SYSTEMS APPROACHES FOR
SUSTAINABLE AGRICULTURAL DEVELOPMENT

Applications of Systems Approaches at the Farm and Regional Levels
Volume 1

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Kluwer Academic Publishers
in cooperation with
International Rice Research Institute
International Consortium for Agricultural Systems Applications

Library of Congress Cataloging-in-Publication Data is available.

ISBN 0-7923-4285-2 (vol. 1)
ISBN 0-7923-4286-0 (vol. 2)
ISBN 0-7923-4287-9 (set)

Published by Kluwer Academic Publishers,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

Kluwer Academic Publishers incorporates
the publishing programmes of Martinus Nijhoff,
Dr W. Junk, D. Reidel, and MTP Press.

Sold and distributed in the U.S.A. and Canada
by Kluwer Academic Publishers,
101 Philip Drive, Norwell, MA 02061, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers Group,
P.O. Box 322, 3300 AH Dordrecht, The Netherlands.

Printed on acid-free paper

Printed and bound in Great Britain by
Hartnolls Limited, Bodmin, Cornwall

PART II: REGIONAL LEVEL

Flow modelling with ECOPATH: providing insights on the ecological state of agroecosystems

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Key words: agroecology, systems modelling, sustainability indicators

Abstract
ECOPATH is an ecological modelling software developed for the analysis of aquatic ecosystems. Incorporating elements of ecosystem theory and more recent developments within network analysis of trophic interactions, it computes a series of system attributes. Such quantified properties can also be useful for evaluation of agroecosystems and for providing insights into their ecological performance, productivity and efficiency. This has been demonstrated for integrated agriculture-aquaculture systems at both the farm subsystem and whole-farm level. The paper summarizes the major findings in modelling and analysing agroecosystems using ECOPATH. It is anticipated that this type of approach and comparison of ecological properties across different natural resource management scenarios, and of various levels throughout the agroecological hierarchy, will help identify quantifiable indicators towards ecological sustainability in agricultural development.

Introduction

Concepts and approaches introduced to promote ecologically sound and productive farming towards sustainable agriculture have been reported in the literature and include low-external-output agriculture, organic farming, agroecological engineering, integrated production, permaculture, integrated agriculture-aquaculture, agroforestry and integrated natural resources management (Young 1989; Mollinson 1991; Reintjes et al. 1992; Lightfoot et al. 1993a; Altieri 1995; Pretty 1995).

To assess the ecological performance of farming calls for quantitative measures. Given the complexity of natural resources and their management, systems-oriented approaches are in the future likely to play a prominent role within this area of research and development.

Agricultural systems can be viewed as assemblages of plants and animals linked in multiple ways. This perspective is useful as stocks and flows which can be described, modelled and analysed, as well as assessed and compared, on a system level. Agroecosystems further have certain properties because of their parts and intra-relationships. We assume that modelling such systems and investigating their aggregate properties can provide useful agroecological insights.

The agroecological hierarchy

A farm activity and its interaction with the environment constitutes an agroecosystem. In the wide sense, agroecosystem refers to both biophysical and socioeconomic

P.S. Teng et al. (eds.): Applications of Systems Approaches at the Farm and Regional Levels, 203–212.

aspects of farming (Conway 1985). However, in the more narrow sense adopted here, the agroecological system emphasizes the ecological and biophysical aspects of farming (Altieri 1995).

The agroecological system can be viewed at many levels such as: an individual rice plant forming part of a soil-water-plant continuum; and a population of rice plants (a rice field) host not only to rice, but also to a variety of organisms such as insects, molluscs, fish, reptiles, birds, zooplankton, phytoplankton, benthic organisms, soil microbes, macrophytes, grasses and weeds. Such field communities form part of a larger system wherein crops, trees, poultry, livestock, fish, etc. combine to make up a farm; groups of farms constitute villages located within watersheds; and so forth (Figure 1).

In theory, the agroecological system can be defined at any level throughout this nested hierarchy. Each level within the hierarchical framework shares a number of common characteristics such as stocks (or components), inputs and outputs and flows of resources between components. Thus, the agroecological system at any level identified by the observer can be viewed as an assemblage of resource components and flows. This generic feature indicates the potential for applying general analytical tools at multiple and possibly at complementary levels.

Modelling agroecological systems

Agroecological systems are dynamic systems. It is a goal of ecological modelling to construct dynamic and structural dynamic models (Jørgensen 1994) that adequately emulate organic systems. Their complexity and dynamism even at the most basic level can be overwhelming, and where limitations to our state of knowledge prevent the application of such methods, we must look for alternatives.

An option is to initially ignore the temporal component and take a more static view. Despite a generally lower level of mathematical sophistication (linear as opposed to differential equations), this approach should not necessarily be seen as only a second-best option. A mass-balanced model can provide an accurate and useful picture of an ecological system in an average state, and hence facilitate comparisons between different states of ecosystems. The insights provided through this type of modelling can fulfil many of our requirements and modelling expectations.

ECOPATH models produce average pictures or 'snapshots' of systems. Repeated over time these 'snapshots' can be combined to provide a time series view of a system's performance – one way of recapturing some of the dynamics that are otherwise ignored through the static approach. Another useful aspect of the average state concept is the insights it may provide into aggregate system properties. Diversity, for instance, is not measured by looking at a single component or species, but is a community attribute as are cycling, stability, and sustainability. These attributes, along with other key properties, such as productivity and efficiency, may equally be addressed and assessed at the system level.

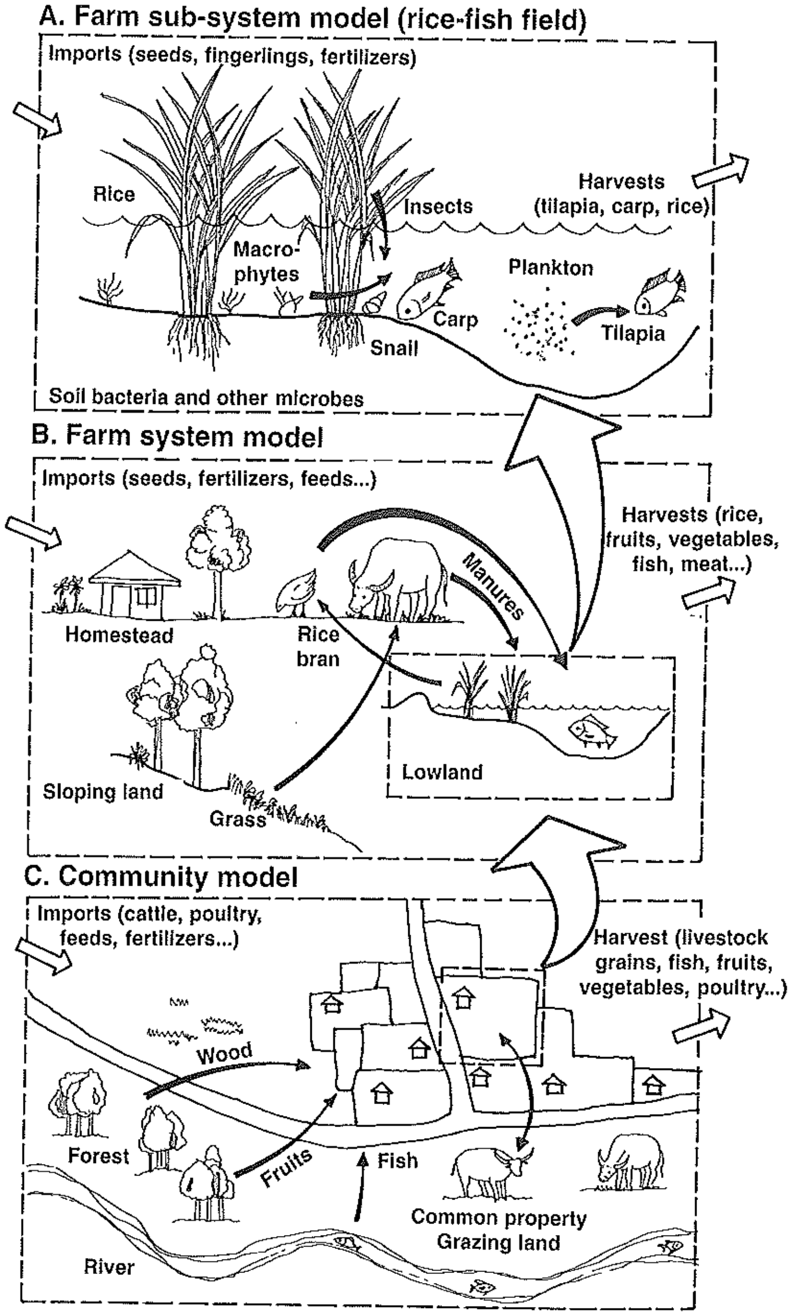

Figure 1. Example of a nested agroecological hierarchy.

Features of ECOPATH

The ECOPATH approach was developed with the purpose of constructing mass-balance models of aquatic ecosystems (Christensen and Pauly 1992a,b). The utility of the non-commercial software implementing the ECOPATH approach as a structuring, analytical and synthesizing tool is documented in Christensen and Pauly (1995). Here, ECOPATH applications were focused across large- and small-scale, tropical and temperate aquatic systems including oceans, lakes and rivers, as well as fishponds and rice field ecological systems.

Aquatic and terrestrial ecosystems have many commonalities, and the mass-balance concept and basic ecological principles upon which ECOPATH is founded apply equally well to both types of environments. Through network analysis of trophic interactions, ECOPATH provides a practical means of incorporating and synthesizing some of the dominant thinking in ecological systems theory over the last decades into the modelling and quantitative analysis of ecosystems. Several attributes of development and maturity in natural ecosystems suggested by Odum (1969) are incorporated into the analytical routines. These and other systems attributes, notably ascendancy (Ulanowicz 1986), are computed as ratios, indices and summary statistics which provide a basis for evaluating the ecological state of a given system.

Model parameterization

To construct an ECOPATH model, data on resource stocks and flows are required. The basic input parameters needed for each defined group of organisms are: average standing biomass (B); production per unit of biomass (P/B ratio); consumption per unit of biomass (Q/B ratio); harvests; other exports (e.g. losses); and the diet matrix giving the composition of food (i.e. energy or nutrient sources) for each group of plants and animals.

For instance, a rice plant gets all its nutrients from the detritus (soil) box, whereas a group of livestock typically will derive their food from a variety of sources such as grasses/weeds, straw and feed imports into the system. These different flows must be quantified. Finally, the model is balanced by the software so that input equals output for each system component.

Model outputs

On the basis of the mass-balanced model, ECOPATH quantifies a range of ecosystem concepts and properties. These include cycling indices, pathways, mixed trophic impacts, food niche overlap, mortality coefficients, energy/nutrient transfer efficiencies through the food web, and other descriptive statistics. Model statistics, ratios and indices included are primarily those commonly applied within fisheries biology and aquatic ecology. Although not all of these are easily interpreted within or necessarily relevant to the agroecological analysis, many of the other output functions have already been explored through agroecological modelling. Furthermore, it is the intention to modify future versions of the software so as to facilitate agroecological applications.

ECOPATH applications

A number of applications of ECOPATH to agroecosystems have already been made (Lightfoot et al. 1993b; Cagauan et al. 1993; Ruddle and Christensen 1993; Van Dam et al. 1993; Dalsgaard et al. 1995).

A cooperative study between the International Rice Research Institute, Central Luzon State University and the International Center for Living Aquatic Resources Management was made to use ECOPATH to compare rice field scenarios with and without fish (Figure 2). Preliminary results from on-station research showed that stocking rice fields with fingerlings not only produced marketable fish, but also led to a greater nitrogen efficiency in rice production (Lightfoot et al. 1993b). They also suggested that the results of using ECOPATH can assist in the identification of long-term experiments and important parameters for further study to better understand how these ecosystems work. A follow-up study by Cagauan et al. (1993) confirmed the greater ability of the integrated rice-fish system to capture and use nitrogen. A negative impact of fish on weeds, snails and insects as found by the model, showed the usefulness of fish (carp) in biological pest control.

Ruddle and Christensen (1993) found ECOPATH to represent a robust modelling approach in investigating the energy flow of a Chinese mulberry dike-carp pond farming system (Figure 3). The analysis showed the system to have very high through-put and production. Developed over hundreds of years, this is indeed a well-designed integrated agriculture–aquaculture system.

Van Dam et al. (1993) evaluated the trophic interactions in a napier grass-fed aquaculture pond in Malawi. Results shows that constructing a mass-balanced model demonstrated the gaps in our knowledge on food web structure, and on the productivity of various groups of organisms in grass-fed ponds.

Moving up one step in the agroecological hierarchy, Dalsgaard et al. (1995) used ECOPATH II as the main tool in the analysis, quantification and comparison of system attributes across four rice-based farms (Figure 4). It was found that our intuitive or qualitative sense of ecologically sound farming seems to stand up to a more quantitative scrutiny based on key indicators including diversity, nutrient cycling, stability and productive capacity.

The above-mentioned results show how the application of ECOPATH has gradually expanded and broadened to include farm enterprises, as well as the aquatic rice and fish units. Typical examples are being drawn no longer from on-station research, but increasingly from farms. Models have also been developed at different hierarchical levels and, where initial analyses focused on detailed trophic interactions at the farm subsystem level, other models are now being generated at the whole-farm system level.

An on-form study is presently underway in which four Philippine smallholder rice farm scenarios are being closely monitored for subsequent modelling, analysis

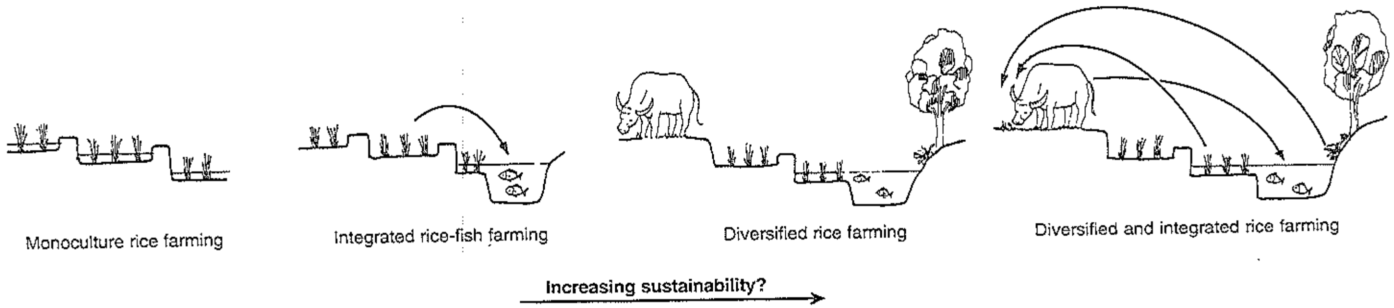

Figure 4. Ecological sustainability in rice farming.

and comparisons of productivity and nutrient (nitrogen) efficiency, as well as nutrient cycling, diversity and other agroecological attributes (Dalsgaard 1996; Dalsgaard and Oficial 1996a,b,c). The farms range from a low-external-input to a high-external-input system with and without integrated aquaculture, livestock, poultry, vegetable and tree components. It is expected that these types of investigations of aggregate system properties at the farm level will assist in the identification of quantifiable indicators of ecological sustainability, and in deriving general guidelines for sustainable, i.e. productive and ecologically sound, integrated farming systems.

Conclusions

The general broadening of the application of ECOPATH from aquatic towards terrestrial-based systems suggests that the approach could become, in the future, an example of a general tool unifying fields of fisheries, science, limnology, aquaculture, farming systems and agroecological research (Christensen and Pauly 1995).

At present, the mode of application of ECOPATH in agroecological analysis has been descriptive. Added facilities in new versions of ECOPATH (Appendix 1) could eventually open up possibilities for using the software in a more predictive mode. Combined with other modelling facilities and tools which simulate system behaviour and responses to different forcing functions, ECOPATH could become a very useful quantitative instrument in the exploration of feasible paths towards an ecologically sustainable management of natural resources.

Acknowledgements

Wholehearted thanks are due to Dr. Clive Lightfoot, Information Centre for Low External Input and Sustainable Agriculture (ILEIA), for fruitful and inspiring cooperation. The work of the authors is funded by the Danish International Development Assistance (Danida). This is ICLARM Contribution No. 1164.

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Appendix 1

ECOPATH version 3.0 (a Windows-based version released in 1996) incorporates an 'EcoRanger' module featuring a least-squares approach for construction of trophic models. This module introduces uncertainty into ECOPATH analysis by opening up the possibility for entering a range and mean/mode values for all the basic parameters, for the biomasses, consumption rates and production rates, as well as ecotrophic efficiencies and diet compositions.

Random input variables are then drawn using user-selected frequency distributions for each parameter type and the resulting model is evaluated (based on user-defined criteria, and physiological and mass balance constraints). The process is repeated in a Monte-Carlo way and of the model runs that pass the selection criteria, the best-fitting one is chosen using the least-squares criterion. The EcoRanger module thus introduces a statistical approach to the model fitting and, importantly, it helps the user in selecting the model that best fits a given set of constraints (Christensen and Pauly 1995).