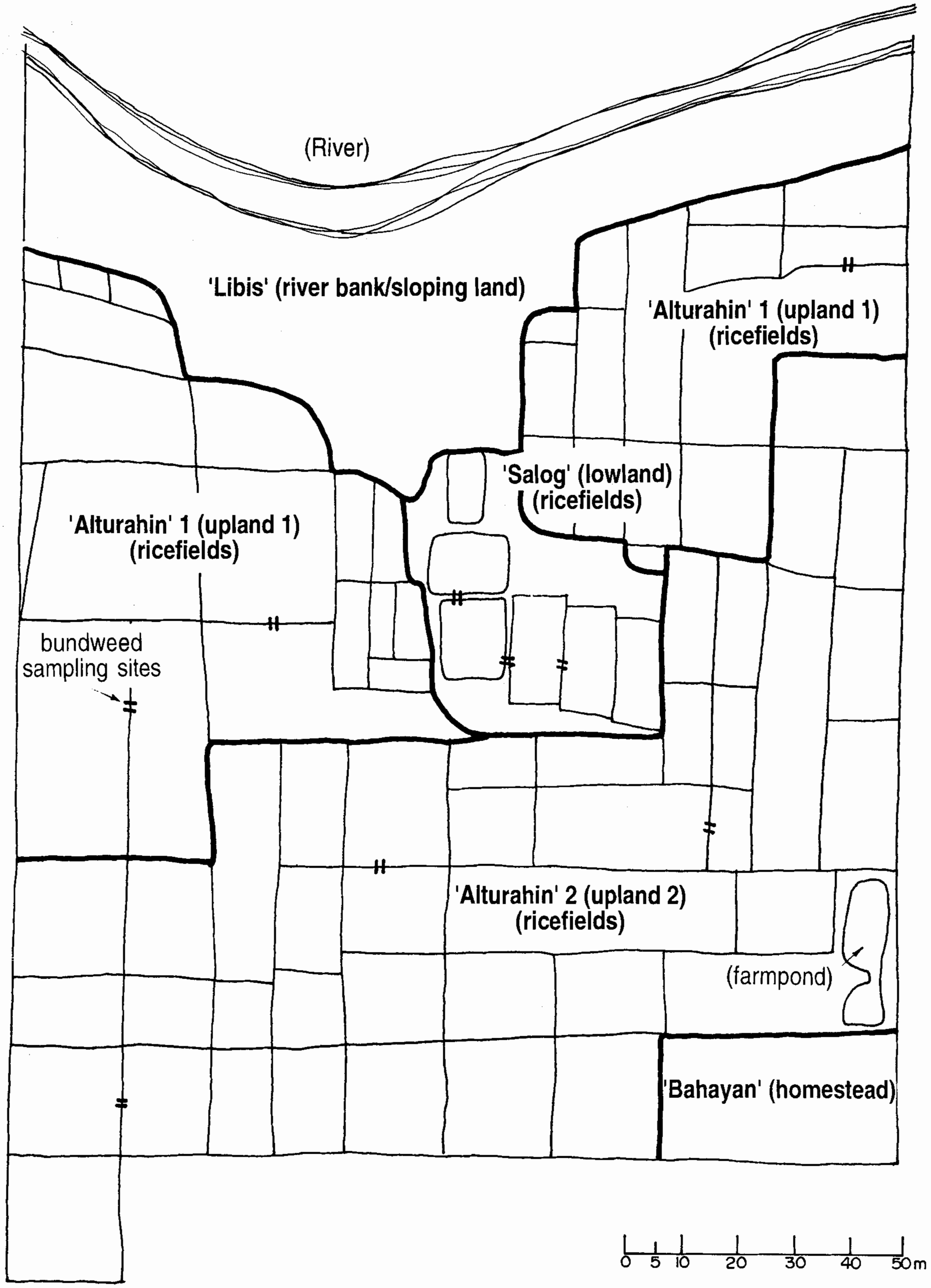

Fig. 2.2. A map showing the land management units (using local and translated terms) of the case study farm, with an example of a layout for bundweed sampling across the ricefield area.

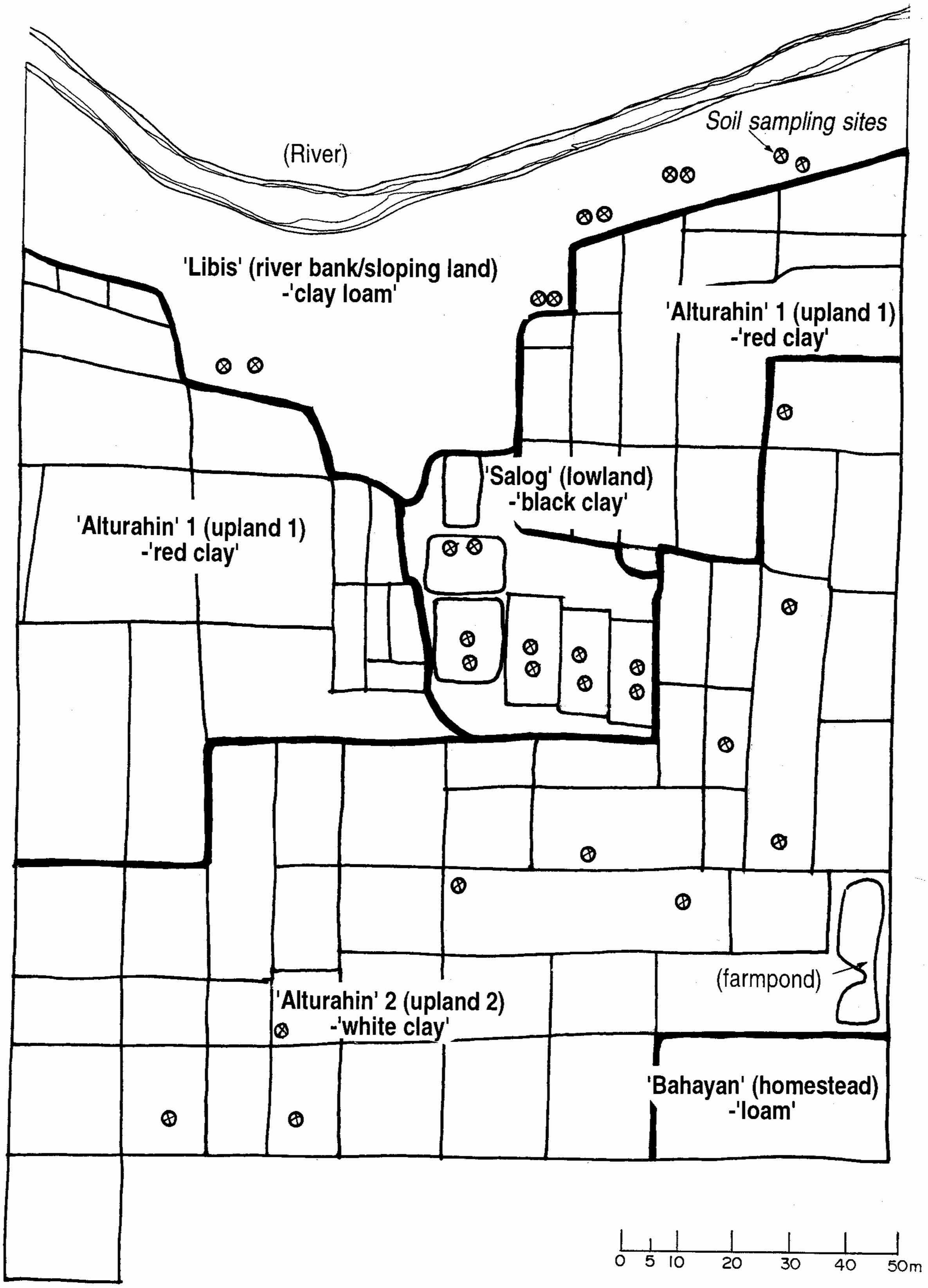

Fig. 2.3. A map of the case study farm showing an example of a soil sampling layout covering three land management units (from Dalsgaard and Oficial 1997).

representing different conditions for plant growth. Such information can guide transect design and help ensure systematic and representative sampling.

We adopted a scheme of three samplings to monitor the growth of annual crops (rice, weeds and vegetables) within each of the land management units in which the crop occurred. Representative sample sites were identified by visual inspection in the field. Each sample site consisted of a 1 x 1 m^2 square (confined using a quadratic sampling frame) within which all above ground vegetation was cut and weighed. An average value for the samples of a land management unit was computed before calculating the overall farm total on the basis of weighted averages (weighted according to the areal proportions of the land management units). Fresh weights were usually recorded in the field, with subsamples brought back to a laboratory for nitrogen (N) analysis. If wet, plant sampling was either postponed or samples were air dried before the weighing and recording.

We found the use of a 20 kg balance, with a resolution of 0.05 kg, to be an indispensable aid in the field. Equipping the household with a scale also permitted regular weighing throughout the monitoring period of various minor harvests of fruits and vegetables — products that otherwise tend to elude attention and remain unrecorded.

A flexible and systematic approach was also adopted when sampling soils (Fig. 2.3). A farm represents a heterogeneous "mini-ècosystem" and it is usually not advisable to settle on one intensity or transect spacing and apply it rigidly across such an area. Some parts may well need a different approach, with higher or lower intensity (Landon 1991). On the basis of the information provided by the farmer on soil conditions within the various land management units, three units were identified to represent the variation in soil conditions found across the farm. Within each land management unit, ten composite soil samples were collected along a diagonal transect. The soils were sampled to a depth of ~12 cm (commonly used sampling depth for ricefields) using a soil auger during the dry season and 2.5 cm diameter PVC tubes during the wet season. Samples within each land management unit were dried, ground and submitted to a laboratory for routine analysis.

For the general monitoring of farm activities, weekly field visits turned out to be a workable schedule. Daily visits were too demanding on both parties, whereas monthly visits ran the risk of missing unrecorded data not easily retrieved through recall. Keeping track of activities and bioresource flows soon becomes quite a task where farmers engage in a wide range of crop and animal activities, as many smallholders do. There may be particular times during the season when the frequency of farm visits can be reduced, e.g., during slack and peak periods. The appearance of slackness may sometimes be deceptive. After harvest of the main crop, households often engage in a range of smaller enterprises. These are exactly the activities that often elude research but are important to understand and evaluate the dynamics and performance of the whole agroecosystem. Households may not initially appreciate keeping records and may not have the time or ability to do so. Giving feedback, e.g., by presenting and handing over beautified versions of farm maps and transects, and discussing the results of economic and ecological assessments helps motivate participants.

Rarely is one household member solely responsible for all the farm activities and an attempt should be made to involve several members in the monitoring and recording schemes. Regular farm walkabouts and field inspections with household members are an important means of triangulation and double-checking of records. The word 'field' here also refers to parts of the farm that are not cultivated but utilized for other purposes, e.g., for the collection of wild fruits, wood or other products.

Suggestions on how to monitor, record, and collect data on the standing stocks and primary and secondary produce of the different plant and animal groups identified on the case study farm are given below.

2.4 Rice

Oryza sativa (variety: Masagana 75)

Grains are usually packed within the field in sacks of 45-50 kg right after harvest. A good estimate of the total grain production can be obtained by counting the number of sacks. If this information is obtained from the household, it is important to assure that the overall figure includes not only the portion of the harvest sold but also the share retained by the harvester/ thresher, grains stored for consumption and seeds, the share paid for land rental, etc. The main crop usually serves several such social and economic purposes. To derive an estimate of the straw production, one can either refer to harvest indices and calculate backwards from the figures obtained for the grain harvest, or sample straw *in situ*, shortly before harvest, when fields are drained.

2.5 Vegetables

Ipomea batatas Linn. Lamk. (sweet potato), *Phaseolus vulgaris* Linn. (snap bean or common bean), *Solanum melongena* Linn. (eggplant), *Vigna sesquipedalis* Fruw. (string bean or long bean).

In this case study, vegetables constituted a minor crop cultivated on small parts of the fallow rice land during the dry season. Harvests were staggered and the produce consumed on-farm. Asking the person(s) responsible for the harvest or cooking to perform regular weighing turned out to be a feasible way to obtain reasonable yield estimates. Recordings were made on a species basis, as the content of nitrogen (our model currency) can vary considerably for different kinds of vegetables.

Leaves and stems may be fed to animals, removed, burnt or left in the field to decompose. Young and nutritious leaves are sometimes harvested for human consumption. Whatever their fate, we need to estimate the biomass contained in the vegetative non-harvested portion. Vegetable plots are sometimes rather small, however, with little room for sampling without severely affecting the crop. There may be no easy way of estimating this particular variable in the field and using secondary data, such as (nitrogen-based) harvest indices, may offer the best solution.

2.6 Grasses/weeds

Cyanodon dactylon (L.) (bermudagrass), *Cyperus rotundus* (L.) (purple nutsedge), *Echinocloa colona* (L.) (junglerice or awnless barn yardgrass), *Echinocloa glabrescens* (no common name found), *Elusine indica* (L.) (goosegrass or crowsfootgrass), *Fimbristylis millacea* (L.) (globe fingerush), *Imperata cylinidrica* (L.) (cogongrass), *Ipomocea aquatica* Forssk. (swamp morning glory or water spinach), *Leersia hexandra* Sw. (swamp ricegrass or southern cutgrass), *Monochoria vaginalis* (Burm. f.) (monochoria), *Paspalum distichum* L. (knotgrass or water couch).

Ignoring weed production can lead to a severe underestimation of the productive capacity of the rice agroecosystem. The weed box usually contains a wide range of species (Ampong-Nyarko and De Datta 1991) and the case study farmer was capable of naming more than 15 different kinds of weeds using vernacular. For practical purposes weeds were classified into bundweeds, plotweeds and aquatic weeds:

Bundweeds refer to the weeds that grow on the (small) embankments which surround and separate individual ricefields. Farmers often adhere to a schedule of bund weeding thrice per rice crop: before transplanting, 45 days after transplanting (or halfway through the crop) and shortly before harvest. Such a weeding scheme provides a convenient sampling scheme: sampling and subsampling weeds at the same intervals just before the actual weeding permits accurate monitoring of weed growth and biomass production. By sampling one meter sections of bunds across the farm and measuring total bund length as well as bund widths, total bund area and thus total bundweed production can be extrapolated. Bunds typically occupy from 5% to 20% of the total ricefield area according to microtopography and slope.

Plotweeds refer to the weeds growing on the drained and dry ricefields between rice crops. Where fields are left fallow for longer periods of time, such as 5-6 months over the dry season, estimation and sampling may be problematic. Weeds may wither and die off as fields dry out and field water availability drops below wilting point, so frequent field inspections may be necessary to decide on appropriate sampling time(s). The assessment of plotweed production is further complicated where free-ranging or tethered animals graze the fallow land. Sampling from adjacent ungrazed areas may then provide the best approximation.

Aquatic weeds grow within submerged ricefields during the rice crop. Sampling is conveniently carried out shortly before the harvest of the rice crop, after the fields have been drained and the weeds are still intact. Farmers may perform *ad hoc* weeding during the rice crop. This complicates the sampling procedure, but fields may only be partly weeded, in which case it might still be possible to identify representative sampling sites. In such cases one may have to contend with a suboptimal sampling scheme or refer to secondary data.

2.7 Phytoplankton

Water levels fluctuate and differ from one ricefield to the next, as well as within individual fields. A few inches of difference in elevation can mean the difference between permanent flooding, intermittent flooding and regular drying out of fields. One can therefore expect large variations in the conditions for phytoplankton growth across a smallholder rice farm area. Measurements of dissolved oxygen and phytoplankton counts require access to proper (expensive) equipment and laboratory facilities, something not all field researchers have. This makes the monitoring of the phytoplankton component unrealistic in many cases. We implemented a minimalist scheme conducting measurements only thrice during the rice crop in order to obtain a rough indication of the overall level of phytoplankton biomass and production. Consulting the literature on this particular variable is probably a better option in many cases (see for instance Roger 1996). As most research on the growth of algae in ricefields has been undertaken on-station, results should be transferred to on-farm conditions with caution.

2.8 Fruit Trees

Annona muricata Linn. (soursop), *Artocarpus altilis* (breadfruit), *Artocarpus heterophyllus* (jackfruit), *Carica papaya* Linn. (papaya), *Citrus microcarpa* Bunge (Philippine lemon fruit or 'kalamansi'), *Cocos nucifera* Linn. (coconut) *Mangifera indica* Linn. and *Mangifera philippinensis* Mukh. (mango), *Musa* spp. (various banana), *Psidium guajava* Linn. (guava), *Sizygium cumini* (Linn.) Skeels (black plum or java plum), and *Tamarindus indica* Linn. (tamarind).

Fruit trees include both fruit-producing trees and palms. Several species of fruit trees, often represented by a single or few specimens, are frequently found on smallholder farms, particularly in and around the homestead area. Fruit is regularly consumed on the farm in an *ad hoc* fashion which makes recording and quantification difficult. When fruits are harvested for marketing and sale, the estimation of output is easier. In many cases, only rough estimates can be obtained. Fruits are often of minor importance when viewed within the overall farm production picture. Wood is harvested for fuel, construction, fencing, etc. Wood consumption can be estimated by regular weighings and recordings by the household assisted by the research team.

The most difficult parameters to estimate are tree biomass and growth. Well established methods for assessing tree volume exist, but these are usually developed for and applied to large stretches of forest or uniform, even-aged stands in plantation forestry. Assessing volume and biomass of individual trees is very difficult. The standard mensuration technique involves measuring girth at breast height, assessing height using a hypsometer or simple geometric triangulation methods (for smaller trees using a bamboo pole of known length), and estimating a form factor — a coefficient employed to reduce the volume of a cylinder to that of a tree or log (Philip 1994). Each of these estimates is associated with a range of potential errors so that measuring and computing volumes of individual trees is characterized by lack of precision. When a farm contains only a few small trees this potential error may not matter much within the overall farm model. However, a few large trees soon make up a significant portion of the standing biomass stock, and estimating their biomass and turnover is important for balancing the model.

Another limitation to the conventional mensuration procedures is that they are developed to derive biomass figures for the main product, timber, in the bole (trunk) only. Large amounts of biomass, however, are also stored and produced in secondary products, namely, in branches, twigs and leaves. For smallholder households, these outputs may be more important than the bolewood.

2.9 Multipurpose Trees

Acacia spp. (acacia), *Gliricidia sepium* (gliricidia), *Leucaena leucocephala* (leucaena), *Sesbania rostrata* (sesbania).

The term 'multipurpose' is applied to trees that serve several functions, such as production of wood for fuel, fencing and construction material, prunings for livestock fodder, leaves for green manuring, shade for field crops, etc., and are capable of fixing nitrogen. On the case study farm, multipurpose trees were used for firewood, vegetable trellises and in compost-making.

The problems with mensuration techniques also apply to multipurpose trees, although their lower height (6-8 m) makes it possible to derive fairly accurate height estimates by using a bamboo stick. The correlation between height and biomass, however, is usually poor for multistemmed trees. As Stewart and Salazar (1992) comment, ".. height is included in almost every trial assessment, probably because until recently foresters were dealing almost exclusively with straight, single-stemmed trees. For such trees, height and diameter are both closely correlated with volume...". For bushy plants, diameter at breast height is inappropriate because there may be several stems at that height. Most assessments of multipurpose trees have instead measured the 'basal diameter' at some convenient point between the ground and 10 cm up the stem (Stewart and Salazar 1992).

We were limited to non-destructive measurements. On more than one occasion though, whole trees were felled by the farmer allowing total biomass, including bole, branches and leaves/twigs, to be weighed and apportioned.

2.10 Bamboo

Bambusa blumaena Schultes f.

There are 54 known species of bamboo in the Philippines (Lessard and Chouinard 1980). Despite its widespread occurrence and use throughout southeast Asia, little has been published on the ecology of bamboo. As bioresources are becoming increasingly scarce and valuable, however, many plants and animals hitherto regarded as marginal within research and extension are now also receiving more attention. Dransfield and Widjaja (1995) provide an excellent overview of the botany, ecology, agronomy, breeding, use and prospects of bamboo.

Throughout the Philippines, bamboo either grows wild or is cultivated in backyards, along real estate boundaries, rivers and creeks. The culms (shoots) have many uses, e.g., in the construction of houses and furniture, as boat masts and outriggers, for making fish traps, etc. A *Bambusa blumaena* clump typically consists of 10-20 culms growing to a height of around 20 m. We were able to weigh cut and fallen culms of varying lengths and thus derive a rough length-weight correlation, from which the total standing biomass was estimated.

The number of bamboo culms in each clump were counted at the beginning and at the end of the monitoring period. At the end of the year we revisited each clump with the farmer to double-check on the number of harvested culms and the number of new culms (i.e., less than a year old). Shoots appear during the wet season and grow rapidly to reach full height within 60-120 days after emergence (Dransfield and Widjaja 1995).

2.11 Large Ruminants

Bubalus bubalis (water buffalo or 'carabao'), *Bus indicus* Linn. (zebu cow).

It is customary for smallholder rice farmers to keep one to two water buffaloes (carabaos) for land preparation. Cattle are less common in the Philippine rice smallholder landscape. Smaller ruminants, primarily goats, are kept for 6 months to 1 year before being sold for slaughter. Microlivestock (National Research Council 1991) are rare, except for poultry.

Live weights can be estimated through girth measurements (IIRR 1994). We recommend that all individual livestock be measured at the beginning and the end of the monitoring period, and when disposed of or acquired, in order to estimate standing stock and stock changes. We found farmers' assessments of live weights to be gross underestimates, often by more than 50%.

Livestock is usually housed during the growth of the rice crop and grazed during fallow periods. When housed, weeds and grasses are cut and carried and daily feeding rates can be monitored. Assuming similar consumption rates when grazing, one can compute rough estimates of quantities of grasses/weeds grazed.

2.12 Pigs

Sus scrofa Linn. (a commercial breed).

One or two pigs are often kept and housed for fattening and slaughtering on special occasions, such as weddings and town fiestas. A common routine is for a household to purchase 6-8 week old piglets, weighing 10-15 kg, for fattening over a period of 3-4 months, to reach a final weight at slaughtering of 50-60 kg. As with ruminants, live weights can be estimated through girth measurements. Where available, commercial feeds often form the basis of the diet, supplemented by available on-farm by-products such as rice bran and kitchen leftovers. As commercial feeds are usually paid for in cash, the farmers tend to have good recollection of the amounts purchased. Other feeding rates are best accounted for via records and regular measurements.

2.13 Poultry

Anas platyrhynchos (mallard duck), *Anser cygniodes* (white geese), *Cairina moschata* (muscovy duck), *Gallus gallus* or *Gallus domesticus* (native chicken), *Meleagris gallopavo* (turkey).

Most Philippine smallholder rice farmers keep some poultry for egg and meat production. The poultry are either free-ranging, housed or both. They are typically fed by-products and wastes such as rice bran and kitchen leftovers. Occasionally, farmers purchase broilers for fattening on commercial feeds. By monitoring approximate daily feeding rates, total feed amounts can be computed. Alternatively, one can ask the household to estimate total feeds given, e.g., the number of sacks of broken rice and bran used over a given period.

Counting and weighing individual poultry at the beginning and end of the monitoring period gives a reasonable estimate of average standing stock and stock changes. Egg production rates vary throughout the year. During feathering, egg laying ceases altogether. On the case study farm, duck eggs were the preferred food item and, at times, 12-14 eggs were collected daily and consumed on the farm. Duck eggs were weighed in at around 60-65 g apiece, or 16 eggs per kg. Household members recorded the number of eggs consumed and counted and weighed poultry consumed, given away, or sold on a daily basis.

2.14 Fish

Oreochromis niloticus (Nile tilapia).

Warm water aquaculture (Little and Muir 1987) and the combination of agriculture with aquaculture is widely practiced throughout south, east, and southeast Asia. Fish are cultivated in ponds, often several species together in a polyculture system or in integrated rice-fish systems, e.g., *Cyprinus carpio* (common carp), *Clarias batrachus* (Thai catfish), *Clarias gariepinus* (African catfish), *Melanogaster pectoralis* (gourami), Indian and Chinese major carps (Dela Cruz et al. 1992). In the Philippines, however, aquaculture is mostly equated with commercial production in high-input, large-scale undertakings. Fish culture on smallholder rice farms is not common. Often a few kilograms of wild fish are caught in the rice floodwater around the time of land preparation. The case study farmer did venture into pond aquaculture with the intention of practicing integrated rice-fish culture on a small portion of the farm. The integration never materialized due to unpredictable and insufficient irrigation water supply and the fish enterprise was largely considered a failure in this particular year.

Knowing the quantities of fish stocked and harvested and assuming that harvest is complete, one can compute the approximate average standing biomass. Fishponds are prone to contamination with wild species, including predators entering with the irrigation floodwater. Accurate production figures may be hard to derive where fish escape or are lost through predation, theft and other mortality (Christensen and Pauly 1993).

Different species of fish derive their food from different sources including benthic organisms (living in the pond mud), phytoplankton and zooplankton, aquatic weeds, insects, snails, other fish and supplied feeds. Quantifying the various food flows and the exact food composition is difficult. Where the aquaculture enterprise plays a dominant role within the farm and quantification of these flows becomes important to balance the model, accurate species-specific estimates of the diet composition should be sought (see for instance Palomares and Pauly 1996).

2.15 Other Groups and Pests

Insects, snails, zooplankton, birds, reptiles, rodents and a whole range of soil organisms are also likely to be present on the farm. These organisms are usually not directly utilized or utilized only to a small extent, e.g. certain species of snails are sometimes collected and fed to ducks. Most of them, however, play an essential role in the general functioning of the agroecological system. At the level of analysis presented here we need not consider them, unless they have an impact on system performance that is not otherwise accounted for. In the case of pests, for example, their negative impact on crop performance is captured in crop production and harvest figures.

2.16 The Soil (Detritus) Boxes

The soil forms the base of the agroecological system and serves as a repository for dead and decaying plant material and animal wastes. It is the source of nutrients for all primary producers (plants) and its state determines the overall health and performance of the agroecological system. An ECOPATH model can, in principle, be developed without knowing much about the processes within the soil — or 'detritus' in ECOPATH terminology. However, this should not prevent the modeler from seeking additional information about the soil. On the contrary, knowledge about the condition of the system's resource base will always enhance the explanatory power of the model and the ability to interpret agroecosystem behavior. One detritus box only is usually defined for the whole farm, although it is possible to define several boxes, e.g., for separate fields or areas of the farm.

Soils were sampled and analyzed thrice during the monitoring period in order to get a good picture of soil conditions and possible changes. Core samples were made to a depth of around 0.12 m for routine analysis, including pH, N (using the modified Kjeldahl method), P (using the Bray No. 2 method), K, organic matter content, and texture (PCARR 1980).

CHAPTER 3

Building the Model: ECOPATH Parameter Estimations

3.1 Model Currency: Nitrogen

The next step is the conversion of field data into parameter sets for the ECOPATH model. When developing a model of a complex organic system, a common currency in which all state and rate variables can be expressed must be selected (Jørgensen 1994). Model currencies are usually either energy or nutrient based. With respect to ECOPATH models of aquatic ecosystems have largely been energy based, whereas both energy and a nutrient (nitrogen) have formed the basis for models of culture systems (Christensen and Pauly 1993). In the model developed here we identified nitrogen (N), measured in kilograms (kg) per hectare (ha) per year as a useful currency unit. N is probably the macro nutrient whose fate has received the most attention in research on agricultural production systems and its pathways have been carefully studied and quantified. N and P (phosphorous) are frequently identified as the limiting nutrients in both tropical and temperate soils. The N content of feeds, fertilizers and harvested produce (grains, vegetables, fruits, meat, etc.) are commonly available in food and feed composition tables[2] (Göhl 1981; FNRI 1990). This still leaves a range of items uncovered, including wood, leaves, crop residues and animal wastes. Unless secondary data can be found, there is no alternative to sampling these variables in the field for N analysis.

Fig. 3.1 provides a summary overview of the characteristics of the case study farm, with all the field data collected over the entire 12-month monitoring period. Each of the groups of plants and animals identified on the case study farm in Chapter 2 are revisited below, and model values are derived for their biomasses (B), production rates (P), consumption rates (Q), harvests (H), exports/losses, and diet composition.

3.2 Rice

The household recorded a total wet season harvest of 118 cavans (sacks) of rice. No rice was cultivated during the dry season. One cavan weighs around 50 kg yielding a total harvest figure of around 5 900 kg. Straw was sampled across the rice area and a straw production of

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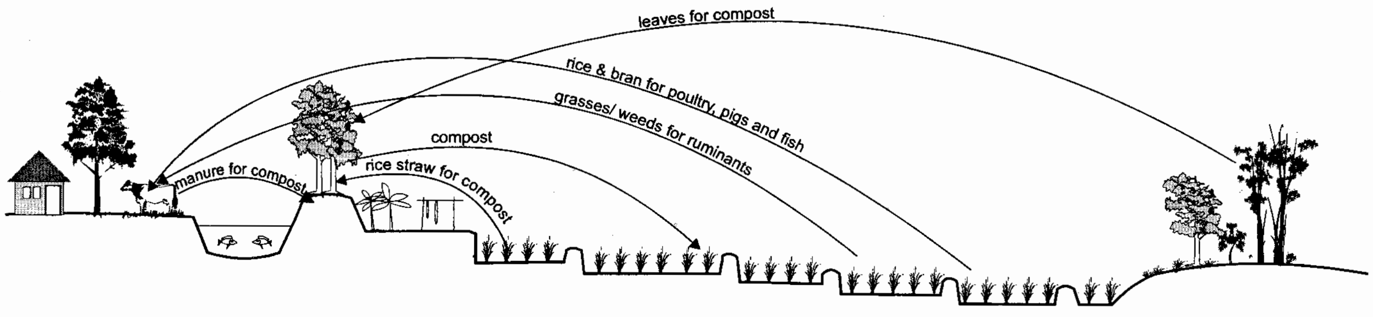
[2] Food composition tables usually list food protein contents. From this N contents can be computed by multiplying with a conversion factor of 1/6.25.



Land management unit	Homestead (0.26 ha)	Upland 1 (1.09 ha)	Upland 2 (0.82 ha)	Lowland (0.08 ha)	Sloping land/river bank (0.50 ha)
Soil type farmer researcher	- 'loam'	- 'red clay' - clay	-'white clay'	- 'black clay' - clay	- 'white clay' - clay loam
Water supply wet season dry season	- rainfed - (rainfed)	- rainfed/intermittent irrigation - rainfedfallow			- rainfed - rainfed
Plant and animal components	poultry (chicken, ducks geese, turkeys) pigs large ruminants (cows, water buffaloes) fish (tilapia) fruit trees (banana, guava, jackfruit, kalamansi,mango, papaya, tamarind) multipurpose trees (Acacia, Gliricidia, Leucaena) bamboo	- rice (1 crop) - weeds - phytoplankton vegetables (common bean, eggplant, long bean, sweet potato)			fruit trees (banana, java plum, mango, papaya) multipurpose trees (Gliricidia, Leucaena) bamboo weeds
Nutrient imports (feeds and fertilizer)	20 kg commercial poultry feed 800 kg commercial pig feed 6,000 kg grass for ruminants	rice: - 115 kg urea			
Net yield	170 kg poultry & 75 kg eggs 195 kg pigs 600 kg buffalo sold live 16 kg tilapia 36 kg papaya, 15 kg guava 30 kg mango, 2 kg jackfruit 20 kg tamarind, 1 kg kalamansi	3,750 kg rice 50 kg sweet potato tops 6 kg sweet potato tubers 30 kg eggplant 12 kg long beans 11 kg common beans	- 1,300 kg rice	- 600 kg rice	200 kg mango 1,600 kg bamboo 1,400 kg multipurpose tree wood (fuel wood and vegetable trellies) 15 kg banana

Fig. 3.1. A transect summary overview of the natural resource characteristics and flows on the case study farm (From Dalsgaard and Oficial 1997).

19 000 kg computed. Given that rice was the dominant crop and that N contents of grain and straw vary according to cultivar and soil conditions, both plant components were subsampled for N analysis, yielding the following dry matter (DM) and N values (as a percentage of DM):

Grain: 96% DM and 1.13% N
Straw: 48% DM and 0.67% N

Subtracting the 200 kg seed input, the following net production was computed:

Grain : (5 900-200) kg$*$0.96$*$0.0113 kg N kg^{-1} year^{-1} = 61.8 kg N year^{-1}
Straw : 19 000 kg$*$0.48$*$0.0067 kg N kg^{-1} year^{-1} = 61.1 kg N year^{-1}

giving a per ha production figure of[3]:

P = (61.8 + 61.1) kg N year^{-1} / 2.75 ha = 44.7 kg N ha^{-1} year^{-1}

Plants consume the same amount of N as they produce, i.e.,

consumption (Q) = production (P) = 44.7 kg N ha^{-1} year^{-1}

Assuming that seasonal and annual crops follow a sigmoidal growth curve, one can assume a value for the average standing biomass (B) equal to half of the total plant growth, or plant biomass production, i.e., P/B = 2 year^{-1}:

B = 44.7 kg N ha^{-1} year^{-1} / 2 year^{-1} = 22.35 kg N ha^{-1}

The amount of harvested material extracted from the system is equivalent to total grain production minus the fraction of grain used (recycled) within the system. In this case rice and bran were used to feed fish (11 kg bran), poultry (825 kg grain + 200 kg cooked rice leftovers), ruminants (80 kg grain), and pigs (180 kg bran). N contents of bran and cooked rice are approximately 1.25% and 1.00% (FNRI 1990), giving the following internal recycling flows:

905 kg$*$0.96$*$0.0113 kg N kg^{-1} = 9.8 kg N (recycled grain)
191 kg$*$0.0125 kg N kg^{-1} = 2.4 kg N (recycled bran)
200 kg$*$0.01 kg N kg^{-1} = 2.0 kg N (recycled cooked rice)
Total internal recycling = 14.2 kg N year^{-1}

thus leaving a harvest (H) of:

H = (61.8 - 14.2) kg N year^{-1} / 2.75 ha = 17.3 kg N ha^{-1} year^{-1}

In summary, we derived the following set of ECOPATH parameters for rice:

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[3] Total farm area was measured at 2.75 ha. All parameters are computed on a per hectare basis throughout this chapter.

B = 22.35 kg N ha^{-1}
P/B = 2 year^{-1}
Q/B = 2 year^{-1}
Harvest = 17.3 kg N ha^{-1} year^{-1}

3.3 Vegetables

Household records showed the following vegetable harvests: 12 kg of string beans, 11 kg of common beans, 30 kg of eggplant, 6 kg of sweet potatoes and 50 kg of sweet potato leaves. Based on their respective protein contents (FNRI 1990), the following harvest values were computed:

12 kg*0.0050 kg N kg^{-1} = 0.06 kg N (string bean)
11 kg*0.0053 kg N kg^{-1} = 0.06 kg N (common bean)
30 kg*0.0016 kg N kg^{-1} = 0.05 kg N (eggplant)
6 kg*0.0018 kg N kg^{-1} = 0.01 kg N (sweet potato tubers)
50 kg*0.0053 kg N kg^{-1} = 0.27 kg N (sweet potato tops)
Total harvest = 0.45 kg N year^{-1}

i.e., H = 0.45 kg N / 2.75 ha = 0.16 kg N ha^{-1} year^{-1}

Assuming an average N harvest index of 0.5 (Norman et al. 1984), and that the harvests represent total vegetable production (the farmer did not report any losses or discards), we computed a vegetable biomass production of:

P = H / 0.5 = 0.32 kg N ha^{-1} year^{-1}

Assuming a sigmoidal growth curve (i.e., average standing biomass is equal to half the total biomass produced) the following parameter set was derived:

B = 0.16 kg N ha^{-1}
P/B = 2 year^{-1}
Q/B = 2 year^{-1}
H = 0.16 kg N ha^{-1} year^{-1}

3.4 Grasses/Weeds

Bundweeds

Average weed production, per weed (re)growth (recall that bundweeds were cut thrice per rice crop), was measured to be 0.51 kg per meter of bund. Total bund length was measured at 3 000 m. Laboratory analysis yielded an average DM content of 27% and an average N content of 1.79%. Production was thus computed as:

P = 3*3 000 m*0.51 kg m^{-1}*0.27*0.018 kg N kg^{-1} year^{-1} / 2.75 ha
= 8.1 kg N ha^{-1} year^{-1}

Given that bundweeds grew thrice, and assuming a sigmoidal growth curve during each growth period, we get:

$$P/B = Q/B = 3*2 \text{ year}^{-1} = 6 \text{ year}^{-1}$$

and, $B = 8.1 \text{ kg N ha}^{-1} \text{ year}^{-1} / 6 \text{ year}^{-1} = 1.35 \text{ kg N ha}^{-1}$

Plotweeds

The sampling and analysis of plotweeds within the fallow dry season rice plots gave the following average values: 0.75 kg m^{-2} (fresh weight), 25% DM, and 1.06% N. Total rice area was measured at 1.81 ha:

$$\begin{aligned} P &= 18\,100 \text{ m}^2 * 0.75 \text{ kg m}^{-2} * 0.25 * 0.0106 \text{ kg N kg}^{-1} \text{ year}^{-1} / 2.75 \text{ ha} \\ &= 13.1 \text{ kg N ha}^{-1} \text{ year}^{-1} \end{aligned}$$

With only one growth period, no exported harvest (weeds were cut and fed to ruminants and thus recycled within and not harvested from the system) and assuming a sigmoidal growth curve, for plotweeds we get:

$$\begin{aligned} B &= P/2 = 6.5 \text{ kg N ha}^{-1} \\ P/B &= 2 \text{ year}^{-1} \\ Q/B &= 2 \text{ year}^{-1} \end{aligned}$$

Aquatic Weeds

This group of weeds was sampled shortly before rice harvest, with the following results: 0.25 kg m^{-2} (fresh weight), 20% DM, 1.80% N. Total ricefield area, minus bund area, was measured at 1.69 ha. There was only one 'crop' of aquatic weeds:

$$\begin{aligned} P &= 16\,900 \text{ m}^2 * 0.25 \text{ kg m}^{-2} * 0.20 * 0.018 \text{ kg N kg}^{-1} \text{ year}^{-1} / 2.75 \text{ ha} \\ &= 5.5 \text{ kg N ha}^{-1} \text{ year}^{-1} \\ B &= P/2 \text{ year}^{-1} \\ &= 2.75 \text{ kg N ha}^{-1} \\ P/B &= 2 \text{ year}^{-1} \\ Q/B &= 2 \text{ year}^{-1} \end{aligned}$$

Combining all weed data, we computed the following final parameter set for grass/weeds:

$$\begin{aligned} B &= (1.35+6.5+2.8) \text{ kg N ha}^{-1} &&= 10.6 \text{ kg N ha}^{-1} \\ P &= (8.1+13.1+5.5) \text{ kg N ha}^{-1} \text{ year}^{-1} &&= 26.7 \text{ kg N ha}^{-1} \text{ year}^{-1} \\ P/B &= 26.7/10.6 \text{ year}^{-1} &&= 2.5 \text{ year}^{-1} \\ Q/B &= P/B &&= 2.5 \text{ year}^{-1} \\ H &= 0.0 \text{ kg N ha}^{-1} \text{ year}^{-1} \end{aligned}$$

The overall average standing biomass of grasses/weeds on the farm was thus 10.6 kg N ha^{-1}, an amount that was produced 2.5 times per year, corresponding to a primary productivity over half of that of the rice crop. Ignoring weeds may thus seriously underestimate the productive capacity of the rice agroecosystem and the cycling of organic materials and nutrients via weed growth, decay and regrowth.

3.5 Phytoplankton

Our measurements indicated a low production of phytoplankton including diatoms, N-fixing and non-fixing blue-green algae (BGA). For simplicity, we assumed no import or export of phytoplankton with incoming and outflowing irrigation water. From the laboratory analysis we derived the following (crude) parameter set for phytoplankton:

B = 0.13 kg N ha^{-1}
P/B = 24 $year^{-1}$
Q/B = 24 $year^{-1}$
H = 0.0 kg N ha^{-1} $year^{-1}$

For more information and secondary data on phytoplankton see Roger (1996) and Christensen and Pauly (1993).

3.6 Fruit Trees

A tree count produced the following inventory: 20 banana hills, 1 breadfruit, 4 coconut palms, 2 java plum, 5 guava, 3 jackfruit, 1 kalamansi (Philippine citrus), 22 mango, 7 papaya, 1 soursop, and 8 tamarind.

Measurements of tree circumference at breast height varied from 0.7 to 4 m and height estimates from 5 to 13.5 m. The majority of the trees fell within a range of 1.0 to 1.5 m (circumference) and 10 to 11 m (height). Below is an example of how to derive the standing biomass for individual trees:

Example: Mango tree: circumference (c) 1.4 m; height (h) 12.5 m; form factor[4] (f) 0.75. The cross sectional area or girth (g) of the bole is equal to $c^2 / 4p$. Bole height was estimated to be half of tree height (6.25 m). The first step is the computation of bole volume (v):

$$v = g * h * f = (1.4\ m)^2 / 4\pi * 6.25\ m * 0.75 = 0.73\ m^3$$

Assuming a fresh wood density of 1 000 kg m^{-3} and a dry matter content of 50% we have:

$$\text{Fresh weight (bole)} = 1\,000\ kg\ m^{-3} * 0.73\ m^3 * 0.50 = 365\ kg$$

The relative distribution of biomass in bole, branches, and leaves/twigs is site and species specific. Crude estimates for savanna and woodland trees are given in Table 3.1. Excluding roots and using average values, we assumed a dry matter distribution of: bolewood 50%; branches 35%; leaves/twigs 15%, thus:

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[4] The form factor typically lies in the range 0.5-1.0 (Philip 1994). We assumed an average value of 0.75 for all trees.

Dry weight (branch) = 255 kg
Dry weight (leaf/twig) = 110 kg

Table 3.1. Dry matter composition in trees. (Source: Philip 1994)

	Forest trees	Savanna/ Woodland trees
Twigs and leaves	10	10
Branches	15	30
Bole	30	30
Roots > 5 cm diam.	45	30

Finally, we assumed the following N contents: bole 0.5%; branches[5,6] 0.75%; and leaves/ twigs[7] 1.5%, and computed tree N as:

N (bole) = 365 kg $*$ 0.005 kg N kg^{-1} = 1.83 kg N
N (branch) = 255 kg $*$ 0.0075 kg N kg^{-1} = 1.91 kg N
N (leaves/twigs) = 110 kg $*$ 0.015 kg N kg^{-1} = 1.65 kg N
N (tree) = 5.4 kg N

By adopting this procedure for all trees we arrived at an overall approximate tree biomass of:

B = 76.0 kg N ha^{-1},

of which around 17.2 kg N ha^{-1} were located in the leaf/twig portion.

Wood Production

The production of wood can be computed by inserting values for the relative increases in girths and heights in the above formula for bole volume computation. Numerical examples are given in Philip (1994). The difficulty and uncertainty involved in measuring and estimating these parameters, however, made us resort instead to an overall rough relative growth estimate for the entire group of fruit trees. In general, relative tree growth depends on management, site conditions, tree species, age and health. As trees age and mature, their growth rate approaches zero. On the case study farm, with tree ages varying from less than 3 years to around 100 years, we would clearly expect large differences in individual growth rates. Our field measurements showed increases in height and circumference varying between 0 and 10%. From this we

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[5] Branches contain a higher relative proportion of bark and live tissue than the bole portion, thus the higher N content for branches than for bole.

[6] Szott et al. (1991) find an average wood N concentration in four leguminous tree species of around 1.0% N. We assumed a somewhat lower value here for broadleaved non-leguminous species.

[7] The list of 37 broadleaved species provided in Drechsel and Zech (1991) shows an average N level in leaves of around 2%. We assumed a somehow lower value of 1.5% due to an expected lower N content in the twig portion.

assumed an overall average increase in standing stock of ~5%. Growth, or accumulated biomass (ΔB), was thus computed as:

$$\Delta B = B * 0.05 = 76.0 \text{ kg N ha}^{-1} \text{ year}^{-1} * 0.05 = 3.8 \text{ kg N ha}^{-1} \text{ year}^{-1}$$

Leaf Production

In mixed broad-leaved stands one may assume that leaves are produced continuously. Leaf turnover rates, however, vary with soil conditions and water availability. A drought can induce heavy leaf fall and reduce lifespan substantially. For more information on sampling and data on tropical fruit-bearing trees see Martin-Prevel et al. (1987). Mango, a dominant evergreen on Philippine smallholder farms, typically has individual leafspans of up to around 5 years under average conditions. Assuming an average leafspan of 2-3 years, i.e., a renewal of the crown approximately every 2.5 years, we derived an approximate annual leaf production of:

$$17.2 \text{ kg N ha}^{-1} \text{ year}^{-1} / 2.5 = 6.9 \text{ kg N ha}^{-1} \text{ year}^{-1}$$

Fruit Harvest

A range of fruits were consumed on-farm, whereas only mangoes were sold at the local market[8]:

Banana	:	15 kg * 0.0018 kg N kg^{-1}	=	0.027 kg N
Java plum	:	20 kg * 0.0013 kg N kg^{-1}	=	0.026 kg N
Guava	:	15 kg * 0.0014 kg N kg^{-1}	=	0.021 kg N
Jackfruit	:	2 kg * 0.0022 kg N kg^{-1}	=	0.004 kg N
Kalamansi	:	1 kg * 0.0006 kg N kg^{-1}	=	0.001 kg N
Mango	:	227 kg * 0.0010 kg N kg^{-1}	=	0.227 kg N
Papaya	:	36 kg * 0.0008 kg N kg^{-1}	=	0.029 kg N
Tamarind	:	20 kg * 0.0014 kg N kg^{-1}	=	0.028 kg N

i.e., Total fruit harvest = 0.37 kg N / 2.75 ha year^{-1} = 0.13 kg N ha^{-1} year^{-1}

Total production of fruit, wood and leaves amounts to 0.13 + 3.8 + 6.9 kg N ha^{-1} year^{-1} = 10.8 kg N ha^{-1} year^{-1}, and we ended up with a fruit tree parameter set of:

B = 76 kg N ha^{-1}
ΔB = 3.8 kg N ha^{-1} year^{-1}
P/B = 0.14 year^{-1}
Q/B = 0.14 year^{-1}
H = 0.13 kg N ha^{-1} year^{-1}

As seen from the above example, deriving values for wood densities, DM contents and N contents for the various parts of a tree is difficult and can only be an approximation. Basic wood density, i.e., the density of dried wood as opposed to that of 'green' or fresh wood, varies with species, age, and site conditions (Philip 1994). Species specific DM values are not commonly found in the literature and foliar nutrient levels differ by a factor of 2 to 3 (Drechsel and Zech

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[8] N-values from FNRI (1990).

1991) within the same species, depending on site conditions, tree and leaf age, season, shade and sampling procedure. Philip (1994) concludes a chapter on forest mensuration by stating that, "The forest produces not only wood, it also produces bark, foliage, resins and gums, fibers, medicinal plants, etc. Whenever the production of these has to be measured or predicted, then mensurational techniques have to be developed and adapted to suit the particular circumstances. In most circumstances the principles already in use in forest mensuration will serve to guide a forester to improvise suitable techniques to meet his requirements". Clearly, accounting for the role of trees on individual farms in quantitative terms is anything but straightforward. Trees are often overlooked as a component of farm system, and, apart from activities specifically concerned with tree management on smallholder farms, scant or no attention is paid to them. Thus, while their presence is sometimes acknowledged, trees are usually not systematically accounted for and analyzed, even though they often play an integral part in the functioning and well-being of the agroecosystem.

3.7 Multipurpose Trees

Leguminous, i.e., N-fixing trees have lately received much attention due to their multiple functions and utility, e.g., in the mitigation of soil nutrient depletion (Giller and Wilson 1991; Shepherd et al. 1996). Information on the composition of the various tree segments (bole, branches and leaves/twigs) was found to be more readily available than for fruit trees.

The cutting down of whole trees allowed us to establish initial average fresh weight at around 80 kg per tree, with 50% contained in the bole, 35% in branches, and 15% in the leaf/twig portion. We assumed DM contents of bole 50%, branches 40%, leaves/twigs 30%; and N contents of bole[9] 0.75%, branches 1.0%, and leaves/twigs[10] 3.5%. A total of 85 trees was counted at the beginning and 65 trees at the end of the monitoring period; 20 trees had been cut and used for firewood, fencing and vegetable trellises. Average tree height increased by around 15%, from 6-7 m to 7-8 m, and circumference by around 10%. These relative increases are additive (Philip 1994) suggesting an overall increase in tree biomass of around 25%, from the initial 80 kg to a final weight of around 100 kg. From this we computed an average total standing biomass of:

$$B\ (\text{fresh weight}) = (85 \ast 80\ \text{kg} + 65 \ast 100\ \text{kg}) / 2 = 6\,650\ \text{kg},$$

with an approximate N distribution of :

$B\ (\text{bole})$: $6\,650\ \text{kg} \ast 0.50 \ast 0.50 \ast 0.0075\ \text{kg N kg}^{-1} = 12.5\ \text{kg N}$
$B\ (\text{branches})$: $6\,650\ \text{kg} \ast 0.35 \ast 0.40 \ast 0.010\ \text{kg N kg}^{-1} = 9.3\ \text{kg N}$
$B\ (\text{leaves/twigs})$: $6\,650\ \text{kg} \ast 0.15 \ast 0.30 \ast 0.035\ \text{kg N kg}^{-1} = 10.5\ \text{kg N}$

and an overall average standing biomass of:

$$B = (12.5 + 9.3 + 10.5)\ \text{kg N} / 2.75\ \text{ha} = 11.7\ \text{kg N ha}^{-1}$$

---

[9] Examining the tissue content of four leguminous species, Szott et al. (1991) found an average N content in branches of around 1.0%. Given the lower relative portions of bark and live tissue in the bole we assumed a lower N content of 0.75% in this portion.

[10] Estimates of N in leaves and prunings vary from around 3.5-4.5% (Budelman 1989; Young 1989; Drechsel and Zech 1991; Szott et al. 1991).

20 trees, with an average weight of 90 kg per tree, were harvested during the year:

$H = (90 \text{ kg} * 20 / 6\,650 \text{ kg}) * 11.7 \text{ kg N ha}^{-1} \text{ year}^{-1} = 3.2 \text{ kg N ha}^{-1} \text{ year}^{-1}$

The change in standing stock from 85 to 65 trees corresponded to a decrease of:

$\Delta B = (65 * 100 \text{ kg}) - (85 * 80 \text{ kg}) \text{ year}^{-1} = -300 \text{ kg year}^{-1}$

thus, $\Delta B = (-300 \text{ kg} / 6\,650 \text{ kg}) * 11.7 \text{ kg N ha}^{-1} \text{ year}^{-1} = -0.5 \text{ kg N ha}^{-1} \text{ year}^{-1}$

Assuming that leaves were renewed once a year, we computed an annual leaf production of:

$P \text{ (leaves/twigs)} = 10.5 \text{ kg N year}^{-1} / 2.75 \text{ ha} = 3.9 \text{ kg N ha}^{-1} \text{ year}^{-1}$

giving a total annual biomass production of:

$P = H + \Delta B + P\text{(leaves/twigs)} = 6.6 \text{ kg N ha}^{-1} \text{ year}^{-1}$

With consumption (Q) equal to production, we ended up with a parameter set of:

$B = 11.7 \text{ kg N ha}^{-1}$
$\Delta B = -0.5 \text{ kg N ha}^{-1} \text{ year}^{-1}$
$P/B = 0.56 \text{ year}^{-1}$
$Q/B = 0.56 \text{ year}^{-1}$
$H = 3.2 \text{ kg N ha}^{-1} \text{ year}^{-1}$

3.8 Bamboo

Eight clumps with a total of 144 culms were counted at the outset, increasing to 168 culms a year later, giving an average of 156 culms. Recorded harvest was 40 culms. The fresh weight of mature individual culms was estimated to be around 40 kg. Dried bamboo leaves (can be used as forage) contain around 10% protein, or 1.6% N on a dry weight basis (Dransfield and Widjaja 1995) and 30% DM. For the culm portion the following data were assumed: 50% DM and 0.75% N. Lessard and Chouinard (1980) suggest a biomass distribution (fresh weight) of 95% in culms and branches, and 5% in leaves. From this we calculated the following:

$B \text{ (culms+branches)} : 156 * 40 \text{ kg} * 0.95 * 0.50 * 0.0075 \text{ kg N kg}^{-1} = 22.2 \text{ kg N}$
$B \text{ (leaves)} : 156 * 40 \text{ kg} * 0.05 * 0.30 * 0.016 \text{ kg N kg}^{-1} = 1.5 \text{ kg N}$

thus, $B = (22.2+1.5) \text{ kg N} / 2.75 \text{ ha} = 8.6 \text{ kg N ha}^{-1}$

Assuming a complete annual leaf turnover gives a leaf production of:

$P \text{ (leaves)} = 1.5 \text{ kg N year}^{-1} / 2.75 \text{ ha} = 0.5 \text{ kg N ha}^{-1} \text{ year}^{-1}$

The change in the number of culms from 144 to 168 corresponds to a stock increase of:

$$\Delta B = 24/156 * 8.6 \text{ kg N ha}^{-1} \text{ year}^{-1} = 1.3 \text{ kg N ha}^{-1} \text{ year}^{-1}$$

A harvest of 40 culms gives:

$$H = 40/156 * 8.6 \text{ kg N ha}^{-1} \text{ year}^{-1} = 2.2 \text{ kg N ha}^{-1} \text{ year}^{-1}$$

yielding a total annual bamboo production of:

$$P = (0.5 + 1.3 + 2.2) \text{ kg N ha}^{-1} \text{ year}^{-1} = 4.0 \text{ kg N ha}^{-1} \text{ year}^{-1}$$

From this we derived the following parameter set for bamboo:

$$\begin{aligned}
B &= 8.6 \text{ kg N ha}^{-1} \\
\Delta B &= 1.3 \text{ kg N ha}^{-1} \text{ year}^{-1} \\
P/B &= 0.47 \text{ year}^{-1} \\
Q/B &= 0.47 \text{ year}^{-1} \\
H &= 2.2 \text{ kg N ha}^{-1} \text{ year}^{-1}
\end{aligned}$$

3.9 Large Ruminants

Stock assessments at the beginning (2 500 kg) and end (2 000 kg) of the year gave an average live biomass of around 2 250 kg. Two buffaloes (500 kg and 100 kg) were sold during the course of the year. Data on the protein contents of the edible parts were found in food composition tables, and similar levels were assumed for the non-edible portions (bones, rumen, hides, etc.):

$$\begin{aligned}
B &= 2\,250 \text{ kg} * 0.032 \text{ kg N kg}^{-1} / 2.75 \text{ ha} &&= 26.1 \text{ kg N ha}^{-1} \\
\Delta B &= -500/2\,250 * 26.1 \text{ kg N ha}^{-1} \text{ year}^{-1} &&= -5.8 \text{ kg N ha}^{-1} \text{ year}^{-1} \\
H &= 600/2\,250 * 26.1 \text{ kg N ha}^{-1} \text{ year}^{-1} &&= 7.0 \text{ kg N ha}^{-1} \text{ year}^{-1} \\
P &= (600-500)/\,2\,250 * 26.1 \text{ kg N ha}^{-1} \text{ year}^{-1} &&= 1.2 \text{ kg N ha}^{-1} \text{ year}^{-1}
\end{aligned}$$

A total of around 5.3 t of weeds (~50 kg per day) were cut and carried to the animals while housed for 3.5 months. Approximately 50% were gathered on-farm and 50% collected off-farm. The remainder of the time the animals grazed, around 6.5 months on-farm and 2 months off-farm. Assuming similar daily consumption rates during grazing as when housed and fed, we derived the following approximate total consumption figures:

$$\begin{aligned}
Q \text{ (on-farm grasses/weeds)} &= 12\,500 \text{ kg year}^{-1} \\
Q \text{ (off-farm grasses/weeds)} &= 5\,700 \text{ kg year}^{-1}
\end{aligned}$$

The laboratory analyses of weeds gave average figures of ~26% DM and ~1.4% N:

$$\begin{aligned}
Q \text{ (on-farm grass/weeds)} &= 12\,500 \text{ kg} * 0.26 * 0.014 \text{ kg N kg}^{-1} \text{ year}^{-1} / 2.75 \text{ ha} \\
&= 16.5 \text{ kg N ha}^{-1} \text{ year}^{-1} \\
Q \text{ (imported grass/weeds)} &= 5\,700 \text{ kg} \quad 0.26 \quad 0.014 \text{ kg N kg}^{-1} \text{ year}^{-1} / 2.75 \text{ ha} \\
&= 7.5 \text{ kg N ha}^{-1} \text{ year}^{-1}
\end{aligned}$$

i.e., Q (total) = 24.0 kg N ha^{-1} year^{-1}

We ended up with a parameter set for large ruminants of:

B = 26.1 kg N ha^{-1}
ΔB = -5.8 kg N ha^{-1} year^{-1}
P/B = 0.046 year^{-1}
Q/B = 0.92 year^{-1}
H = 7.0 kg N ha^{-1} year^{-1}

Diet composition:
Grasses/weeds = 0.690 (69%)
Import = 0.310 (31%)

3.10 Pigs

Five piglets were purchased, fattened, and slaughtered over the course of the year. The live weight of imported piglets came to around 75 kg, and the live weight of slaughtered animals to around 270 kg. Total weight gain was thus approximately 195 kg. Pork has an average protein content of around 15%, or 2.4% N (FNRI 1990). Assuming, as for ruminants, that the non-edible portion contains a similar level of protein as the edible portion, we computed the following parameters:

B = (75 kg + 270 kg) / 2 $*$ 0.024 kg N kg^{-1} / 2.75 ha = 1.5 kg N ha^{-1}
P = 195 kg $*$ 0.024 kg N kg^{-1} year^{-1} / 2.75 ha = 1.7 kg N ha^{-1} year^{-1}
H = P = 1.7 kg N ha^{-1} year^{-1}

The pigs were fed 780 kg of commercial feeds containing 21-22% protein, or ~3.5% N, supplemented with rice bran using 180 kg of own bran and 370 kg of purchased bran. Bran has a protein content of 7.8% or 1.25% N (FNRI 1990). Based on this we computed the following diet composition:

Internal (on-farm) feed flows:
Rice bran: 180 kg $*$ 0.012 kg N kg^{-1} year^{-1}/ 2.75 ha = 0.82 kg N ha^{-1} year^{-1}

Feed imports:
Commercial feeds = 780 kg $*$ 3.5 kg N kg^{-1} year^{-1} / 2.75 ha
= 10.2 kg N ha^{-1} year^{-1}
Rice bran = 370 kg $*$ 1.25 kg N kg^{-1} year^{-1} / 2.75 ha
= 1.68 kg N ha^{-1} year^{-1}

thus, Q = (0.82 + 10.2 + 1.68) kg N ha^{-1} year^{-1} = 12.7 kg N ha^{-1} year^{-1}

This gave a final parameter set for pigs of:

B = 1.5 kg N ha^{-1}
P/B = 1.13 year^{-1}
Q/B = 8.5 year^{-1}
H = 1.7 kg N ha^{-1} year^{-1}

Diet composition:
Rice = 0.065 (6.5%)
Imports = 0.935 (93.5%)

3.11 Poultry

Stock assessments at the beginning (130 kg) and end (100 kg) of the monitoring period show a reduction of 30 kg and an average standing stock of 115 kg. Household consumption and sale amounted to 170 kg poultry (live weight) and 75 kg eggs. Poultry contains around 18% crude protein, or 2.9% N, whereas eggs contain around 12% crude protein or 1.9% N (FNRI 1990):

$B = 115\ \text{kg} * 0.029\ \text{kg N kg}^{-1} / 2.75\ \text{ha} = 1.21\ \text{kg N ha}^{-1}$

$\Delta B = -30\ \text{kg} * 0.029\ \text{kg N kg}^{-1}\ \text{year}^{-1} / 2.75\ \text{ha} = -0.32\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

$H\ (\text{meat}) = 170\ \text{kg} * 0.029\ \text{kg N kg}^{-1}\ \text{year}^{-1} / 2.75\ \text{ha} = 1.79\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

$H\ (\text{eggs}) = 75\ \text{kg} * 0.019\ \text{kg N kg}^{-1}\ \text{year}^{-1} / 2.75\ \text{ha} = 0.52\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

i.e., $H\ (\text{total}) = 2.31\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

and, $P = (0.32+2.31)\ \text{kg N ha}^{-1}\ \text{year}^{-1} = 2.63\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

The poultry was fed own rice (825 kg), purchased rice (825 kg), cooked rice leftovers (200 kg) and commercial feeds (20 kg). Our analysis showed a rice N content of ~1.13%. FNRI (1990) suggests a rice crude protein content of 7.4% (1.18% N), and a protein content of cooked rice leftovers of 6.2% (0.99% N). No information was provided on the commercial feed packaging, so a protein content of 22% (~3.5% N), as for pigs, was assumed:

Internal (on-farm) feed flows:

$\text{Rice} = 825\ \text{kg} * 1.13\ \text{kg N kg}^{-1}\ \text{year}^{-1} / 2.75\ \text{ha}$

$= 3.4\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

$\text{Cooked rice} = 200\ \text{kg} * 0.99\ \text{kg N kg}^{-1}\ \text{year}^{-1} / 2.75\ \text{ha}$

$= 0.72\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

Feed imports:

$\text{Rice} = 825\ \text{kg} * 1.18\ \text{kg N kg}^{-1}\ \text{year}^{-1} / 2.75\ \text{ha}$

$= 3.5\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

$\text{Commercial feed} = 20\ \text{kg} * 3.5\ \text{kg N kg}^{-1}\ \text{year}^{-1} / 2.75\ \text{ha}$

$= 0.25\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

thus, $Q = (3.4 + 0.72 + 3.5 + 0.25)\ \text{kg N ha}^{-1}\ \text{year}^{-1} = 7.9\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

This yielded the following parameter set for poultry:

$B = 1.21\ \text{kg N ha}^{-1}$

$\Delta B = -0.32\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

$P/B = 2.2\ \text{year}^{-1}$

$Q/B = 6.5\ \text{year}^{-1}$

$H = 2.5\ \text{kg N ha}^{-1}\ \text{year}^{-1}$

Diet composition:

Rice (own) = 0.520 (52%)

Imports = 0.480 (48%)

3.12 Fish

Seven hundred tilapia fingerlings of 3 to 5 g per piece, or a total of ~3 kg, were stocked early in the wet season in a 35 m² holding pond. Due to irregular irrigation and insufficient water supply the farmer was unable to transfer the fingerlings into a prepared rice field. Instead the fish were released into a 90 m^2 pond, but only after nearly half escaped into an irrigation canal when the combination of heavy rains and incoming irrigation water caused the pond to overflow. At the end of the wet season 19 kg of tilapia were harvested and eaten. Tilapia contains 17.5% crude protein or 2.8% N (FNRI 1990). Ignoring fish loss and other mortalities (disease, stress, predation) and assuming a constant absolute growth rate, gives the following parameters:

$B = (3\text{ kg} + 19\text{ kg}) / 2 * 0.028\text{ kg N kg}^{-1} / 2.75\text{ ha} = 0.11\text{ kg N ha}^{-1}$
$P = (19\text{ kg} - 3\text{ kg}) * 0.028\text{ kg N kg}^{-1}\text{ year}^{-1} / 2.75\text{ ha}$
$= 0.16\text{ kg N ha}^{-1}\text{ year}^{-1}$
$H = P = 0.16\text{ kg N ha}^{-1}\text{ year}^{-1}$

From Christensen and Pauly (1993), we identified a Q/B ratio of 15, i.e.:

$Q = 15*0.11\text{ kg N ha}^{-1}\text{ year}^{-1} = 1.65\text{ kg N ha}^{-1}\text{ year}^{-1}$

The fish were fed a total of 11 kg of rice bran containing around 1.25% N (FNRI 1990). Assuming that all the bran provided was eaten by the fish, this would yield a feed flow of:

$11\text{ kg} * 0.0125\text{ kg N kg}^{-1}\text{ year}^{-1} / 2.75\text{ ha} = 0.05\text{ kg N ha}^{-1}\text{ year}^{-1}$

The remaining consumption of 1.60 kg N ha^{-1} was derived from natural food sources. We assumed for simplicity that the remaining food was all phytoplankton. We thus ended up with the following parameter set for the fish component:

B = 0.11 kg N ha^{-1}
P/B = 1.45 $year^{-1}$
Q/B = 15 $year^{-1}$
H = 0.16 kg N ha^{-1} $year^{-1}$

Diet composition
Rice bran = 0.03 (3%)
Phytoplankton = 0.97 (97%)

3.13 Soil (Detritus) & BNF

Tropical soils vary in their reserves of nitrogen, from a few tonnes (t) to more than 50 t·ha^{-1} in the surface 1.0 m (Stephenson and Raison 1988). Different measurements of soil nitrogen give divergent results because varying proportions of different types of nitrogen (organic compounds, nitrate and nitrite anions, and ammonium ions) are extracted (Landon 1991). Levels of nitrogen within a given soil will also vary according to the time (season) and cultivation history. Our routine soil analysis yielded the following average data for the three sampled land management units (see the sampling layout in Fig. 2.2):

1) Upland rice area (0.92 ha): pH 5.8; 2.38% organic matter; 0.12% N; available P (ppm) 2.34; exchangeable K (me/100 g soil) 0.87; sand 13.9%; silt 43.5%; clay 52.6%; bulk density 0.80 g/cc. Texture: clay.

2) Lowland rice area (0.08 ha): pH 5.6; 2.69% organic matter; 0.15% N; available P (ppm) 1.87; exchangeable K (me/100 g soil) 0.76; sand 12.8%; silt 30.4%; clay 56.8%; bulk density 0.78 g/cc. Texture: clay.

CHAPTER 4

ECOPATH: Data Entry and Analysis

4.1 Hardware and Software[15]

The hardware requirements for running Version 3.0 of the software are: 80386+ CPU (Windows requirement), coprocessor (preferred), 4 Mb RAM, 2 Mb hard disk space, VGA display and a Windows 3.x operating environment for the Windows-based version 3.0. For the preceding DOS-based ECOPATH Version 2.2 (also referred to as ECOPATH II) the minimum requirements are: 8086 CPU, coprocessor (preferred), 640 Kb RAM, 1 Mb harddisk, CGA monitor, and an MS-DOS 6.2 environment. The manual[16] which used to accompany the earlier versions (Christensen and Pauly 1992b) has been replaced by an extensive help function in v3.0.

The software was developed for the quantitative analysis of trophic flows in aquatic ecosystems, but is now also being applied to model and research the performance of agroecological systems (Christensen and Pauly 1993; Dalsgaard 1995; Dalsgaard et al. 1995; Dalsgaard and Christensen 1997). Because of its origin within aquatic ecosystem and fisheries science, some of the software terminology will be new to agricultural scientists. In this chapter we introduce the reader to the basic data entry screens and output screens and apply the basic concepts and terminology within the agroecological context.

4.2 Data Input

Units/Remarks screen (Fig. 4.1.): on this opening screen we select the model currency unit. In our case we identified a nutrient-related currency, and enter kgN/ha under 'Other unit'. Our selected 'Time' unit is year. Under 'Total primary production' we enter the sum of the biomass produced by all plants, which in this case comes to 109 (kg N ha^{-1}). The 'Remarks' field is a free text field, i.e., any kind of information useful for describing the particular model may be entered here.

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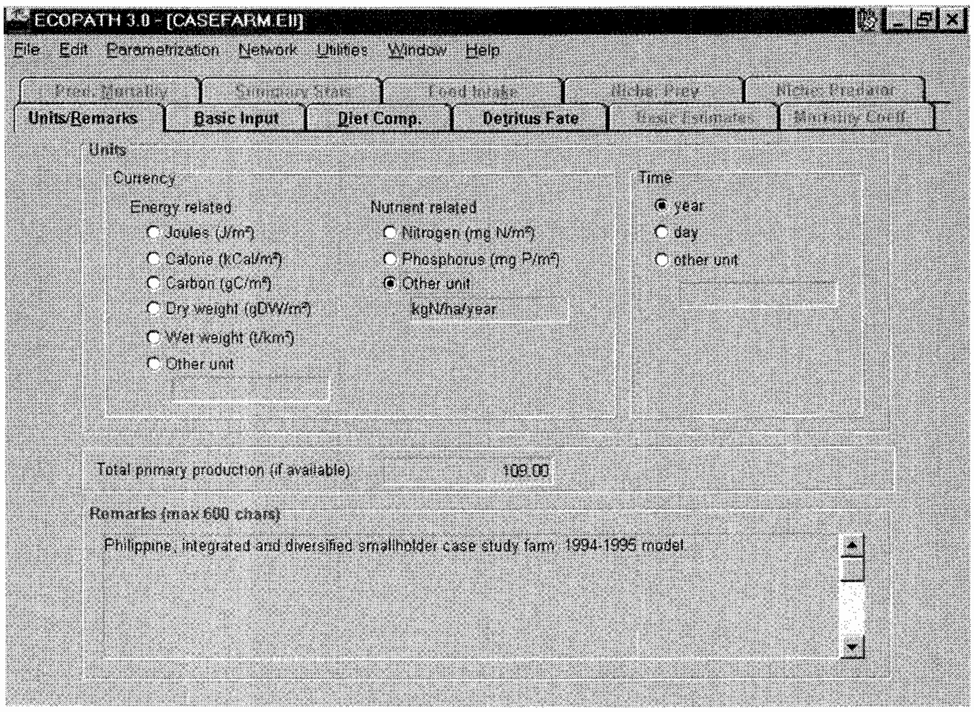
[15] The ECOPATH software (2 HD 3 1/2" DOS-formatted disks) is available free of charge from ICLARM, and can also be downloaded from ICLARM's homepage http://www.cgiar.org/iclarm/

[16] The DOS-version manual is now out of print. Photocopies or a disk version in English, French, or Spanish, may be requested from ICLARM (iclarm@cgnet.com).



Units

Currency

Energy related
○ Joules (J/m²)
○ Calorie (kCal/m²)
○ Carbon (gC/m²)
○ Dry weight (gDW/m²)
○ Wet weight (t/km²)
○ Other unit

Nutrient related
○ Nitrogen (mg N/m²)
○ Phosphorus (mg P/m²)
● Other unit
kgN/ha/year

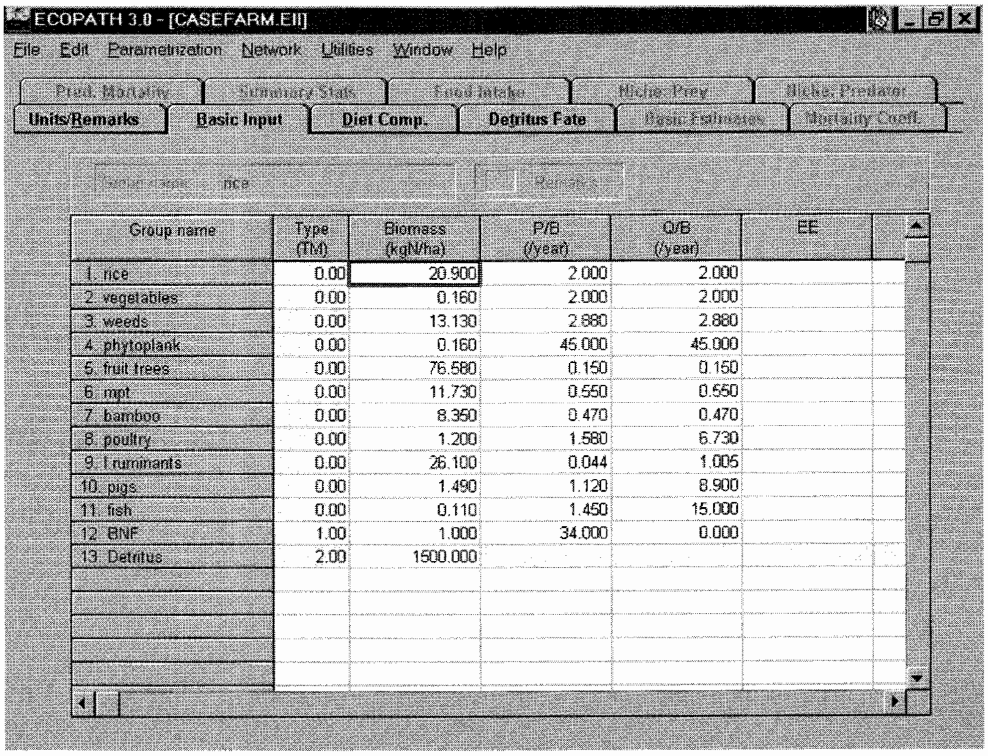
Time
● year
○ day
○ other unit

Total primary production (if available): 109.00

Remarks (max 600 chars)

Philippine, integrated and diversified smallholder case study farm. 1994-1995 model.

Fig. 4.1. Unit/Remarks screen.

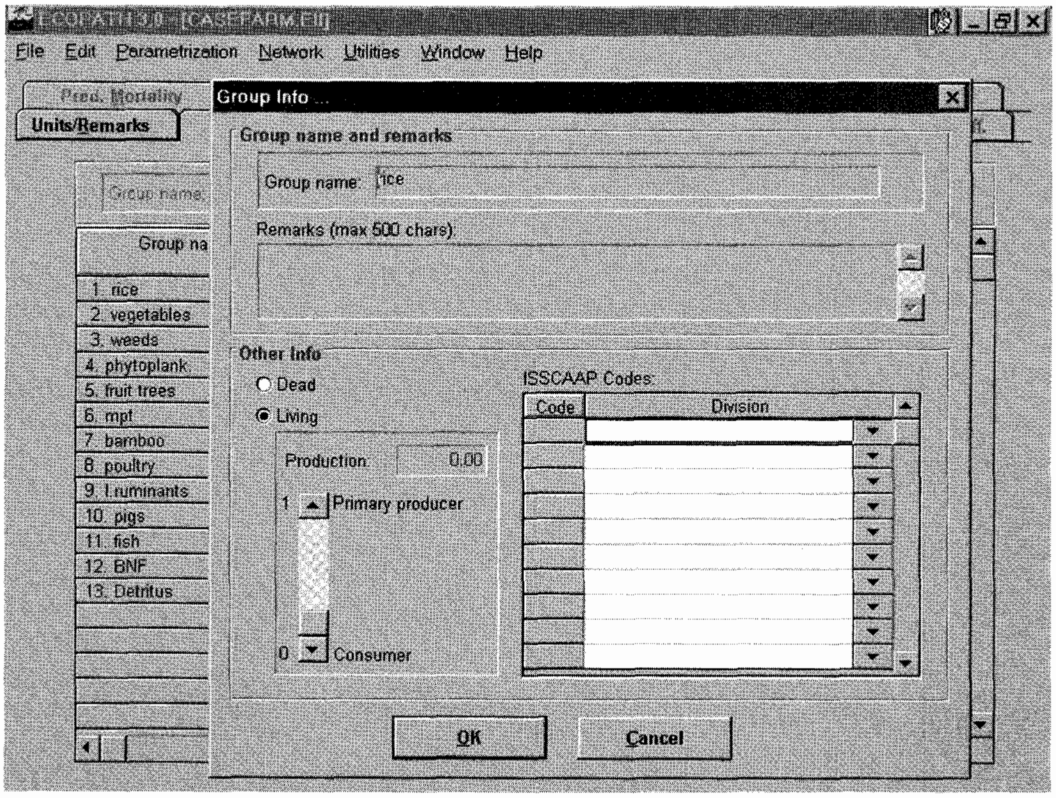


Group name	Type (TM)	Biomass (kgN/ha)	P/B (/year)	Q/B (/year)	EE
1. rice	0.00	20.900	2.000	2.000	
2. vegetables	0.00	0.160	2.000	2.000	
3. weeds	0.00	13.130	2.880	2.880	
4. phytoplank	0.00	0.160	45.000	45.000	
5. fruit trees	0.00	76.580	0.150	0.150	
6. mpt	0.00	11.730	0.550	0.550	
7. bamboo	0.00	8.350	0.470	0.470	
8. poultry	0.00	1.200	1.580	6.730	
9. l ruminants	0.00	26.100	0.044	1.005	
10. pigs	0.00	1.490	1.120	8.900	
11. fish	0.00	0.110	1.450	15.000	
12. BNF	1.00	1.000	34.000	0.000	
13. Detritus	2.00	1500.000			

Fig. 4.2a. Basic Input screen (first part).

<u>Basic Input screens (Figs. 4.2a, 4.2b, 4.2c, 4.2d)</u>: here we enter all the parameter values computed in Chapter 3. Fig. 4.2a shows the first six columns: 'Group names', 'Type', 'Biomass' (B), 'P/B', 'Q/B' and 'EE'. EE is the ecotrophic efficiency (Christensen and Pauly 1992b). It expresses the part of production that is either passed up the trophic foodweb or exported. EE varies between 0 and 1, has no unit and its entry is optional. Where it is possible to determine beforehand and enter all B, P/B and Q/B values, as in our model, all EE values are automatically computed by the software.

By clicking on the group name fields in the first column, the 'Group Info' box (Fig 4.2b) appears for the user to enter group name and PP-value. The purpose of the PP (primary producer) column is to classify groups according to their status as producers or consumers. Plants are conventionally classified as primary producers because of their ability to fix carbon in photosynthesis. The net primary production by plants is available for consumption by heterotrophic organisms (bacteria, fungi, and animals), i.e., by consumers. Producers are allocated a PP of 1.00 and consumers a value of 0.00, whereas mixed producers-consumers are given values between 0.00 and 1.00 according to the degree of self-sufficiency. This classification applies when operating with energy-based models. Where the model currency is a nutrient the 'rules' are different. Detritus is given a value of 2.00 in order to distinguish it from all other groups, whereas BNF gets a 1.00 value in order to signify its ability to produce (fix) all N by itself. Upon entering a value of 1.00 for BNF, the user will notice that group consumption (Q/B) value for BNF automatically is set at 0.000. All other groups, plants as well as animals, are given PP-values of 0.00 as they all consume N. The leguminous plants are connected to both the BNF and the detritus boxes, indicating that they derive N from both places, whereas non-leguminous plants are connected to the detritus box only as we shall see later.



Group name: rice

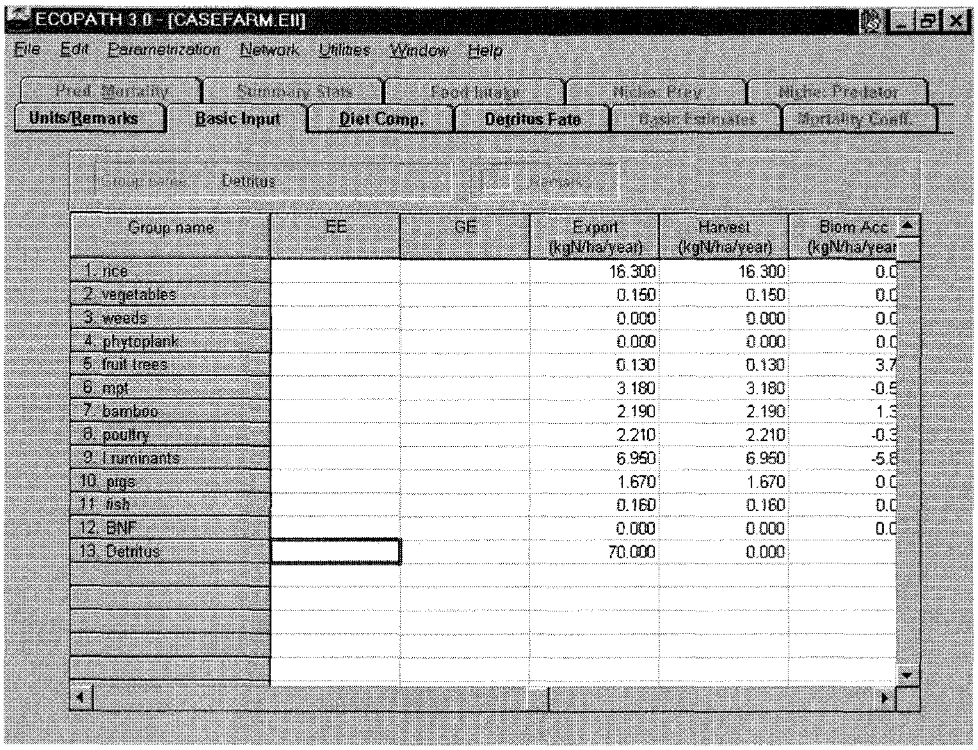
○ Dead

● Living

Production: 0.00

Fig. 4.2b. Group Info screen.

As we move further to the right on the Basic Input screen (Fig. 4.2c) we find another six columns. GE (the gross food conversion efficiency) is the ratio between production and consumption. Like EE it has no unit and its entry is optional. Where values for P/B and Q/B are provided, GE is automatically calculated. Knowing beforehand and entering EE and GE-values can, on the other hand, be used to derive P/B- or Q/B-values where these are unknown. The 'Harvest' and 'Biom.Acc.' (biomass accumulation) values were computed in Chapter 3 and their entry is straightforward. Under 'Export' we enter non-harvested exports/losses from the system, including those from the soil (detritus). 'UnAssim' (unassimilated food) refers to the part of the food consumed by an organism which is excreted as urine and feces. The default values of 0.200 intended for energy-based systems values should be replaced by straight zero values. In the last column, 'Import to det.', we enter the total N import into the detritus box, including both fertilizers and natural inflows as discussed in section 3.13.

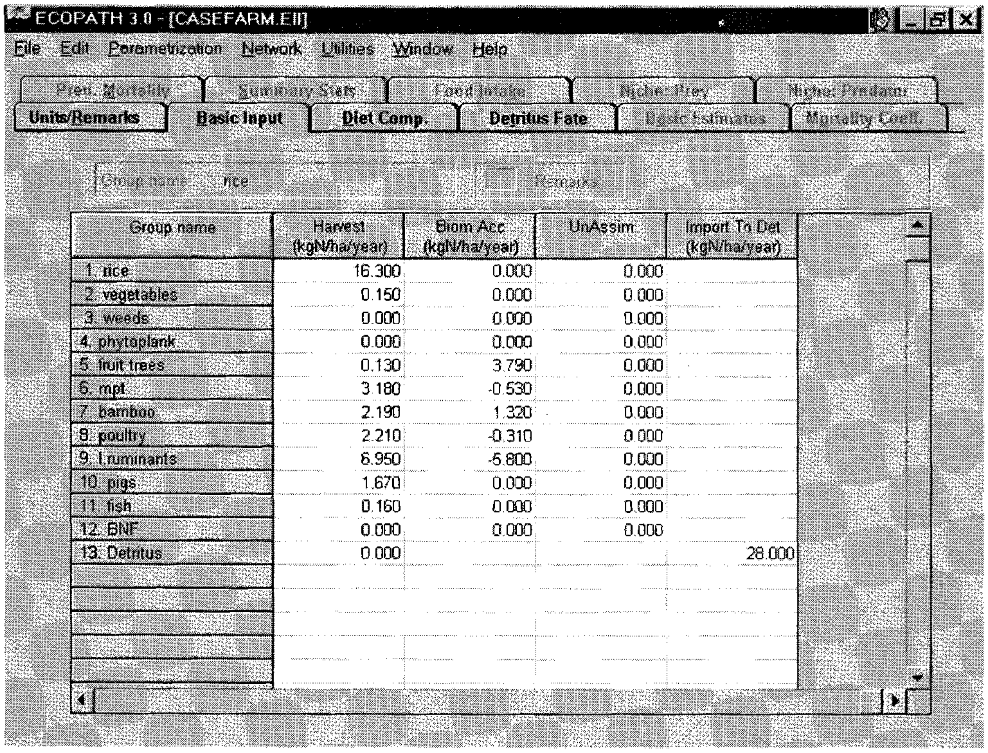


Group name Detritus

Group name	EE	GE	Export (kgN/ha/year)	Harvest (kgN/ha/year)	Biom.Acc (kgN/ha/year
1. rice			16.300	16.300	0.0
2. vegetables			0.150	0.150	0.0
3. weeds			0.000	0.000	0.0
4. phytoplank			0.000	0.000	0.0
5. fruit trees			0.130	0.130	3.7
6. mpt			3.180	3.180	-0.5
7. bamboo			2.190	2.190	1.3
8. poultry			2.210	2.210	-0.3
9. l.ruminants			6.950	6.950	-5.8
10. pigs			1.670	1.670	0.0
11. fish			0.160	0.160	0.0
12. BNF			0.000	0.000	0.0
13. Detritus			70.000	0.000	

Fig. 4.2c. Basic Input screen (second part).

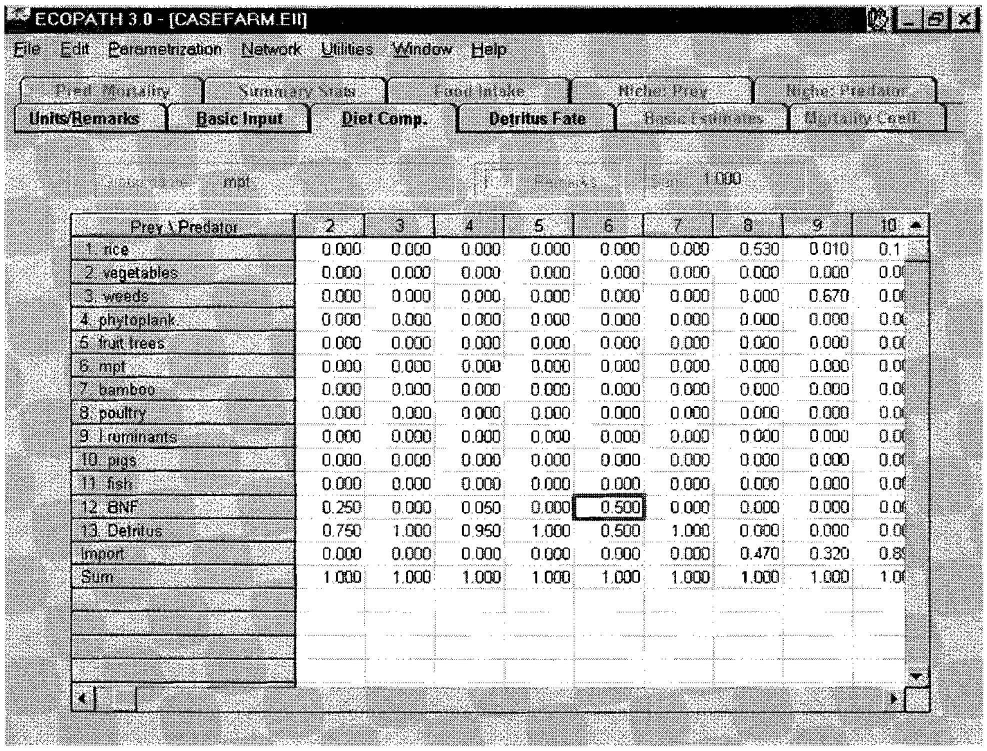
Diet Composition screen (Fig. 4.3): next, we need to apportion the dietary inputs for all groups. The relative diet compositions for animal groups were calculated in Chapter 3, and these values are entered into the matrix, assuring that they sum up to 1.000, or 100%, — see the bottom row in Fig. 4.3 — for each individual group. Non-leguminous plants derive all their nutrients from detritus and are given 1.000 values in the detritus row. N-fixing plants derive a proportion of their N from the BNF box. We assumed that legumes are capable of meeting 50% of their N requirements through fixation, thus the 0.500 values in the BNF and detritus rows under multipurpose trees (Fig. 4.3). In the case of vegetables (column 2), legumes only made up half of the total vegetable biomass, thus the value of 0.250 in the BNF row and 0.750 in the detritus row. Lastly, we estimated blue-green algae, capable of



Group name rice

Group name	Harvest (kgN/ha/year)	Biom Acc (kgN/ha/year)	UnAssim	Import To Det (kgN/ha/year)
1. rice	16.300	0.000	0.000	
2. vegetables	0.150	0.000	0.000	
3. weeds	0.000	0.000	0.000	
4. phytoplank	0.000	0.000	0.000	
5. fruit trees	0.130	3.790	0.000	
6. mpt	3.180	-0.530	0.000	
7. bamboo	2.190	1.320	0.000	
8. poultry	2.210	-0.310	0.000	
9. l.ruminants	6.950	-5.800	0.000	
10. pigs	1.670	0.000	0.000	
11. fish	0.160	0.000	0.000	
12. BNF	0.000	0.000	0.000	
13. Detritus	0.000			28.000

Fig. 4.2d. Basic Input screen. (third part)



mpt

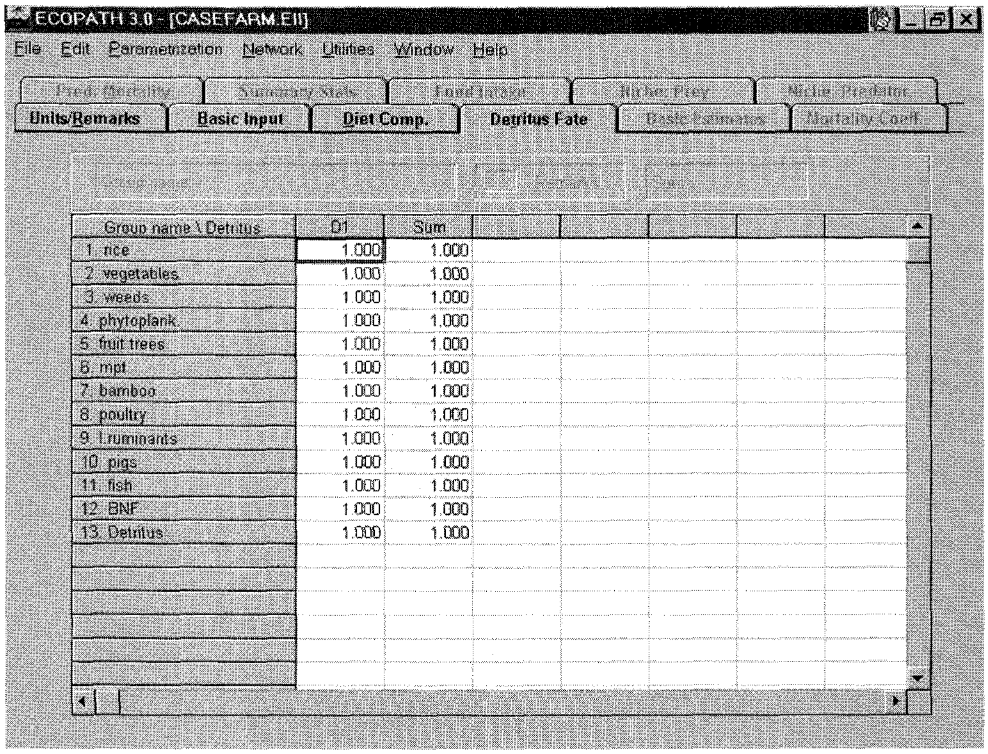
Sum 1.000

Prey \ Predator	2	3	4	5	6	7	8	9	10
1. rice	0.000	0.000	0.000	0.000	0.000	0.000	0.530	0.010	0.1
2. vegetables	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0
3. weeds	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.670	0.0
4. phytoplank	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0
5. fruit trees	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0
6. mpt	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0
7. bamboo	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0
8. poultry	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0
9. l.ruminants	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0
10. pigs	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0
11. fish	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0
12. BNF	0.250	0.000	0.050	0.000	0.500	0.000	0.000	0.000	0.0
13. Detritus	0.750	1.000	0.950	1.000	0.500	1.000	0.000	0.000	0.0
Import	0.000	0.000	0.000	0.000	0.000	0.000	0.470	0.320	0.8
Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.0

Fig. 4.3. Diet Composition screen.

meeting half of their N requirements through fixation, to make up 10% of the phytoplankton biomass giving the values of 0.050 and 0.950 in the BNF and detritus rows, respectively.

Detritus Fate screen (Fig. 4.4): it is possible to define more than one detritus (soil) box for an agroecosystem. This is useful where detritus is moved around within the system, as in pond mud being applied as a growth medium on vegetable beds, and might also assist in identifying and quantifying nutrient sinks and sources within the farm. We defined only one detritus box to which all residues and wastes were returned. Thus values of 1.000 (100%) should be entered for each group in the one detritus column.



Group name \ Detritus	D1	Sum
1. rice	1.000	1.000
2. vegetables	1.000	1.000
3. weeds	1.000	1.000
4. phytoplank.	1.000	1.000
5. fruit trees	1.000	1.000
6. mpt	1.000	1.000
7. bamboo	1.000	1.000
8. poultry	1.000	1.000
9. l.ruminants	1.000	1.000
10. pigs	1.000	1.000
11. fish	1.000	1.000
12. BNF	1.000	1.000
13. Detritus	1.000	1.000

Fig. 4.4. Detritus Fate screen.

4.3 Data Output

The ECOPATH analytical outputs are presented through a series of screens. Those of immediate interest include 'Basic estimates', 'Summary statistics', 'Cycles and pathlengths', and the 'Flow diagram'. The software offers several more analytical routines which will be briefly touched upon here[17].

Basic Estimates screen (Fig. 4.5): the dataset developed for the case study farm was complete in terms of PP, B, P/B, Q/B, harvests, exports, imports and diet composition param-

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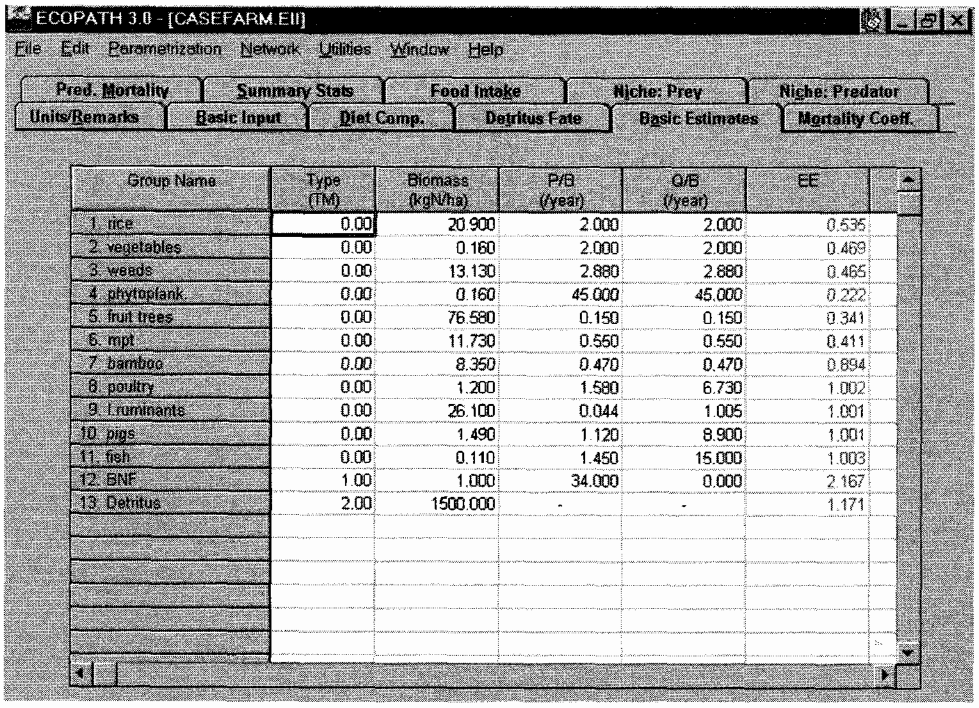
[17] For more details see Christensen and Pauly (1995) and Pauly and Christensen (1995).

eters. Where all computations (Chapter 3) and data entries are correct, the software only needs to compute the missing EE and GE values in order to generate a complete dataset. Warning messages may be displayed at this stage. This indicates either unlikely parameter calculations or wrong data entries, and there may be a need to recheck input parameters. A common warning message, which can usually be ignored, is the following[18]: "P/B is greater than Q/B for weeds; GE for the group is very high [>0.5]".

EE values should lie between 0 and 1. Values slightly above 1.000 (see 'pigs' and 'fish' in Fig. 4.5) indicate small inaccuracies in the parameter computations (Chapter 3), e.g., in the rounding off of decimal figures, and are usually acceptable although it is advisable to recheck the computations. Higher EE values are indicative of erroneous parameter computations and/or data entry and must be rechecked.

The ecotrophic efficiency of detritus expresses the ratio of what flows out of and what flows into the soil box. Under steady-state this should be equal to 1, i.e., inflows balance outflows. An EE of less than 1 means that more N is entering than leaving, whereas an EE larger than 1 means the opposite. In other words, an EE < 1 suggests accumulation of detritus N (the lower the value the higher the relative accumulation), whereas an EE > 1 indicates a net loss of N from the soil. Detritus EE is a potentially very important diagnostic, indicating the direction in which the resource base of the agroecosystem is moving, whether improving or deteriorating.

GE values also vary between 0 and 1. Plants have a GE (gross efficiency) of 1.000 as all consumed N is incorporated into plant tissue. Animals excrete a large portion of the consumed



Group Name	Type (TM)	Biomass (kgN/ha)	P/B (/year)	Q/B (/year)	EE
1. rice	0.00	20.900	2.000	2.000	0.535
2. vegetables	0.00	0.160	2.000	2.000	0.469
3. weeds	0.00	13.130	2.880	2.880	0.465
4. phytoplank.	0.00	0.160	45.000	45.000	0.222
5. fruit trees	0.00	76.580	0.150	0.150	0.341
6. mpt	0.00	11.730	0.550	0.550	0.411
7. bamboo	0.00	8.350	0.470	0.470	0.894
8. poultry	0.00	1.200	1.580	6.730	1.002
9. l.ruminants	0.00	26.100	0.044	1.005	1.001
10. pigs	0.00	1.490	1.120	8.900	1.001
11. fish	0.00	0.110	1.450	15.000	1.003
12. BNF	1.00	1.000	34.000	0.000	2.167
13. Detritus	2.00	1500.000	-	-	1.171

Fig. 4.5. Basic Estimates screen.

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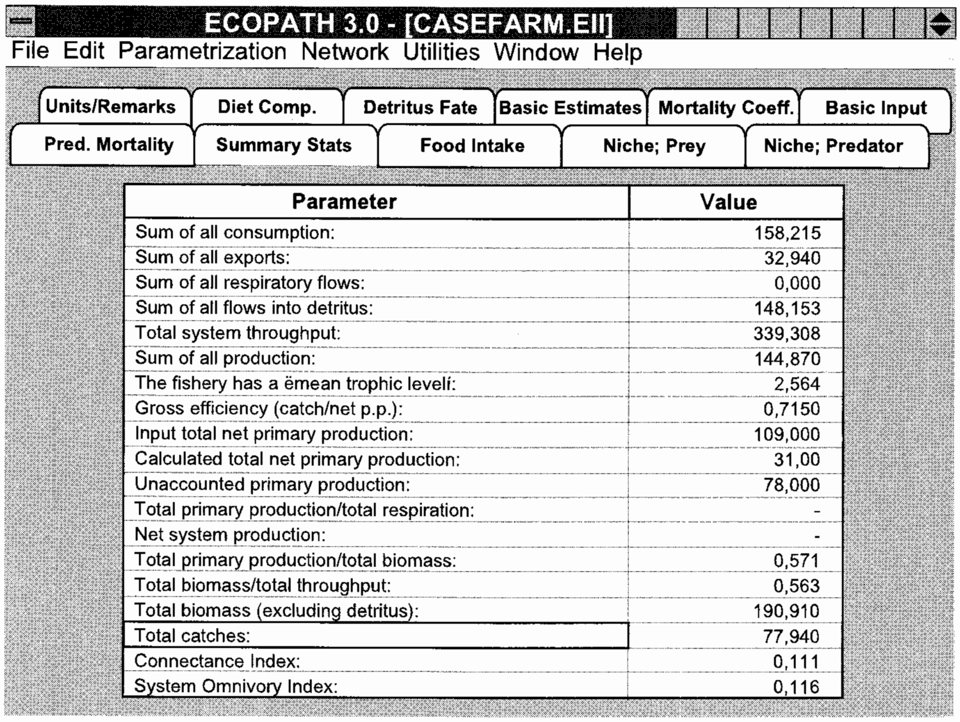
[18] In energy-based ECOPATH models, most consumer groups, i.e., groups with PP-values of 1.00 (animals) usually have GE-values between 0.1 and 0.3. In a nutrient based model, however, plants as well as animals are defined as consumers, with PP-values of 1.0. Plants have GE-values of 1.0, i.e., well above the 'expected' 0.1-0.3 range, thus the warning message.

N, and typically have GE values between 0.1 and 0.3. Low GE values indicate low growth rates and high maintenance costs.

Summary Statistics screen (Fig. 4.6): this is the main output screen and some of the statistics and indices presented here provide important indicators for the performance of the agroecological system:



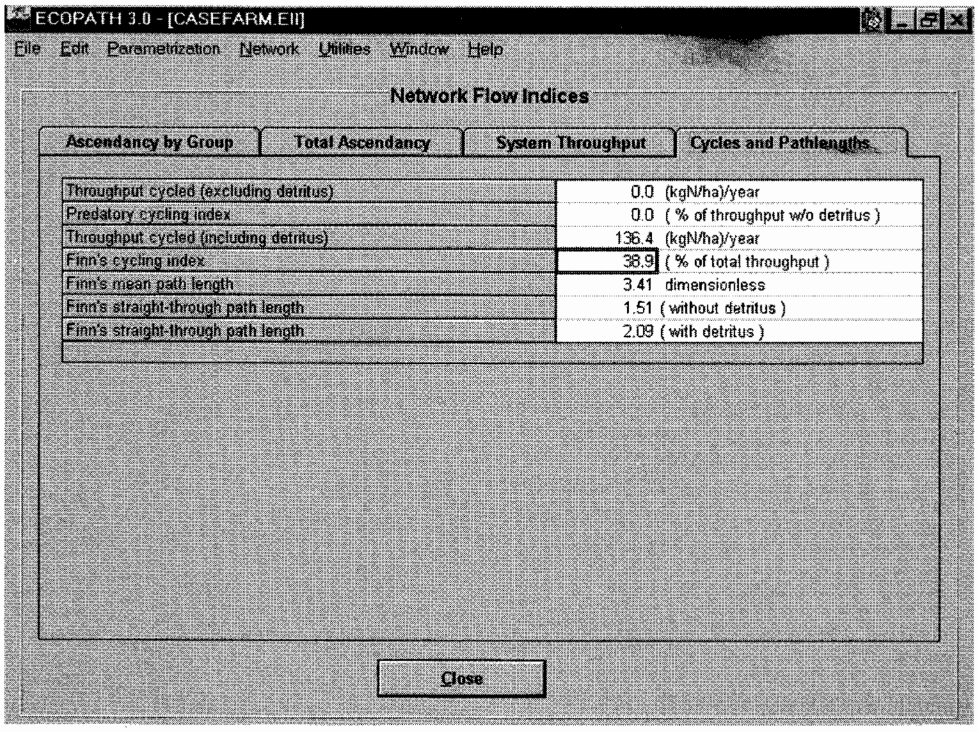
Parameter	Value
Sum of all consumption:	158,215
Sum of all exports:	32,940
Sum of all respiratory flows:	0,000
Sum of all flows into detritus:	148,153
Total system throughput:	339,308
Sum of all production:	144,870
The fishery has a ëmean trophic levelí:	2,564
Gross efficiency (catch/net p.p.):	0,7150
Input total net primary production:	109,000
Calculated total net primary production:	31,00
Unaccounted primary production:	78,000
Total primary production/total respiration:	-
Net system production:	-
Total primary production/total biomass:	0,571
Total biomass/total throughput:	0,563
Total biomass (excluding detritus):	190,910
Total catches:	77,940
Connectance Index:	0,111
System Omnivory Index:	0,116

Fig. 4.6. Summary Statistics screen.

- 'Total system throughput' is defined as the sum of all imports, consumption, returns to detritus, harvests and exports, and represents the size of the system in terms of its flow network (Ulanowicz 1986). Throughput is furthermore used in the computation of the B/E ratio (see below);
- 'Net system production' includes both primary (plant) and secondary (animal) production, i.e., all the (above ground) biomass produced within the system, and is a measure of the system's overall productive capacity;
- 'Total primary production/total biomass', the P/B ratio, is expected to decrease as an ecosystem matures, biomass rates slow down and maintenance costs increase (Odum 1969). If a potential avenue towards an ecologically sustainable agriculture is through the mimicking of natural ecosystems, then we should design systems that develop comparatively low P/B ratios;
- 'Total biomass/total throughput', or the B/E ratio, is expected to increase as an ecosystem matures (Odum 1969). If maturity and sustainability are somehow positively related, we will be looking towards agricultural systems which develop comparatively high B/E ratios;

- 'Total biomass (excl. detritus)' expresses the total average standing biomass (above ground, i.e., the size of the system) in terms of plant and animal stocks. One feature of agroecological systems that might warrant further investigation is the design of farms which maintain high average standing biomasses to buffer the systems, yet are high yielding at the same time;
- 'Total catches' is equal to productivity, or net yield.

Cycles and Pathlengths screen (Fig. 4.7): the attribute of interest is Finn's cycling index (Finn 1980). The index expresses the fraction of total throughput that is recycled. Within agroecological research, there is speculation that increased nutrient recycling is an important means to achieve a more efficient and ecologically sound agriculture. It might, therefore, be of interest to compare cycling indices across different farm scenarios and to observe how cycling relates to other key properties such as throughput, productivity (yield) and efficiency. Using ECOPATH to simulate hypothetical scenarios and investigate maturity in aquatic ecosystems, Christensen and Pauly (1996b) find that a key characteristic of a mature ecosystem is its ability to effectively utilize, retain, and recycle nutrients through detritus. Better use and recycling of detritus facilitate very large increases in consumer biomasses and are seen as necessary ingredients in sustainable aquatic ecosystem management. We believe that the same applies to terrestrial ecosystems.



Throughput cycled (excluding detritus)	0.0 (kgN/ha)/year
Predatory cycling index	0.0 (% of throughput w/o detritus)
Throughput cycled (including detritus)	136.4 (kgN/ha)/year
Finn's cycling index	38.9 (% of total throughput)
Finn's mean path length	3.41 dimensionless
Finn's straight-through path length	1.51 (without detritus)
Finn's straight-through path length	2.09 (with detritus)

Fig. 4.7. Cycles and Pathlengths screen.

Flow diagram (Fig. 4.8): Fig. 4.7 shows the ECOPATH flow diagram of the case study farm — a trophic network model, with all states (boxes) and rates (flows) quantified. Boxes are plotted so that the horizontal axis of symmetry is aligned with the trophic level of the box, and are sized in proportion to the logarithm of their respective biomasses to help visualize the relative role of the organisms in each box (Christensen and Pauly 1992b). The model displays the values of all basic input parameters except for biomass accumulation within boxes.

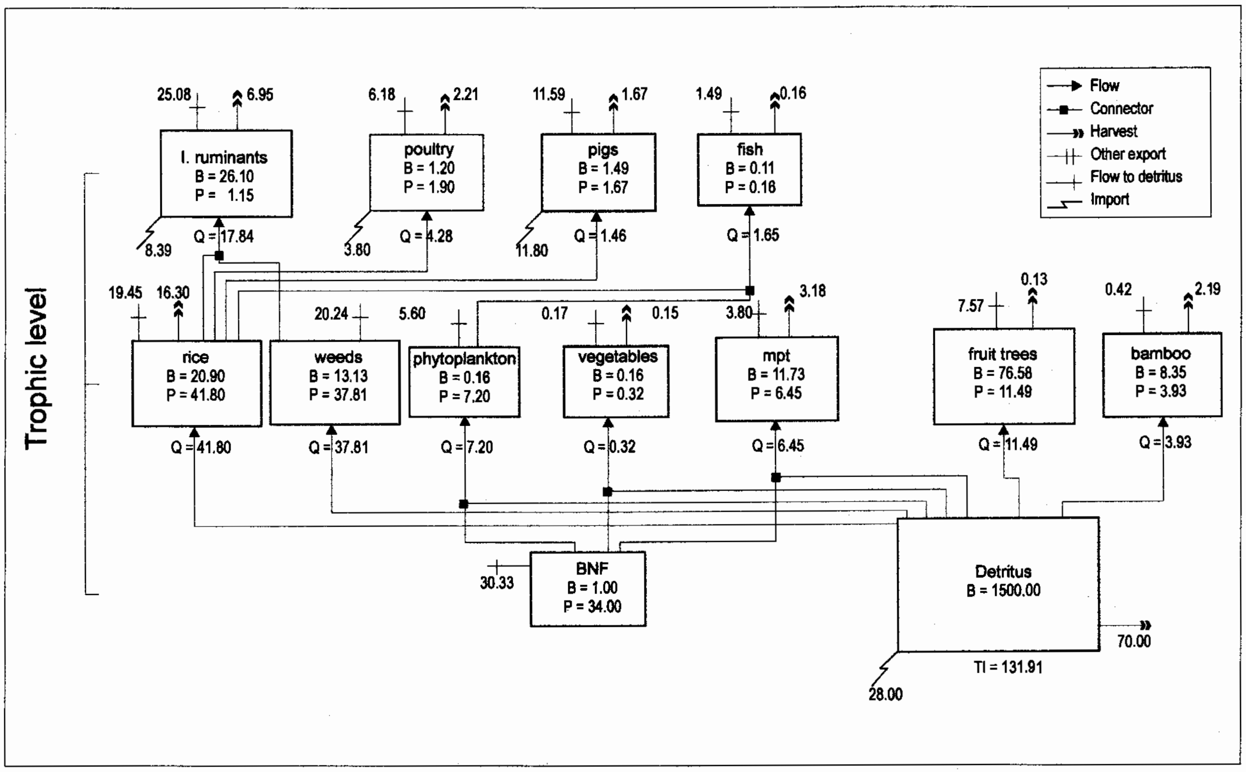


Fig. 4.8. ECOPATH flow diagram of the case study farm with all parameters expressed in kg N ha^{-1} year^{-1}.

CHAPTER 5

Quantitative Performance Indicators

5.1 Indicator Summary

Quantitative measures, as the ones presented in Chapter 4, are useful for assessing and comparing the state and performance of agroecological systems. Table 5.1 provides an overview of attributes computed by ECOPATH, together with additional properties computed outside ECOPATH — species richness, diversity, efficiency (output/input ratio) and system harvest index. The table compares the case study farm with a smallholder monoculture rice farm. The comparative ecological as well as economic performance of these two systems is discussed in depth in Dalsgaard and Oficial (1997) and Dalsgaard (1997). The modeling and analysis suggest that integration and diversification can generate farm agroecosystems which are productive, profitable and manageable, and surpass their monoculture counterparts on several counts as measured through ecological and economic indicators.

A key characteristic associated with the health and performance of both natural ecosystems and agricultural systems is diversity (Magurran 1988; Roger et al. 1991; Paoletti et al. 1992; Brookfield and Padoch 1994; Altieri 1995; Pullin 1995). Diversity is usually quantified within taxa (taxonomic groups) on a species basis. We talk about the diversity of trees, birds, insects, invertebrates, etc. Species diversity is sometimes used interchangeably with species richness, though the latter represents a simple count of the number of species while the former also considers their relative abundance by taking account of numbers of individuals within the species. Computing system diversity within a community of mixed life forms, i.e., including several taxa within the same index, is unconventional. We, nevertheless, propose two agroecosystem diversity expressions (Table 5.1): a common species richness measure, counting the number of farmed and utilized species within the farm, and; what we term 'agricultural diversity' (Dalsgaard and Oficial 1997) computed by weighting each group of organisms in the farm model by its abundance as expressed in terms of its average standing biomass (B), measured in kg N ha^{-1}. Shannon's index (Magurran 1988) was used to compute this agricultural diversity.

Table 5.1. Agroecological performance indicators for two different types of farm systems. (Source: Dalsgaard and Oficial 1997).

Quantitative attributes	Farm A (monoculture rice farm)	Farm B (case study farm)
- Computed outside ECOPATH:		
Agricultural species richness (no. of farmed and utilized species)	4	32
Agricultural diversity (computed using Shannon's index)	0.70	1.56
Efficiency (output/input ratio)	0.19	0.38
System harvest index (net system yield/sum of all production)	0.14	0.22
- Computed by ECOPATH:		
Productivity		
- net system yield (kg N ha^{-1} $year^{-1}$)	43	33
- sum of all production (kg N ha^{-1} $year^{-1}$)	323	144
Total system biomass (excl. detritus) (kg N ha^{-1} $year^{-1}$)	88	191
Nutrient cycling (Finn's index)	0.25	0.40
Nutrient throughput (kg N ha^{-1} $year^{-1}$)	716	340
P/B ratio ($year^{-1}$)	2.8	0.57
B/E ratio ($year^{-1}$)	0.12	0.56
Detritus EE (ecotrophic efficiency)	0.850	0.711

5.2 Ecosystem Goal Functions: System Overhead, Ascendency, Exergy

The application of ecosystem concepts and theory to agricultural systems presents a potential avenue towards the identification of quantifiable agroecological performance indicators. Recent developments within systems ecology have introduced new complex expressions of the state of natural ecosystems:

Stability (Holling 1987; Begon et al. 1990) is a property often associated with the performance and sustainability of (agro)ecosystems (Conway 1985a). ECOPATH computes a potential proxy for stability, called '**system overhead**', and seen as an expression of resistance to external perturbations (Christensen and Pauly 1992b; Christensen 1994, 1995). Relative system overhead was found to be positively correlated with the intuitive perception of maturity in aquatic ecosystems (Christensen 1994, 1995), and appears to be similarly related to our intuitive perception of ecological sustainability in agroecosystems (Dalsgaard et al. 1995; Dalsgaard, unpublished data).

System overhead is related to **ascendency**. Ascendency expresses ecosystem growth and development and quantifies the diversity and articulation of the system's flow network (Ulanowicz 1986). Christensen (1995) found relative ascendency to be inversely related to ecosystem maturity, *sensu Odum,* and Dalsgaard (unpublished data) likewise found indications that relative ascendency, as computed within ECOPATH, is inversely related to an intuitive sustainability perception. This suggests that ecosystem maturity and agroecological sustainability could be related. Definitions and derivations of the ascendency and overhead concepts are provided in Ulanowicz (1986, 1993).

Exergy (Mejer and Jørgensen 1979; Jørgensen 1992) has, like ascendency, been introduced as a goal function in ecosystem theory: through natural evolution an ecosystem is hypothesized to develop so as to optimize its exergy. Exergy expresses the system's 'free energy' relative to a reference system, the thermodynamic equilibrium. This free energy is contained within the system's live biomass (structure) and within the genetic information of its living organisms (organization). Exergy cannot be measured but is computed by multiplying plant and animal biomasses with crude genetic conversion factors (Jørgensen et al. 1995). If mimicking the structure and organization of natural ecosystems can point a way towards an ecologically sustainable agriculture, then we should aim to design agroecosystems which optimize their exergy and structural exergy. The exergy and ascendency goal functions express two sides of the same coin: the former deals with the characteristics of an ecosystem in terms of its state variables (stocks), whereas the latter considers the associated flow network. The two measures are thus complementary (Jørgensen 1992). When addressing the sustainability issue, being armed with a range of descriptors should be seen as an advantage. We cannot expect to capture the concept within a single measure.

5.3 Nutrient Balances

The balance of material flows through an agroecosystem is another important performance indicator (Smaling and Fresco 1993; Shepherd et al. 1996). Production cannot be sustained in the long run, when outputs exceed inputs, without some form of replenishment. Soil conservation measures, reuse of crop residues and animal wastes, combining crops with trees capable of tapping into subsoil resources, cultivation of plants capable of fixing atmospheric N, integrating agriculture with aquaculture, etc., are examples of farm management techniques and strategies, which are useful in designing agroecosystems for enhanced ecological and agronomic performance. Such practices can help improve the nutrient balance sheet.

In section 3.13 we defined and quantified the possible pathways of N gains and losses for the case study agroecosystem. These fluxes can be used to compute rough N balances for the agroecosystem as a whole and for its soil base:

a) Agroecosystem balance =

(feed and fertilizer inputs) + (BNF) + (dry and wet deposition) + (run-on with incoming irrigation water) - (net yield removed from the production system) - (detritus losses[19]) - (other exports/losses)

b) Detritus (soil) balance =

(agroecosystem balance) - (changes in plant and animal stocks)

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[19] Detritus losses via volatilization and denitrification. Detritus losses from run-off and leaching were assumed to be negligible.

Table 5.2 shows the balances for the monoculture farm and the case study farm presented in Table 5.1. In both cases, the computed balances are positive, i.e., more N enters than leaves each system[20]. This suggests more efficient resource use on the case study farm, the integrated system given that it only imports 19 kg N ha^{-1} $year^{-1}$ in the shape of inorganic fertilizers, as opposed to 132 kg N ha^{-1} $year^{-1}$ on the monoculture farm. It also indicates a potential negative impact from the monoculture farm, with excessive N polluting the sourrounding environment. Dalsgaard (1997) has a more thorough discussion on the derivation of complete farm N budgets with the ECOPATH framework.

Table 5.2. Nutrient balances for two different types of farm systems.

	Farm A (monoculture rice farm)	Farm B (case study farm)
Agroecosystem balance: (kg N ha^{-1} $year^{-1}$)	15-20	~ 5
Detritus (soil) balance: (kg N ha^{-1} $year^{-1}$)	15-20	~ 1

5.4 Conclusion

We have presented an analytical framework for monitoring and modeling farms and for deriving potential agroecological performance indicators. These span from simple, common measures such as system productivity and efficiency, to conceptually more complex properties, including diversity, production/biomass, biomass/throughput and measures of ecosystem maturity.

Sustainability indicators are required at several levels. Different users need different indicators. The resource managers, or farmers, are more concerned with specific technologies that improve the productive capacity of the farm and help them manage their resource base. Simple, operational indicators are required to communicate research findings to farmers and to generate healthy and productive agroecosystems[21].

Our preliminary investigations suggest that composite measures such as the P/B and B/E ratios, i.e., measures of ecosystem evolution and maturity, *sensu Odum*, and more recent maturity measures (ascendency and exergy) emerging within the academic field of systems ecology and ecosystem health could provide guidelines in the research and development of healthy agroecosystems. Our initial findings also indicate that systems can be generated which perform well on most counts, i.e., are ecologically sound (diverse and integrated, with efficient nutrient cycling), manageable in terms of labor requirements and productive in both the biological and economic sense (Dalsgaard et al. 1995; Dalsgaard and Oficial 1997). Further application

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[20] Positive soil N balances are also supported by the Detritus EE-values of less than 1.0 in Table 5.1.

[21] The RESTORE framework (Research Tools for Natural Resources Management, Monitoring and Evaluation) developed at ICLARM uses simple economic and ecological indicators (productive capacity, economic efficiency, diversity [species richness], and recycling) to assess the performance of integrated agroecosystems developed through farmer-led experimentation.

and refinement of the proposed framework at different spatial scales throughout the agricultural landscape (at farm, village, and watershed levels) is required to explore the behavior and robustness of the different descriptors, their critical limits and their possible trade-offs.

Lightfoot et al. (1993c) demonstrates some of the potential advantages of analyzing systems at different agroecological levels. Their investigation of ricefields and rice-fish fields constitutes an analysis of what we in the context of the case study of this report would label subsystems. Our modeling and analysis at the farm level did not yield insights into the interactions, performances and roles of various groups of organisms within the soil and water resource base. Moving one step down in the hierarchy from farm to field level, however, is all it takes to research these aspects.

5.5 Further Explorations with ECOPATH

ECOPATH offers more than the basic analytical outputs covered in this report. To describe the remaining routines adequately would require many more pages. We felt that the need was to introduce the software to an agriculture oriented audience, rather than to give an exhaustive stand-alone account of its full analytical potential. However, a couple of routines do deserve a brief mention, partly to preempt criticism and partly to describe better the full capacity of the software.

EcoRanger: the EcoRanger module allows the entry of a range and mean/mode values for all the basic parameters (biomasses, consumption rates, production rates, and ecotrophic efficiencies). The user specifies frequency distributions for each parameter type as well as certain model criteria. Random variables are drawn from this and the resulting model evaluated. The process is repeated in Monte-Carlo fashion and, of the runs that pass the selection criteria, the best fitting one is chosen using a least squares criterion. EcoRanger thus introduces a statistical approach to model fitting (Christensen and Pauly 1995, 1996b).

EcoSim: 'A major new development concerning ECOPATH, but too recent to be included in version 3.0, is the suggestion that the system of coupled linear equations underlying ECOPATH can be reexpressed as a system of coupled differential equations, which can be integrated in time. This has led to a program called EcoSim which can run ECOPATH files in simulation mode (Walters et al. 1997). Work is underway to make this program function as an integrated routine of ECOPATH, and it is anticipated that the future software releases will support simulation modeling (Christensen and Pauly 1996a).

Mixed trophic impact: another potentially powerful analytical and graphic output is the 'Mixed trophic impact routine', which describes the direct and indirect impacts all groups have on each other. Using this routine in the investigation of ricefield ecosystems, with and without fish, led researchers to speculate that the intensification of rice might lead to a decrease in soil microbial biomass and thus in soil-available N and long-term fertility (Lightfoot et al. 1993c). The comparative modeling and analysis also indicated a positive impact of fish (tilapia) on the performance of rice, suggesting that stocking fish in ricefields may lead to greater efficiency in rice production.

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