The Tradeoff Analysis Model Version 3.1: A Policy Decision Support System for Agriculture

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User Guide

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Preface

This document reports on a decision support system that has been developed by a research project carried out by Montana State University (MSU), Wageningen University (WU), and the International Potato Center (CIP), in cooperation with several national research institutes and universities in Peru and Ecuador. Three donors supported the project. The International Service to National Agricultural Research (ISNAR)-administered Ecoregional Fund to Support Methodological Initiatives financed a project called "Regional scaling of field-level economic-biophysical models." The United States Agency for International Development (USAID) finances a project entitled "Tradeoffs in Sustainable Agriculture and the Environment in the Andes: A Decision Support System for Policy Makers" through its Soil Management Collaborative Research Program (SM-CRSP). The International Development Research Centre (IDRC) through its Canadian-CGIAR Collaborative Research Grants in Agro-Ecosystem Management for Human Health program finances a project entitled "Human Health and Changes in Potato Production Technology in the Highland Ecuadorian Agro-Ecosystem." Through mutual agreement of the donors, the three projects are managed as a single entity. The decision support system reported here is a second application of the tradeoff analysis method. The initial development was in a study of the environmental and human health aspects of pesticide use in potato production in Ecuador funded by the Rockefeller Foundation and documented in Crissman *et al.* (1998[a]).

The principal objective of the combined project is to develop a decision support system for assessing tradeoffs between agricultural production and the environmental and human health impacts of agriculture, for different economic, agricultural, environmental and health policies, and agricultural research. The conceptual model put forth in this document is a significant advance in the development of an integrated approach to agro-ecosystem assessment.

In a call for international ecosystem assessment, Ayensu *et al.* (1999) notes that integrated ecosystem management requires three basic types of information. First they note that reliable site-specific baseline information on ecosystems must be widely available. Second, they state that the knowledge of how the production of goods and services in specific ecosystems will respond to biophysical changes must be made available to decision makers in the public and private sectors. Finally, they note that "integrated regional models that incorporate biophysical, economic, and technical change must be developed to provide policy makers with a better understanding of the consequences of different management options". The authors recognize that these models must be able to communicate across scales so that global models can be informed by regional and local data.

The call that is made in the above-cited article is directed towards ecosystems. Even though the authors define ecosystems in general terms, we feel that the call for integrated analysis is made on too narrow a basis. The Tradeoff Analysis Model we propose here answers each of the concerns stated above but also incorporates specific aspects of agriculture systems and incorporates aspects of human health.

The decision support system is developed and tested in the potato/pasture production system of the tropical Andean region. This decision support system has the following key features:

- provides decision makers with information on tradeoffs between key sustainability indicators under alternative policy and technology scenarios,
- links disciplinary data and models in a GIS framework,
- utilizes minimum data necessary for decision support and policy analysis,
- is generalizable: results can be extrapolated to larger geographic regions using a GIS framework, and
- is transportable: the generic structure of the system can be adapted to other geographic settings and applications.

Field research is being conducted in two sites, San Gabriel (Carchi, Ecuador) and La Encañada (Cajamarca, Peru). Both are among the set of six pilot study sites of CONDESAN (*Consorcio para el Desarrollo Sostenible de la Ecorregión Andina*) of which CIP is a partner (CONDESAN, 1999). As pilot study sites, Carchi and Cajamarca were chosen as representative of a particular agro-ecoregion of the Andes. These sites capture a range of agro-ecological conditions typical of the northern, humid páramo Andes with Cajamarca considered by some as a transitional zone between the páramo and the dryer puna Andes. As consortium sites, there are selected research and development activities underway by other CONDESAN partners. The presence of other research programs offers the opportunity for collaboration in various areas such as the Integrated Pest Management (IPM)-CRSP in Carchi and the CIP Late Blight program in Cajamarca. Research in this project in both sites is concentrated in the upper hillside or valley wall agricultural zone dominated by cool weather crops, especially potatoes and grains, and pasture for milk and livestock production.

The research team that developed the Tradeoff Analysis Model applied for an extension of the Tradeoff Analysis Project in the second phase of the SM-CRSP. The proposal entitled “The Tradeoff Analysis Project Phase 2: Scaling Up and Technology Transfer to Address Poverty, Food Security and Sustainability of the Agro-Environment” (2001) was approved by US-AID and finances applications of the Tradeoff Model in different environments while focusing on a number of methodological issues related to scaling up the analysis to larger regions that may have a higher policy interest.

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Summary

This document is a users guide to the Tradeoff analysis and the model integration software denominated the Tradeoff Analysis Model. Tradeoff analysis is a process that enables policy makers to quantify the tradeoff between agricultural development and a wide range of possible sustainability indicators (including productivity, environment, and human health). An analysis to quantify these relationships should be based on a multi-disciplinary approach and as such requires the usage of bio-physical as well as econometric-process simulation models. The communication between these very different models is based on explicit definitions of spatial and temporal scales and a model integration software. In this document special attention is paid to data requirements in general, the different simulation models, and the integration software. In addition, a sample application is presented for the Carchi study area in Northern Ecuador.

1 Introduction

1.1 Regional Land Use Analysis and Tradeoff Analysis

With an increasing pressure on land, it becomes ever more important for policy makers to monitor land use changes and, if necessary, to influence these changes according to their specific objectives through agricultural policies and other policy mechanisms. Likewise, increasing resource scarcity increases the urgency to understand the environmental consequences of agricultural technologies. Changes in policy and technology can either mitigate or aggravate land use conflicts, minimize adverse environmental effects, and maintain or increase agricultural production. A key component in achieving more sustainable agricultural production systems is the capability to assess the impacts of changes in policy or technology on land use and on the economic and environmental consequences of farmers' related production decisions. In this document, we build upon the concept of regional land use analysis, showing how it can be integrated into a more general, multi-disciplinary Tradeoff analysis to assess the impacts of changes in policies and technologies on economic, environmental, and human health outcomes associated with agricultural land use.

Several methodologies have been developed in the past to project (e.g., CLUE by de Koning *et al.*, 1999) and explore (e.g., SysNet by Hoanh *et al.*, 1998; SOLUS by Bouman *et al.*, 1999) agricultural land use. However, the process of assessing prospective impacts of policies and technologies does not end with the projection of trends nor with the exploration of opportunities. To effectively develop, select and implement agricultural and other land use policies we need to project, explore, and predict agricultural land use (van Ittersum *et al.*, 1998). Relatively little attention has been paid to the prediction of land use changes and its economic, environmental and human health consequences.

This report describes a modelling system being developed as a decision support tool for agricultural and environmental policy analysis and policy decision making. The system is a tool to implement a process that allows policy makers to quantify economic, environmental and health tradeoffs. Part of the process is a modelling system that is designed specifically to integrate disciplinary data and models at the field scale, and aggregate economic and environmental outcomes to a scale relevant to policy analysis, in order to quantify tradeoffs between competing economic and environmental policy objectives. Motivating this approach is the view that quantifying tradeoffs is an essential ingredient in setting research priorities and in designing and implementing the criteria of sustainable agriculture in agricultural research programs, as described in detail in Crissman *et al.* (1998[a]).

The ultimate goal of the research programs supporting the development of the Tradeoff Analysis Model is to construct a flexible tool that can be used to integrate disciplinary data and models to provide information about agricultural production systems needed by policy decision makers. This tool is intended to be used by a team of researchers and adapted to fit the production systems of interest. The modelling system described here is a prototype of this type of policy decision support system. It is designed to represent a specific production system – the economically important potato/pasture system typical of the tropical Andes. The objective of ongoing research is to develop methods for generalizing the structure of the system and for simplifying the model components to the degree possible while maintaining the degree of accuracy needed for policy analysis. This report concentrates on the agriculture and environmental aspects of model development.

1.2 Basic Concepts

Actors and stakeholders

It is impossible to study regional land use without considering the people and institutions that play a role in the region. The most successful land use studies are being carried out in close interaction with the people and institutions involved. We distinguish between stakeholders and actors. The stakeholders are the parties directly interested in the outcomes of the study. They will be the future users of the results of the study or the methodology under development. Despite studies that are strictly scientific exercises, studies (e.g., in development projects) are (or should be) shaped around the objectives of the stakeholders. The actors, on the other hand, are all the people in the region that to some extent play a role in the agricultural sector. Farmers, for example, make land allocation and land management decisions and, as a result, play a key role in agricultural land use. They are, however, not the target group for the results and methodologies of regional land use studies and, consequently, they are referred to as actors and not as stakeholders. Many tools for regional land use analysis are developed to answer questions of regional or national policy significance and as a result policy decision makers, politicians, and the general public are the principal stakeholders. When the analysis focuses on the impacts of technology adoption, research administrators and related interests also should be considered stakeholders.

Model objectives

Policy-oriented, regional land use studies are often sub-divided on the basis of their objectives into explorative, projective and predictive models (van Ittersum *et al.*, 1998).

Explorative studies determine what can be done where and when. Agricultural land use is restricted by numerous bio-physical and socio-economic constraints. The full set of opportunities, hereafter referred to as the opportunity space, includes the range of all possible options. In contrast, the decision space refers to the range and nature of the options considered by the stakeholder being relevant and potentially achievable (Lemon, 1999). Ideally, decision space and opportunity space coincide, but reality shows that the two spaces only partially overlap. As a result three specific situations are identified by the partially overlapping opportunity space A and the decision space B (schematically represented in Figure 1.1).

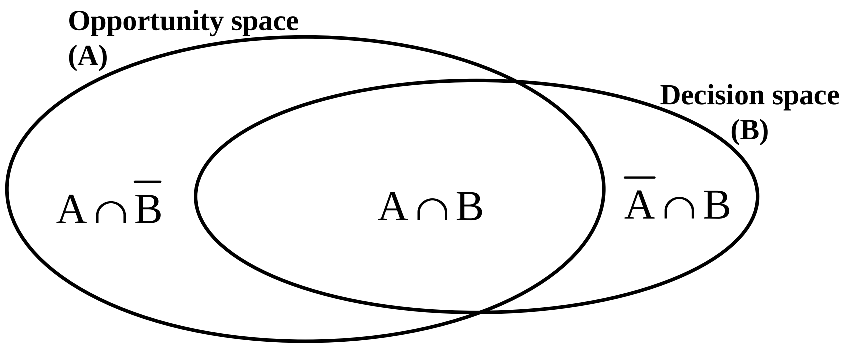


Figure 1.1 Schematic representation of the overlapping opportunity space and decision space

$A \cap B$: Options that are viable (within the opportunity space A) and that are considered to be relevant and potentially viable by the actor(s) (within the decision space B).

$A \cap \overline{B}$: Options that are viable (within the opportunity space A) but that are not considered to be relevant and potentially viable by the actor(s) (outside the decision space B).

$\overline{A} \cap B$: Options that are considered to be relevant and potentially viable by the actor(s) (within the decision space B), but that are not viable (outside the opportunity space A).

Explorative land use studies show the opportunity space to the stakeholders. They pinpoint to viable options the stakeholders are not aware of, and to options considered relevant by the stakeholders that are, in reality, not viable. If the results of explorative land use studies are transferred successfully to the stakeholder, the decision space and the opportunity space will coincide. It is important to realize that the decision space plays a role at different scale levels. The decision space of farmers whilst taking their land allocation decisions is composed of the existing or known land use systems and technologies. The introduction of new crops or alternative technologies will expand the decision space. Similarly, farmer schools may train farmers to recognize that certain practices degrade their resources and as a result are not sustainable in the long term. Each of the actors take decisions and for each of the decisions they look in their specific decision space. In the context of this publication, we focus on the stakeholders of the regional land use analysis. What contains the decision space of the policy maker? It is a range of policy alternatives as well as alternative land use and technology scenarios.

Projective models study past land cover and land use changes in relation to bio-physical and socio-economic parameters and project future trends given certain changes in the parameters. Due to their inherent characteristics, projective models are generally unable to capture abrupt changes in agricultural land use caused by, for example, natural disasters, the collapse of markets, or the introduction of completely new agricultural technologies. Nevertheless, projective studies are important to policy makers because they indicate the changes that are possible without policy interventions or changes in technology. Policy makers can subsequently decide whether these trends are desired or not and whether intervention is justified.

Finally, predictive models have been developed that actually predict land use changes as a result of agricultural policies or technologies. Predictive land use studies answer scenario type 'What-If' questions and indicate where agricultural land use will move within the opportunity space after implementing a certain agricultural policy. Due to uncertainties in the prognoses of many drivers governing land use change, predictive models can only be applied with a short time horizon.

These three groups of models have a large complimentary value. Explorative models identify the possibilities in the opportunity space, projective models indicate what will happen to agricultural land use if trends continue, and the projective models the likely impact of agricultural policy.

Policy instruments

Stakeholders have an array of alternative policy instruments available that allow them to move agricultural land use within the opportunity space according to their specific objectives. A large number of policy instruments can be identified. Some examples from Lemon (1999), van Keulen *et al.* (1998) and Wiebe and Meinzen-Dick (1998) are given below:

<u>Macro-economic policies</u>

- Price liberalization
- Removal of quantitative and administrative trade barriers
- Redefining the role of the government

Price policies

- Subsidies on agricultural inputs and / or products.
- Price support that guaranties prices for agricultural products

Regulatory instruments

- Environmental regulation for pesticide and / or nutrient emissions
- Regulation on banning of certain agricultural inputs (Pesticides)
- Land use regulations

Instruments focused on the farmer

- Management support through an extension service.
- Technological support that enables farms to a better access to production technologies.
- Economic support enabling farmers to obtain credits or crop insurance
- Land tenure.

Agricultural policies, typically, are composed out of one or more policy instruments. Regional land use studies should be able to indicate the (possible) changes that on or a combination of policies will induce. Besides the possible consequences of agricultural policies, stakeholders have to look for policies that are socially acceptable and economically viable. Regulatory instruments, for example, are only successful if they can be enforced. They may therefore not be a feasible solution in many developing countries.

Technological changes

Changes in agricultural land use can be induced through agricultural policies as illustrated above. They can also be the result of technological changes. Technological changes can be the result of scientific research and successful extension, but also stimulated by agricultural policies and innovative farmers. Technological changes can be sub-divided into:

- Introduction of new crops / animals. The new species / varieties can originate from other regions but also from successful breeding programs.
- Introduction of new inputs and / or formulation. Agriculture and animal husbandry is increasingly dependent of agricultural inputs to control pests and diseases, to replenish nutrients, and for traction. The introduction of cheaper, more environmentally friendly, more effective inputs may be necessary to fulfil the criteria imposed on the agricultural sector.
- Management changes. Management changes that are frequently being discussed in scientific and more popular publications are those related to integrated pest management (IPM) and integrated nutrient management. They may coincide with the introduction of new inputs and aim at a more ‘judicious’ manipulation of nutrient stocks and flows, in order to arrive at a ‘satisfactory’ and ‘sustainable’ level of agricultural production. In many cases, management changes will change the resource use efficiencies.

1.3 The Tradeoff Analysis Model

The tradeoff analysis aims to analyse in close interaction with the stakeholders the potential impacts of different policy instruments and technological changes. To which state does the agricultural sector move within the opportunity space. In other words, it is a policy decision support system designed to quantify tradeoffs between key sustainability indicators under alternative policy and technology scenarios. The results are presented in the form of tradeoff curves that are intuitive and easy-to-understand for policy makers using the economic principle of opportunity cost. These tradeoff curves allow for the actual quantification of the sustainability concept. The tradeoff analysis model is based on econometric production models estimated on observed behaviour of the population of farmers. As a result its predictive power is much higher than some of the explorative or projective models. At the same time we have to realise that it its time horizon is also relatively limited. Its application allows a subsequent analysis in which the changes of policy interventions as well as technological changes influence agricultural land use and its impact on the environment.

We start this publication with an overview of the Tradeoff assessment and the conceptual framework (Chapter 2). In the subsequent sections we will discuss the different components of the tradeoff analysis model: data (Chapter 3), crop models (Chapter 4), economic models (Chapter 5), environmental process models (Chapter 6), and health models (Chapter 7). The conceptual framework and the different components are operational through the Tradeoff Analysis Model Software. In Chapter 8 a user manual to the software is provided. All examples of data and models are derived from the application of the Tradeoff Analysis Model in the potato-pasture zone in Northern Ecuador. In Chapter 9 a number of sample results from this application are presented (Chapter 9).

2 Tradeoff Assessment

2.1 Overview

Tradeoff assessment provides an organizing principle and conceptual model for the design and organization of multi-disciplinary research projects to quantify and assess competing objectives in agricultural production systems. This process is illustrated in Figure 2.1. Input from stakeholders (i.e., the general public, policy makers, research administrators) is used to identify the critical dimensions of social concern, i.e., criteria for assessment of the sustainability of the system. Based on these criteria, hypotheses are formulated as tradeoffs between possibly competing objectives, such as higher agricultural production and improved environmental quality. Not all outcomes need to be tradeoffs; win-win cases also can be accommodated.

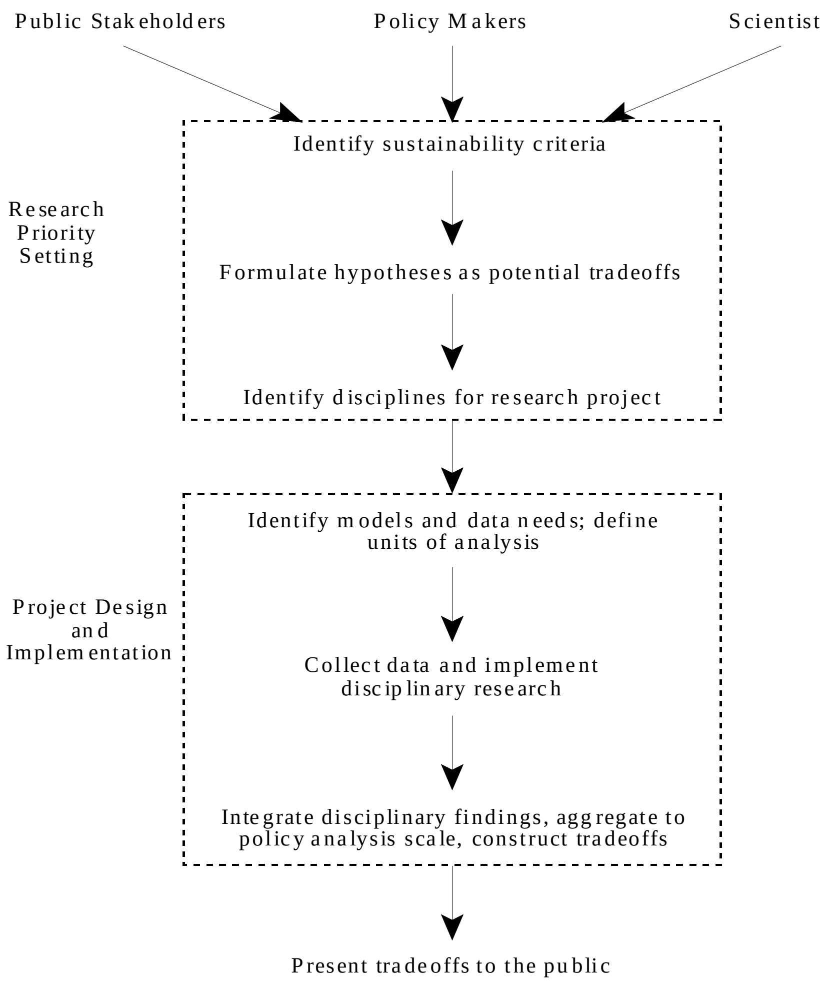


Figure 2.1 Tradeoffs research design and implementation process (Crissman *et al.*, 1998[a])

Once the key tradeoffs are identified, research team leaders can proceed with project design and implementation, and can identify the appropriate scientific disciplines to further design and implement the research needed to quantify these tradeoffs. The next step, critical to quantifying tradeoffs, is the identification of disciplinary models and data needed to quantify each sustainability indicator. A key aspect of this stage of the research design is to identify the data needs for each of the disciplinary components of the analysis, and how the model outputs can be effectively linked for the construction of tradeoffs. As we discuss further below, a key element at this stage is for all of the disciplines to agree upon basic spatial and temporal units of analysis: Will analysis be conducted at the field scale or watershed scale? Will time steps be daily, weekly, monthly, or yearly? Will all disciplinary components of the analysis operate at the same spatial and temporal scales, and if not, how will differences between scales be reconciled? Once these fundamental issues in research design have been resolved; data collection and disciplinary research can proceed. Upon completion of the disciplinary components of research, the respective data and models can be linked to test hypotheses about tradeoffs, and the findings can be presented to policy makers and the general public.

A number of challenges face researchers in implementing this type of research. First, despite the widespread acceptance of the goal of sustainable agricultural systems, a scientific consensus is lacking on how the economic, environmental, and public health impacts of agricultural technologies can be quantified and assessed. Analysis of these complex, interrelated issues raises difficult theoretical and methodological problems for researchers. Environmental, agricultural, and health characteristics of farmers, farmland, and farming technologies vary over space and time.

Second, a key methodological challenge is the choice of the unit of analysis including the spatial and temporal scales. Research in the biological and physical sciences typically deals with a unit of analysis – whether it is at the cellular, plant, animal, or field level – that is different from the farm or sector levels relevant to policy analysis. Policy analysis typically is concerned with large units, usually defined in relation to a geographic or political region that contains a population of the units addressed by biological and physical sciences. The aggregation problem, i.e., the problem of combining heterogeneous small units into a larger unit for policy analysis, must be addressed by all researchers if their data and results are to be useful for policy analysis. While emphasis has been placed on the problem of spatial aggregation in the geo-statistics literature, similar problems arise in the time dimension.

Third, the problems that concern the public involve issues addressed by various fields of science and thus require a multi-disciplinary approach. Overcoming disciplinary biases and establishing effective inter-disciplinary communication is a continuing challenge for a research team. The fact that the various scientific disciplines use different units of analysis frequently means that the data and methods developed for disciplinary research are of limited value for policy research. Disciplinary research typically operates in a format dictated by disciplinary orientation and generates data intended to satisfy disciplinary objectives. This disciplinary orientation of research leads to a situation in which various pieces of the scientific puzzle are investigated without regard to the fitting together of those pieces into the larger picture that is required for policy analysis. Thus, the disciplinary component of research intended to support the assessment of tradeoffs must be planned at the beginning of the research effort to produce methods and data that are required for disciplinary analysis, but that can also be utilized across disciplines to assess tradeoffs. The planning, in advance, of coordinated disciplinary research is one of the key benefits of the tradeoff assessment methodology that is being proposed here.

Fourth is the problem of spatial variability. Tradeoffs associated with agricultural production systems can be defined across several dimensions at a point in time, and can also be defined in one or more dimensions over time. In evaluating the long-term sustainability of a production system, economic and environmental indicators can be used to quantify the productivity and other attributes of a system over time. These indicators may include measures of phenomena such as economic returns, soil erosion, chemical leaching, nitrate movement through soil profiles, and the organic content in the soil. Measuring tradeoffs in these dimensions requires site-specific data and models. Because the environmental impacts of different production systems are generally site-specific, one production system may not have the same impacts in all environmental dimensions at all sites. Thus, any attempt to rank production systems according to sustainability criteria needs to account for spatial variability in economic, environmental, and health outcomes.

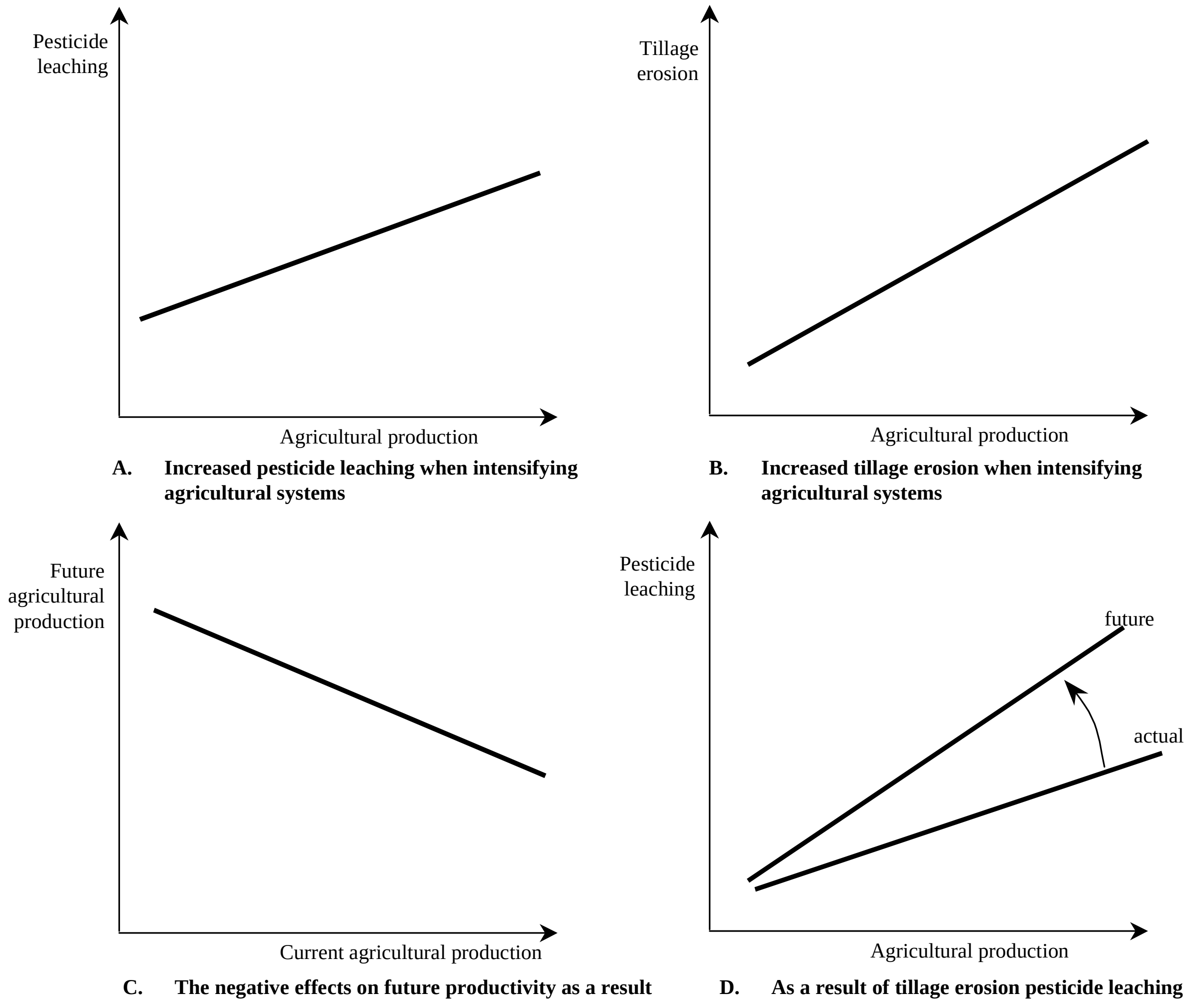
The larger the spatial or temporal scale, the more complex becomes the process of quantifying tradeoffs for analysis of agricultural sustainability. Analysis at the regional or national scale is even more difficult than analysis at smaller scales, such as a watershed. Attempts to develop quantitative indicators of the sustainability of the U.S. farming sector, or the farming sectors of member countries of the Organization for Economic Cooperation and Development (OECD), have relied on aggregate data about production, input use, and resource degradation (U.S. Department of Agriculture, 1994; OECD, 1994). These data do not provide a scientifically defensible foundation for policy analysis because production cannot be linked to environmental and health impacts on a site-specific basis. In contrast, the approach followed in the development of the Tradeoff Analysis Model is to link the site-specific management decisions of producers with environmental and health impacts. By conducting the analysis at a statistically representative set of sites, the site-specific outcomes can be aggregated to represent the relevant human and physical populations and can be used to assess tradeoffs at whatever scale is deemed relevant for policy analysis.

Fifth is the problem of valuation. Political pressure to identify a set of sustainable production technologies implies that there must be some means of ranking the importance of the various impacts. Ranking technologies according to multiple criteria requires a method of converting these criteria to a common unit of analysis. One approach is to utilize multi-attribute decision models, i.e., to assign weights to the alternative outcomes. This raises the question of what weights to use. The economic approach to this problem taken is to convert all impacts to monetary terms and to use this information to conduct a benefit-cost analysis. However, despite decades of research on valuation of environmental and health outcomes by environmental and health economists, a scientific consensus on valuation methods is lacking, and data for valuation of most environmental and health impacts are not readily available, particularly in developing countries. Even when monetary valuations are feasible, their acceptance by the public or by policy decision makers is often questionable (e.g., in the United States, Federal government agencies may not accept results from contingent valuation studies, see Belzer, 1999). The philosophy underlying the Tradeoff Analysis Model is that a more useful approach to informing the policy decision making process is to establish a sound scientific basis for quantifying tradeoffs that exist with alternative production systems, without attempting to value impacts for benefit-cost analysis. The valuation step is left to the policy and political processes.

2.2 The Analysis of Sustainable Production Systems

The concept of tradeoffs between present and future outcomes of an agricultural production system can be used to quantify the concept of sustainability and provide quantitative measures of the sustainability of an agricultural production system.

Figure 2.2 presents tradeoff curves between different outcomes of a production system that illustrate how tradeoffs can be used to quantify sustainability. In Figures 2.2a and 2.2b the tradeoff curves show a positive correlation between agricultural production on the horizontal axis, pesticide leaching and tillage erosion on the vertical axis. They indicate that if we increase agricultural production through, for example, higher prices for agricultural products, this will coincide with an increase in pesticide leaching and tillage erosion. Figure 2.2c shows the tradeoff curve between current and future agricultural productivity. An increase in current agricultural productivity will result in an increase in tillage erosion (Figure 2.2b), resulting in a decrease of future productivity. When the outcomes on both axes have a positive social value, the degree of sustainability of a system can be defined as the inverse of the absolute elasticity of the tradeoff curve between present and future outcomes (Antle and Stoorvogel, 1999). Thus, a steeply-sloped curve in Figure 2.2c represents a relatively low degree of sustainability, meaning that for a given production technology and resource endowment, any changes that induce higher levels of current production lead to a rapid reduction in future production potential. Similarly, a relatively flat tradeoff curve represents a system with a relatively high degree of sustainability, as increases in current production have relatively little impact on future production potential. Figure 2.2d shows that the tradeoff curves are not static in time and that the different indicators are not independent. Tillage erosion will lead to topsoil removal and thus a decrease in the capacity of the soil to fix pesticides and prevent them from being leached to deeper soil layers and ground water. Increasing current productivity will lead to more tillage erosion and the slope of the tradeoff curve will increase.



A. Increased pesticide leaching when intensifying agricultural systems

B. Increased tillage erosion when intensifying agricultural systems

C. The negative effects on future productivity as a result of increasing tillage erosion when intensifying current agricultural production

D. As a result of tillage erosion pesticide leaching increases in the future

Figure 2.2 Samples of tradeoff curves

The tradeoff curve is a concrete visualization of the instinctive mental calculations of politicians and other public decision makers. Except in those rare cases of win-win, policy decisions almost always benefit some group at the cost of another group. As widely recognized in the political economy literature (Krueger, 1992), politicians weigh the consequences of their decisions in terms of the costs to the losers and the benefits to the winners. As sustainable agriculture criteria are increasingly incorporated into the weights for making decisions, the information needed becomes frequently less and less comparable. The comparisons are no longer simply within a single sector but now are more broad and cross into several distinct sectors.

A graphical presentation of a tradeoff in two-dimensional space such as in Figure 2.2 shows the level of agricultural production that can be reached for a given level of environmental impact. The curve traces out all possible levels of this relationship, as agricultural production increases adverse environmental impact increases. The key features of the tradeoff curve are its location in the quadrant and its slope at a point along it.

The slope of the tradeoff curve shows the opportunity cost of increasing agricultural production in terms of foregone environmental quality. This information is critical for informed policy decision making, as it allows policy makers and the public to assess whether a given improvement in environmental quality is worth the sacrifice in agricultural production. Note that the relationship is not necessarily linear; at a certain point more and more of one objective must be sacrificed to reach the desired level of the other. Since the objectives that appear on the axes are those determined as important during the research process, these objectives are *de facto* sustainability indicators of the system of interest.

The particular location on a curve is determined by economic and biophysical factors. Relative prices of agricultural production inputs and outputs determine production through changes in both land use and management intensity. Increasing output prices or reducing input prices induces farmers to allocate more land to the higher priced, more profitable crops, and also encourages them to apply more inputs to those crops. A reduction in output prices or increase in input prices has the opposite effect. In Tradeoff analysis, tradeoff curves are constructed by simulating the response of farmers to various combinations of input and output prices. Each set of prices corresponds to a “tradeoff point” on the tradeoff curve.

2.3 The Eco-Regional Approach to Sustainability Research

Making sustainability operational within the context of international agricultural research calls for new approaches to research priority setting, problem identification, and organization. Several new research initiatives are adopting an eco-regional approach to integrate information at various levels of aggregation (Rabbinge, 1995). CIP and its fellow institutes in the Consultative Group for International Agricultural Research (CGIAR) adopted an eco-regional approach as a means to operationalize the concept of sustainability. The CGIAR identifies eco-regions as agro-ecological zones and defines the role of the eco-regional approach as follows:

The main role of the eco-regional approach is to contribute to the goal of increasing sustainability of agricultural production by providing: first, a process that identifies the right research content due to its holistic and forward looking perspective which contrasts with traditional disciplinary and commodity approaches to research. Second, a mechanism for partnership, among relevant actors with complementary functions, that contributes to achieving their common and individual institutional goals through applied and strategic research on the foundations of sustainable production systems. Third, a mechanism that develops, tests, and supports effective research paradigms for the sustainable improvement of productivity (CGIAR, 1993, p. 4).

The eco-regional approach places emphasis on modeling production systems and their environmental impacts at a small scale, such as the field scale or watershed, and on how those small-scale impacts affect systems at larger scales or higher levels of aggregation. The approach is primarily a systems approach that emphasizes the importance of economic decision-making models to capture changing priorities in farm households and communities. Other tools important to the eco-regional approach include geographic information systems and crop, livestock, and soils models (Bouma *et al.*, 1995). It must be emphasized that these tools build upon the methods and data provided by the traditional experimental approach of agricultural research that is the hallmark of the CGIAR research system (CGIAR, 1995). The Tradeoff Analysis Model provides a methodology for the implementation of research within the eco-regional paradigm.

2.4 General Framework for Tradeoff Analysis

The conceptual framework for disciplinary integration and policy analysis is illustrated in Figure 2.3. A unique aspect of this conceptual model for tradeoff analysis is the location of farmer decision making in the figurative center of the analysis. Above the box indicating farmer decision making are those attributes of the system in which the farmer operates that condition the decisions he or she makes. Immediately below are the boxes that register the consequences of those decisions. Moving from top to bottom, the framework captures the logical sequence of how policy affects farming decisions that result in micro-level impacts, and how those impacts can be measured and aggregated to units useful for policy analysis. At the center of the analysis is an economic model of farmer decision making. By incorporating the decision-making process of the land manager, the model provides the link from economic, physical, and technological factors affecting farmer behavior, to the environmental outcomes that are affected by their management decisions.

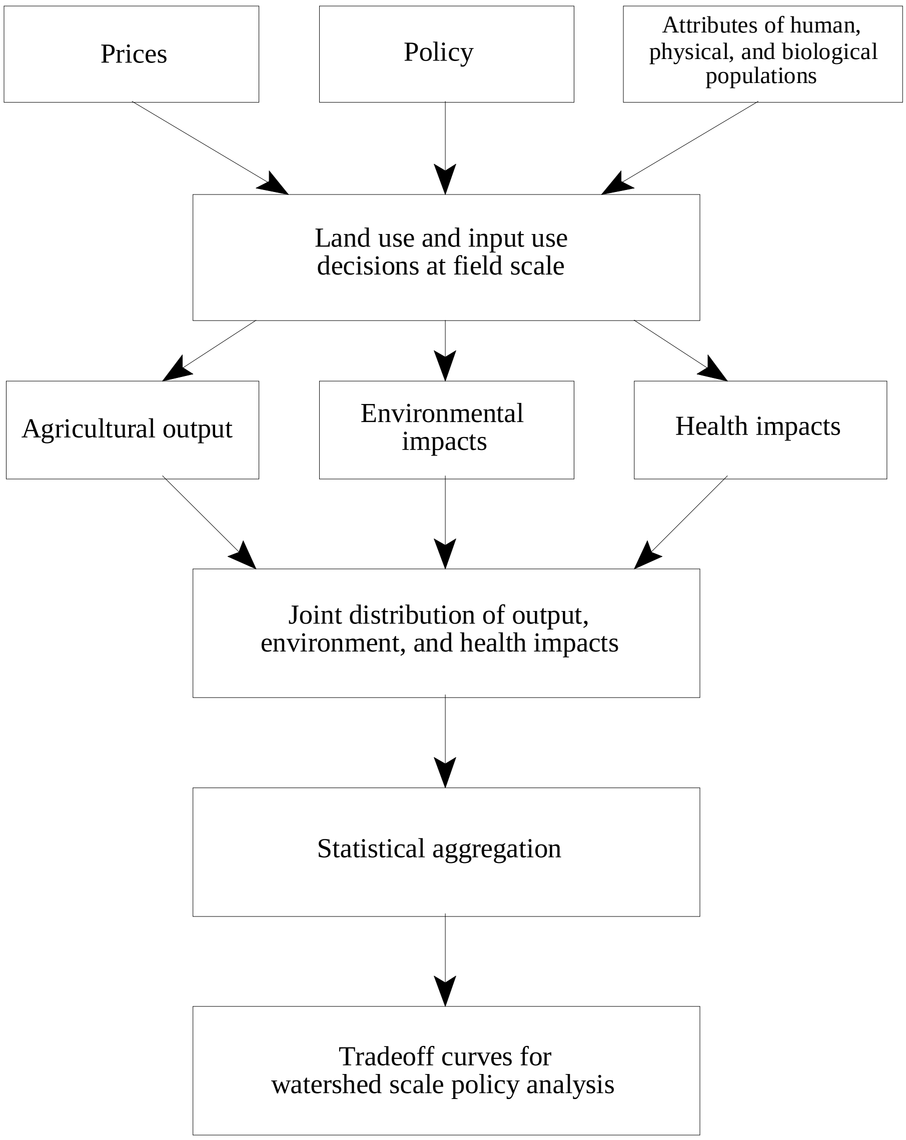


Figure 2.3 Conceptual framework for disciplinary integration and policy analysis (Crissman *et al.*, 1998 [a])

Using a parcel of land as the unit of analysis, the upper part of Figure 2.3 shows that prevailing policies and market prices, technologies, farmer characteristics, and the physical attributes of land affect farmers' management decisions in terms of both land use and input use – the extensive and intensive margin decisions. Physical relationships between the environmental attributes of the land in production and management practices then jointly determine the agricultural output, environmental impacts, and health impacts associated with a particular unit of land in production.

Farm-level decision models show that each unit of land that is in production has management and environmental characteristics which in turn are functions of prices, policies, technology, and other farm-specific variables. As indicated in the lower part of Figure 2.3, the probability distributions of technology, farmer, and environmental characteristics in the region induce a joint distribution of management practices, environmental characteristics, and health outcomes for each field in production, as a function of prices and policy parameters. This joint probability distribution provides a statistically valid representation of the outputs, inputs, environmental impacts, and health impacts for the population. Therefore these individual outcomes can be "added up" to produce an aggregate distribution of impacts. These aggregate outcomes – measured in terms of agricultural output, environmental quality indicators, and health indicators – are used to construct tradeoffs for policy analysis. This information can be utilized in several ways. If monetary values can be assigned to all impacts, then a benefit-cost analysis of policy alternatives can be conducted. However, since monetary values are usually available, the more useful approach is to present information about tradeoffs directly to policy decision makers.

2.5 The Scale of Analysis

A diagram, introduced in a soil science context by Hoosbeek and Bryant (1992), is useful to illustrate the research procedure followed in the Tradeoff analysis (Figure 2.4). They utilize two perpendicular axes to represent combinations or research procedures. One represents the range from qualitative to quantitative procedures and the other from empirical to mechanistic. The vertical axis represents a scale hierarchy, where the plot level (the individual soil) occupies the central position (i level). Higher levels are indicated as i+, while lower levels are i-. The scale in Figure 2.4 ranges from molecular interaction (i-4) to the world level (i+6).

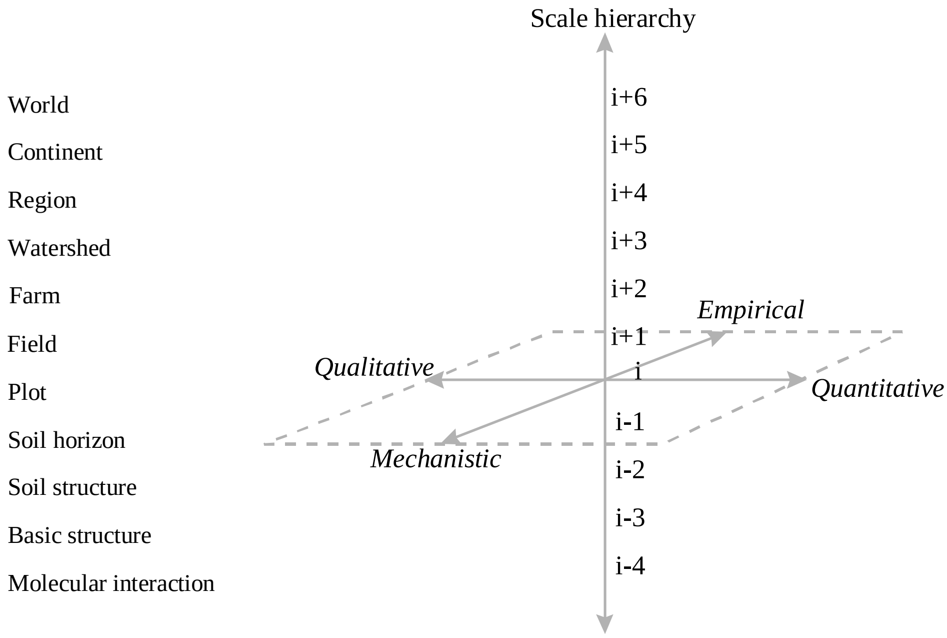


Figure 2.4 Classification scheme for research procedures (Hoosbeek and Bryant, 1992)

Different research approaches can be described with this construct of research procedures and placed within the plane obtained at each scale level (Bouma, 1998):

- K1: Application of user expertise (qualitative, empirical)
- K2: Expert knowledge (qualitative, mechanistic)
- K3: Use of simple comprehensive methods, including modelling (quantitative, empirical)
- K4: Complex, mechanistic methods, including modelling (quantitative, mechanistic)
- K5: Detailed methods, including modelling, which focus on one aspect only, often with a disciplinary character (quantitative, mechanistic)

Within the tradeoff methodology, we work on different scale levels and use different research approaches. The lines in Figure 2.5 represent the so-called “research chain” that corresponds to the Tradeoff Analysis Model. The Tradeoff Analysis Model demonstrates how the problem is analysed using different research procedures at different scales. The problem definition of the Tradeoff Analysis Model is at the regional level and is defined by using expert knowledge (**K2**). For example, what will be the effect of an alternative technology on the tradeoff between development and pesticide leaching? Since decisions are taken at the farm / field level, the problem is re-defined (still in rather qualitative terms) at the field level: How will pesticide use be affected by an increase in economic performance of the cropping system? In a next step, a quantitative, empirical econometric-process simulation model (**K3**) is used to simulate decision making for that field. Crop production and pesticide leaching are modeled for a specific point within a field. If soil variability occurs within a field it is necessary to carry out simulation runs for different locations within the field. While simulating crop growth and pesticide leaching at the point level we use quantitative, mechanistic simulation models (**K5**). During the simulation of these bio-physical processes it is necessary to consider processes of nutrient uptake by roots, mineralization of organic matter, and adsorption/desorption of pesticides, processes that occur at the plot and molecular interaction scales. The quantitative results are aggregated to the field level and finally the results of the simulation for many fields are aggregated to the regional scale in the form of tradeoff curves (**K3**).

Figure 2.5 showed that the Tradeoff Analysis Model works at four different scale levels: the regional level (i+4), the field level (i+1), the plot level (i), and lower levels for components of the bio-physical models (i-4). Scenarios and boundary conditions are defined at the regional level. The final results of the tradeoff analysis will also have to be presented at this level. Land allocation and land management decisions are taken at the field level. Hence, simulation of these decisions takes place at the field level. The crop models and most environmental process models work at the plot level. It is crucial that the different components of the Tradeoff Analysis Model can communicate. This means that data will have to be disaggregated (i.e., to move down in the scale hierarchy) or aggregated (i.e., to move up in the scale hierarchy). The disaggregation of data takes place in two different ways mostly depending on the type of data and the way data have been collected.

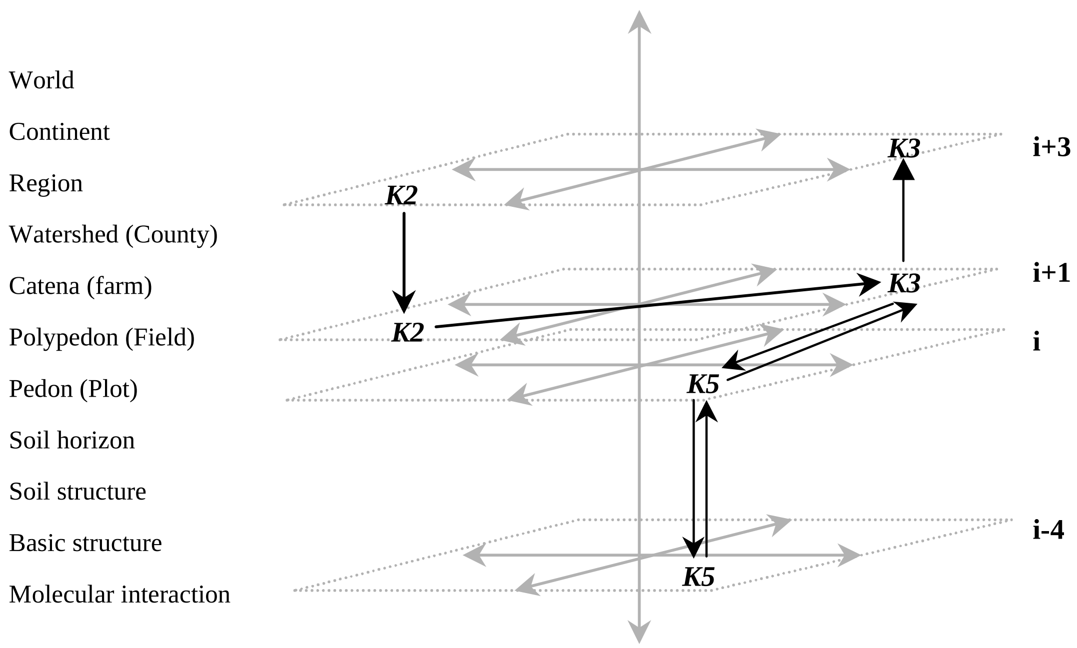


Figure 2.5 An illustration of a research chain representing the sequence of research activities at different scale hierarchies for the Tradeoff Analysis Model

In the case of soil data, in the existing case study sites an exploratory soil survey is available covering the whole study area. Typically one would use this soil survey, describe representative soil profiles for the different mapping units, and use those profiles for subsequent analyses. However, this would imply that any soil variability within the mapping units is discarded. Since this variability is considered to be large in the Andean highlands, alternative procedures have been developed. The exploratory soil survey is disaggregated using detailed information available from a digital elevation model. Relation between soil variability and parameters describing the topography of the terrain (derived from a digital elevation model) are used. This procedure requires additional field observations but provides the detailed information that is necessary.

Again, in the case study sites detailed economic information exists. The data originate from a dynamic survey of farmer's fields. A representative sample of the fields in the study area were surveyed during a two-year period. Although the sample was relatively large it does not provide a spatial coverage of the region. The sample does allow for the calculation of distributions of selected economic parameters at the regional level. Instead of disaggregating the information, stochastic procedures are used and parameters are drawn from the distribution. Since the data are based on stochastic procedures fields can be simulated several times with different results.

For some variables a combination of both procedures is used. In the case of field size, we observe large differences within the region (see the aerial photo in figure 2.6). One single distribution for the entire study area does not describe accurately the variation in field size. Instead we sub-divided the region into zones with similar patterns in field sizes. On the basis of the survey data, we determined the distribution in field size for each zone.

The simulation of crop production, crop selection and management, and pesticide fate takes place at the field level. Where there is a large topographic variation within an individual field, several model runs are necessary to calculate crop production and pesticide fate. Simulations are carried out under different economic conditions (the so-called tradeoff points), for different repetitions (to capture the stochastic character of different input parameters, and for a large number of locations (the fields). The final results are presented as a tradeoff curve. The tradeoff curve is defined by the scatter plot of all the simulation runs. To simplify the results, they are aggregated over the repetitions and over the fields, to obtain one average per tradeoff point. The scattering of individual points can be summarized by a linear or curvilinear regression that effectively gives the tradeoff curve for a region.

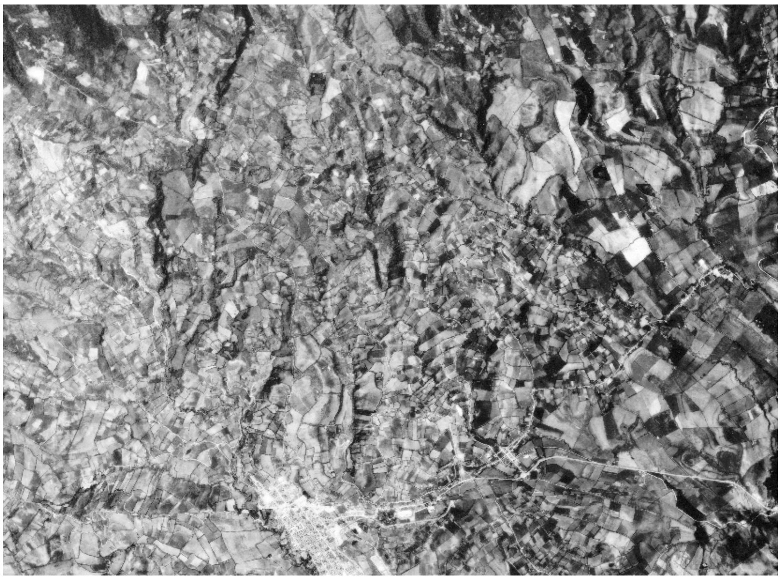


Figure 2.6 Aerial photo of the study area north of the town of San Gabriel (visible in the bottom center)

2.6 Overview of the Tradeoff Analysis Model Structure

Figure 2.7 presents the structure of the Tradeoff Analysis Model. The model can be broken down into components that are discussed in corresponding sections of this report:

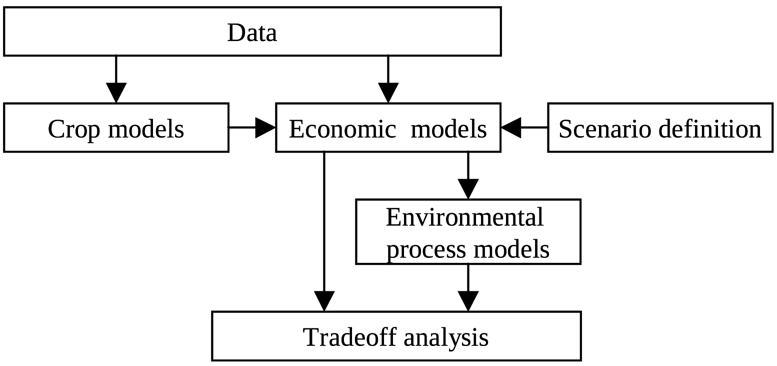


Figure 2.7 The general setup of the Tradeoff Analysis Model

Data (Chapter 3): The model begins with three types of data: environmental data, farm survey data, and experimental data. Environmental data describe the spatial variation in soils and climate and is organized in a GIS format. It is used as input to the bio-physical models and to stratify the study area. Farm survey data describe the way farmers take decisions about land management. This decision making process is described in the econometric production models. The Tradeoff Analysis relies heavily on crop models to describe the inherent productivity of farmers' fields (as an important factor in their decision making process) and environmental impact models to estimate the impact on soil and water resources. Although most of these models have a mechanistic character they need to be calibrated to local conditions for which experimental data are required.

Crop Models (Chapter 4): The crop (and potentially livestock) models discussed in section 4 are used to estimate the spatial and temporal variation in inherent productivity of the land that is driven by soils and climate variations. These measures of inherent productivity are inputs into the economic models to explain variation in management decisions of farmers.

Economic Models (Chapter 5): Econometric production models are estimated using the farm survey data and the inherent productivity indexes derived from the crop models. Parameters for distributions of prices and other exogenous variables in the production models are estimated using the survey data. These parameters are input into an econometric-process simulation model, with the indexes of inherent productivity from the crop models.

Environmental Process Models (Chapter 6): The management decisions from the economic simulation model (e.g., land use, pesticide applications) are input to environmental process models to estimate impacts on soil quality, pesticide fate, and other environmental processes of interest.

Health Models (Chapter 7): The econometric process simulation model simulates pesticide applications that have an impact on human health. The impact of pesticide use on human health is expressed in a quantitative indicator of the neuro-behavioral health of farmer workers.

Scenario Definition, Model Execution, and Analysis of Tradeoffs (Chapter 8): For each policy or technology scenario of interest to policy decision makers, the simulation model is executed for a series of price settings. Economic outcomes from the econometric-process simulation model (e.g., value of crop and livestock production) and environmental outcomes from the environmental process models (e.g, pesticide loadings to the environment, soil erosion) are aggregated. The different prices settings induce changes in management which in turn induce tradeoffs between economic and environmental outcomes. These outcomes are aggregated to the spatial scale deemed appropriate for policy analysis (e.g., to the watershed or regional level).

3 Data

This chapter discusses the data used in the model. The Tradeoff Analysis Model is designed to represent the human, biological and physical populations relevant to the analysis. The data required to implement the model, therefore, need to be sufficient to parameterize the relevant disciplinary models for a randomly selected member of the population, which in the case studies are randomly selected farmers' fields. Certain physical data may be available for the entire population in some generalized form like soil data from soil surveys. If so, simulations can randomly select a field location and use observed data to characterize the site in physical terms. However, for some other physical data and for economic data, a complete survey is not feasible. In those cases, a sample is drawn and surveyed or monitored (the dynamic survey of the farmers' fields). The data are subsequently described in the form of distributions that are used as inputs for the stochastic simulation models.

The Tradeoff Analysis Model utilizes spatially referenced physical and economic data. Data originating from mapping exercises that are stored in GIS are discussed in Section 3.1 while data collected through farm surveys are discussed in Section 3.2. Specific experimental data necessary for the calibration and validation of the bio-physical models are described in Section 3.3.

3.1 GIS Data

The Tradeoff Analysis Model considers spatial variability in resources and socio-economic conditions. As a result geo-referenced data are required. In this Section we will discuss the three major steps in the tradeoff methodology that make use of geo-referenced information:

- A major input in the Tradeoff Analysis Model is a dynamic survey of farmer's fields. Although fields can be selected randomly, preferably the area is stratified into agro-ecological zones. The basis for this zonification lies in the GIS database.
- The Tradeoff Analysis Model is composed of a suite of different disciplinary models. Each of these models need to be parametrized for the specific agro-ecological conditions in the study area.
- Finally, geo-referenced data are needed to actually run the Tradeoff Analysis Model.

To determine dynamic input demand functions and dynamic factor demand equations utilized in the economic models, a detailed farm survey is necessary. It is important to get a representative sample of fields in the survey. To reduce the number of farms to be surveyed, the region is stratified through an agro-ecological zonification. Within the different zones, fields are selected for intensive monitoring. The kind of data necessary for the zonification depends on the region.

Typically, it includes soil and climatic data to explain differences in the production potential. However, topography, farm/field size and distance to markets may be similarly important. The data necessary for the agro-ecological zonification can have a general character. For example, a 1:50,000 soil survey forms an excellent basis. The study area dictates which variables are important and implicitly indicates the kind of data necessary for the analysis.
For the calibration of the different disciplinary models, detailed data sets are necessary at the scale level of the model. Thus, for the econometric-process simulation model, data at the field level are required (see Section 3.2). For the bio-physical simulation models, data at the plot level (and preferably data at more detailed levels) are needed (see also Chapters 4 and 6).

Model runs take place at the field level and consequently data at the field level are required. Data requirements depend on the procedures that are being followed. Crissman *et al.* (1998[a]) carried out simulations for the fields that were included in the original survey. In that particular case only data for those fields are necessary (besides the data required for the zonification) and they can be collected as part of the survey. This procedure has two major disadvantages:

- If the survey is not a representative sample for the region, results will be biased. Even in cases that several fields in all the major agro-ecological zones have been surveyed, this does not necessarily mean that the sample is representative.
- It does not allow for extrapolation of the results to a larger region. New specific agro-ecological conditions will occur outside the survey area and it is likely that the original survey fields do not represent those conditions.

An alternative approach does not simulate field management for the survey fields but draws fields out of the total population of fields. As a result, the selection of fields for the simulation runs will always be a representative sample for the region, but the data requirements are large, as data for all fields is needed. The methodology assumes that dynamic input demand functions and dynamic factor demand equations are constant for the population of fields. Currently the Tradeoff Analysis Model includes a separate draw of fields. This means that a geographical coverage of input data is required at two scale levels: a general characterization of the region to stratify the region for the selection of the survey fields and a detailed characterization for the fields that will be used during the simulation runs. After the fields are selected, the GIS is invoked to retrieve the corresponding characteristics. The type of data included in the characterization depends on the future use of the field data in the Tradeoff Analysis Model.

GIS data is utilized in various parts of the Tradeoff Analysis Model. Below we list where and how geo-referenced information is used when running the model for the case studies.

- Draw the field size from a zone specific distribution. On the basis of aerial photographs, field patterns are characterized. This characterization led to the specification of several zones each containing a large number of survey fields (Figure 3.1). On the basis of the survey fields, for which field sizes were known, a field size distribution was calculated for the different zones. For each zone the GIS database provides the average and standard deviation for the log-normal distribution.
- Calculate the expected production based on the inherent productivity for each of the fields. The inherent productivity is defined as the production that can be obtained in a particular field given the bio-physical conditions and a standardized average agricultural management for the region and the specific crop. To determine the expected production, crop growth simulation models are used. Detailed quantitative data on soils and climate are necessary for these models. The exact data depend on the particular simulation model. For soil information, the soil survey was used (Figure 3.2). Data from weather stations needs to be interpolated to obtain climatic maps. Different procedures can be followed to do so. Due to the large number of parameters per weather station, regular interpolation procedures such as kriging and co-kriging are not feasible. Often Thiessen polygons are used, this simply is a rule to use the nearest weather station to a particular location. Another option, if the number of weather stations is sufficient is to derive a limited number of parameters for a weather generator. For example model parameters can be interpolated using kriging or co-kriging with altitude as a co-variable. A serious limitation of the use of weather generators is that they are not capable of reproducing actual weather to link to the survey data. A procedure used in the project is to create altitude zones with one weather station in each zone. The altitude zones are derived from a digital elevation model (Figure 3.3). The zones are used for rainfall data. In the case of temperature data, a linear interpolation on the basis of altitude between the weather zones is used. An alternative procedure is currently under development by Baigorria *et al.* (2001) in the form of a process-based interpolation model for weather data.
- The economic model uses the expected production and field size, both derived as discussed above. In the future, we may also consider differences in farm gate prices as a result of differences in the distance to markets within the economic model. This implies that we need knowledge about the infrastructure and transport costs.
- The last step in the model involves the calculation of the environmental effects of farm management. Currently, the Tradeoff Analysis Model includes a linkage with LEACHsum, a summary model derived from LEACHP (Wagenet and Hutson, 1989) and PEARL (Tiktak *et al*., 2000). For an application in the Peruvian Andes a linkage with WEPP (Bowen *et al*., 1999[b]) has been established to evaluate the implications of land use decisions on erosion.

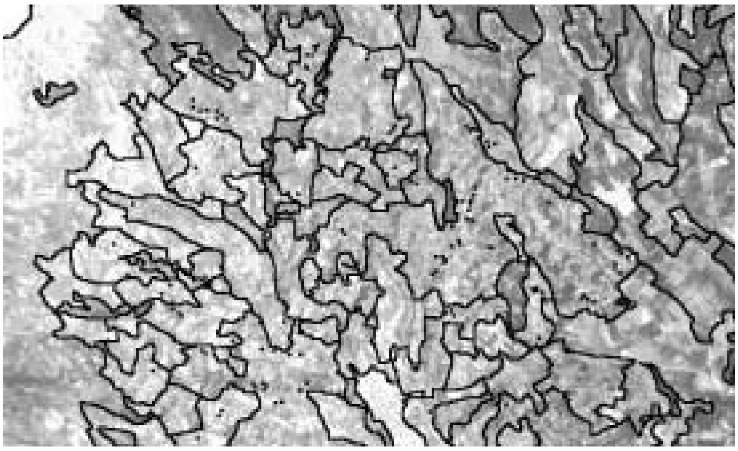


Figure 3.1 Aerial photo of the Carchi study area with a classification based on field size (black lines) and the survey fields (black dots)

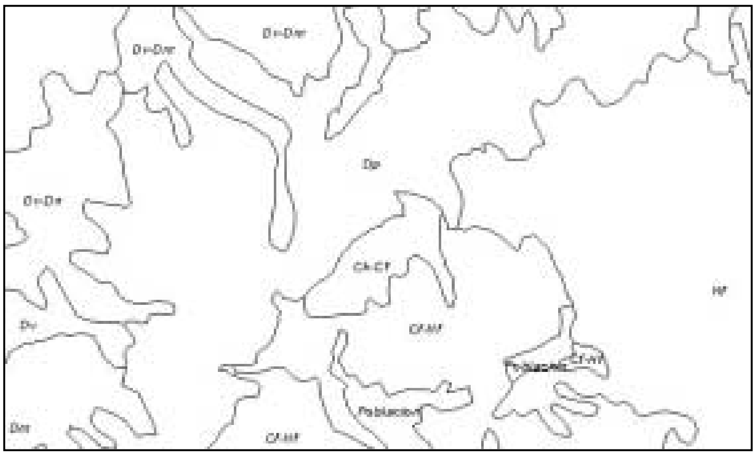


Figure 3.2 1:50,000 soil map of the Carchi study area (MAG and ORSTOM, 1980)

Figure 3.3 Digital elevation model (black is low; white is high) of the Carchi study area and the streams (white lines)

3.2 Farm Survey Data

Farm survey data for the Tradeoff Analysis Model are collected to estimate the land use and management decisions of farmers in the study region. Both economic and environmental processes are spatially and temporally variable, therefore the economic data are collected over time to represent the relationship between management activities and biophysical phenomena. The farm survey data are collected at the field scale at which the economic and bio-physical processes are modeled. The sample size and sample selection procedures for a farm survey depend on several factors. First, a decision must be made as to whether the sample is to be based on physical criteria or economic criteria, or both. For example, a random sample of fields could be drawn if the principal goal of the analysis is to characterize certain physical properties of the landscape. However, this approach may not result in a sample that is adequate to characterize economic characteristics of farms such as farm size if each important farm size stratum is not represented in the sample. As a practical matter, sample size will be limited by time and resources and the availability of information that can be used to stratify samples in either physical or economic terms.

In recent applications of the model, a sample of approximately forty farms was chosen in the region being analyzed. Because each farmer manages multiple fields, and because data were collected over time, the sample sizes at the field level were several times the number of farms. The sampling frame varied as did the criteria for stratifying the sample. In the first application in Carchi, Ecuador, the emphasis of the original study was on pesticide use. County property tax registers were used to define the population, and the sample was stratified by the value of land holdings (Crissman *et al.*, 1998 [a]). In the Cajamarca (Peru) study, the emphasis was on soils and sustainability. A county census provided the sampling frame that was stratified by communities to capture the ecological diversity available in the watershed. In both cases farm households were chosen randomly within the strata.

To ensure accuracy in measurement of farm management information such as quantities of pesticides applied, data need to be collected frequently enough to minimize farmer recall error to the degree possible. This means that the survey data must be collected through a series of interviews during the production period being measured. Data registers for each field in cultivation were designed for the collection of labor, equipment and supplies data based on date-linked activities. In the Ecuador and Peru study areas, farm families typically manage 3-7 fields planted at various times during the year. Potato cultivation is management intensive and may require as many as 15-20 distinct activities from field preparation to harvest. It is unrealistic to expect a farmer to accurately recall for more than a few weeks that he or she used 5 laborers to apply 2750 grams each of two pesticides on the lower field on January 18. The target for the field team was not to exceed a month between data collection visits. To assist recall, farmers were issued individual field register booklets to record activities. This data collection scheme imposes considerable respondent burden. To minimize the burden, visits are typically programmed based on appointments after normal working hours. Other motivational practices such as field days for specific topics of interest to the respondent farmers are used to maintain the sample.

Errors can enter at a number of points in the process of data collection, and data quality control is an essential part of the data collection process. Data entry is done in close contact with the data collectors. Anomalies are checked with the field contacts who can in turn contact farmers again about questionable data. The data are then subjected to further scrutiny as they are prepared for statistical analysis, but at that point it is not possible to return to respondents to correct erroneous data.

Since data collection is coordinated among the disciplines and the staff from the field survey is in frequent contact with farmers and the farm sites, they also assist in collection of biophysical data. Each field is measured for location, area, slope, altitude and other physical characteristics such as presence of terraces. Depending on model requirements, other measurements may be made regarding other soil attributes.

Given the presence of enumerators in the field during data collection, supplementary data can also be collected with minimal additional costs. Livestock and livestock management data and household characteristics data can be collected to further round out the quantitative description of the farming units in the survey area.

This data collection exercise guarantees detailed, accurate information. However it is costly in both time and money. A challenge for subsequent applications of the Tradeoff Analysis Model is seek methods to determine the minimum quantity of data necessary to estimate tradeoffs with an acceptable degree of accuracy.

3.3 Experimental data

The Tradeoff Analysis relies heavily on crop models to describe the inherent productivity of farmers' fields (as an important factor in their decision making process) and environmental impact models to estimate the impact on soil and water resources. Although most of these models have a mechanistic character they need to be calibrated to local conditions for which experimental data are required.
To simulate potato growth, we used the SUBSTOR potato model (Ritchie *et al.*, 1995) that was released with the Decision Support System for Agrotechnology Transfer (DSSAT v.3) (Jones *et al.*, 1998). Using experimental data from the study area, the SUBSTOR model was calibrated to the local conditions in the Ecuadorian Andes (Bowen *et al.*, 1999[a]).

Pesticide leaching was simulated using the PEARL model (Tiktak *et al*., 2000). Wagenet *et al*. (1998) indicated the methodological problems that may arise while assessing the pesticide environmental impact in developing areas. They argue that a proper calibration of the mechanistic simulation models is almost never possible and that monitoring pesticide concentrations in effect is often the most straightforward way to assess pesticide emissions to the environment. However, within the context of the tradeoff analysis model, we are not only interested in current emissions of pesticides, but also focus on possible emissions under alternative policy and technology scenarios. Therefore, an intensive set of experiments was set up to quantify degradation, sorption, and lateral water flow along the slopes as well as a monitoring program of pesticide concentrations in the vadose zone, ground water and streams throughout the study area (Stoorvogel *et al*., 2001). After screening of pesticides used in the Carchi study area, carbofuran was selected as the single most high-risk pesticide. It is a widely used insecticide applied to control the Andean Weevil (*Premnotypes vorax*) and highly toxic.

The process of tillage erosion is relatively slow, but on the long run may have significant impacts on crop productivity and pesticide leaching. Tillage erosion is increasingly recognized as being one of the negative side effects of modern agriculture and receiving increasing attention from researchers developing methods to quantify mass transport as a result of tillage (e.g., Turkelboom *et al*, 1999 and Dercon, 2001). To quantify the current extent and rate of tillage erosion in the study area, 45 fields throughout the study area were surveyed by intensive augering and farmers were interviewed to determine land use history (Veen, 1999).

4 Crop Models and inherent productivity

Generalization and transportability are among the methodological objectives of Tradeoff Analysis Model development. Process-based crop and livestock models provide a generic structure in which commonly found agricultural crops and livestock activities can be addressed. In this chapter we introduce the crop models we utilize in the Tradeoff Analysis Model. Tradeoff Analysis relies on crop models to describe the inherent productivity of farmers' fields (as a factor that explains their land use and input use decisions) and environmental impact models to estimate the impact on soil and water resources. We therefore work with the inherent productivity that is based on the environmental properties of a field and typical crop management.

With continuing advances in computer technology and accessibility, models of soil and plant systems have become increasingly valuable instruments for assimilating knowledge gained from experimentation. Their use within a research program has the potential to increase efficiency by emphasizing process-based research rather than the study of only site-specific net effects. Consequently, a modeling approach lends structure to a research program, helping to focus on the quantitative description of soil and plant processes. This information can then be used to predict how the system might respond to different environmental and management factors. A modeling approach also provides a dynamic, quantitative framework for multidisciplinary input.

By integrating experimental and modeling activities, several multidisciplinary teams of scientists have been able to assemble comprehensive models that provide quantitative estimates of crop production under a wide range of soil, weather, and management conditions (Whisler *et al.*, 1986; Penning de Vries *et al.*, 1989; Boote *et al.*, 1996; Jones *et al.*, 1998). These models are based on an understanding of biophysical processes, and usually simulate plant growth on a daily basis, describing for example carbon assimilation, partitioning of carbon, phenology, and water and nitrogen uptake. Simulation at this level of detail has resulted in crop growth models that realistically simulate the sensitivity of growth and development to changes in solar radiation, temperature, photoperiod, and the availability of water and nitrogen.

The DSSAT crop models

The crop models used in the Tradeoff Analysis Model belong to the Decision Support System for Agrotechnology Transfer (DSSAT) family of models (Jones *et al.*, 1998). The DSSAT is a software package that contains crop growth models, database management programs, utility programs, and analysis programs, each easily executed from within the shell or capable of being run alone. Within the DSSAT shell, a user can (i) input, organize, and store data on weather, soils, crops, experiments, and prices, (ii) run simulations with as many as 16 different crops in single-season, multi-season, or crop-sequencing modes, (iii) retrieve, analyze, and graphically display data, and (iv) evaluate different management practices at a site. This standardization makes the utilization of DSSAT attractive in the context of the Tradeoff Analysis Model.

The DSSAT contains seven separate models for simulating the growth of 16 different crops (Table 4.1). Although these models have been developed by different groups of researchers and institutions, there has been a coordinated effort to standardize input and output data formats (Hunt and Boote, 1998), and to implement the same soil water and N balance in each model (Ritchie, 1998; Godwin and Singh, 1998). Therefore, all seven models contain similar subroutines for describing soil-related processes and for reading and writing data using the same variable names. They differ only in the way crop growth and development processes are simulated.

Table 4.1 Principal crop models released as part of the DSSAT version 3.5

Crop Model	Crops Simulated
CERES-Generic	Maize, Wheat, Barley, Millet, Sorghum
CERES-Rice	Rice (upland and flooded rice)
CROPGRO	Soybean, Peanut, Dry Bean, Chickpea, Tomato, Pasture
OILCROP-SUN	Sunflower
SUBSTOR-Potato	Potato
CROPSIM-Cassava	Cassava
CANEGRO	Sugarcane

The minimum data set concept

Earlier efforts at model building and testing have helped to define a minimum set of soil, weather, crop, and management data that is essential for the effective interpretation and comparison of field experiments. The definition of such minimum data sets helps (i) to achieve adequate documentation of field experiments, (ii) to provide experimental data for model development and testing, and (iii) to run scenarios for evaluation in the Tradeoff Analysis Model. What follows is a brief description of the main components of these minimum data sets.

Weather variables: All of the models need as input daily values for rainfall (mm), minimum and maximum temperature (ºC), and solar radiation (MJ m^{-2} d^{-1}). These four variables are what drive the models. Incoming radiation might be measured as sunshine hours during the day, which can then be converted to solar radiation estimates.

Soil profile characteristics: The models simulate soil processes based on properties defined for different layers down to at least the maximum depth of rooting. The more important properties for each layer include: depth to the bottom of the soil layer from the surface (cm), volumetric water content at plant wilting point (defined as lower limit in the models), volumetric water content at field capacity (defined as drained upper limit; both drained upper limit and lower limit are best estimated in the field, but initial estimates might be obtained from texture, bulk density, and organic C content), bulk density, organic C and total N content, soil pH, and available P.

Cultivar-specific coefficients: The models simulate the effect of both temperature and photoperiod on vegetative development, reproductive development, and growth processes. To accomplish this, cultivar-specific coefficients are estimated which describe the sensitivity of each cultivar to temperature and photoperiod, with threshold values defined for emergence, flowering (or tuber initiation) and physiological maturity. Other cultivar-specific coefficients are also needed depending on the crop being modeled. These coefficients are usually estimated from field experiments where growing conditions have been optimized. If estimated with a sufficient number of field observations, a cultivar's coefficients should remain the same for all locations.

Management variables: The management variables needed are:

- planting date, planting depth, plant population, row spacing
- irrigation date, amount applied, and type of irrigation
- N fertilizer application date, amount, method of application, depth of application, and type of N fertilizer
- previous crop residue dry matter amount, N and P content of the residue, depth of incorporation, and date of incorporation
- P fertilizer application date, amount, method of application, depth of application, and type of P fertilizer
- Total and soluble P_2O_5 of PR sources

Initial conditions: The models need to start the simulation with some estimate of initial soil water, nitrate, ammonium, and available P. If possible, these variables should be measured with depth either at planting or some time prior to planting. For example, initial conditions might be determined for each 10 or 15 cm layer down to a depth of 120 cm. If these variables are measured, the date that soil samples are taken and their corresponding depth interval should be recorded.

Measured variables: These variables are not required to run the models, but they are useful for evaluating model performance. They may include only a few variables such as final yield and N uptake, or they may include the type of detailed data collected with time in growth analysis studies. These field measurements are then easily compared to simulated values using a graphical interface or any other data analysis program.

DSSAT within the Tradeoff Analysis Model

The productivity a farmer can expect from a field plays an important role in the land use and management decisions for that particular piece of land. The inherent productivity is determined through the incorporation of the DSSAT models into the Tradeoff Analysis Model user shell to provide a user-friendly interface. Note that the DSSAT user shell is not being used. The usage of the inherent productivity in the economic simulation models is explained in Chapter 5. The Tradeoff Analysis Model creates the appropriate input files for the crop growth simulation models. To get the specific data for a field, the GIS database is invoked and the data required by the model are extracted and exported to the DSSAT input files. In a second step, the Tradeoff Analysis Model calls the executable of the simulation model. The simulation model creates a data file with the simulation results that is subsequently read by the Tradeoff Analysis Model.

5 Economic Models

Farmer decision making is a central organizing concept of the Tradeoff Analysis Model. We model that decision making through a series of econometric regression equations that are derived from a model of the farmer's economic behavior. These models have to be tailored to each application of the Tradeoff Analysis Model. This application utilizes models to (i) estimate expected returns to crop and livestock production, (ii) estimate quantity and timing of pesticide applications and (iii) estimate the value of production realized at the end of the growing season. The econometric production models are estimated using farm-level data, and these models are used to parameterize an econometric process simulation model that represents short-run land use and management decisions on a site-specific basis. This type of model is discussed in detail in Antle and Capalbo (2001).

The model described here goes beyond Antle *et al.* (1998) by introducing an explicit link between the spatially-explicit econometric production models and the spatially-referenced bio-physical production models for crop and livestock production. The spatially-referenced bio-physical models are used to represent the effects of spatial variations in bio-physical conditions (soils and climate) on what is defined as the inherent productivity of the land. The econometric models incorporate this inherent productivity into the estimation of behavioral relationships that are utilized in the simulation model to represent the spatial variation in land use and management decisions.

5.1 Conceptual Model

We define a production process at field i for crop j in period t in terms of the production function $q_{ijt} = f(\mathbf{v}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})$, where **v** is a vector of variable inputs, **z** is a vector of allocatable quasi-fixed factors of production and other fixed effects, and **e** is a vector of environmental characteristics of the field. The expected profit function corresponding to this production function is $\pi_{ijt} = \pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})$ where p_{ijt} is expected output price. Define $\delta_{ijt} = 1$ if the j^{th} crop is grown at field i at time t and $\delta_{ijt} = 0$ otherwise. If the land is not in crop production then it is in a conserving or other productive use that earns a return π_{cit}. Letting $\delta_{ict} = 1 - \sum_j \delta_{ijt}$, the land use decision is defined as solving

(1) $$\max_{(\delta_{i1t},\ldots,\delta_{\text{int}})} \sum_j \delta_{ijt}\pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it}) + \delta_{ict}\pi_{cit}$$

The solution takes the form of a discrete step function

(2) $$\delta_{ijt}^* = \delta(\mathbf{p}_{it}, \mathbf{w}_{it}, \mathbf{z}_{it}, \mathbf{e}_{it}, \pi_{cit})$$

where $\mathbf{p}_{it}$ is a vector of the p_{ijt} and likewise for the other vectors. Using Hotelling's lemma, the quantity of planned production on the i[th] field is given by

(3) $$q^*_{ijt} = \delta^*_{ijt}\partial\pi_j\left(p_{ijt,}\mathbf{w}_{ijt},\mathbf{z}_{jit},\mathbf{e}_{it}\right)/\partial p_{ijt} = q_{ijt}\left(\mathbf{p}_{it},\mathbf{w}_{it},\mathbf{z}_{it},\mathbf{e}_{it},\pi_{cit}\right)$$

Variable input demands are likewise given by

(4) $$\mathrm{v}^*_{ijt} = -\delta^*_{ijt}\partial\pi_j\left(p_{ijt,}\mathrm{w}_{ijt},\mathrm{z}_{jit},\mathrm{e}_{it}\right)/\partial\mathrm{w}_{ijt} = v_{ijt}\left(\mathrm{p}_{it},\mathrm{w}_{it},\mathrm{z}_{it},\mathrm{e}_{it},\pi_{cit}\right)$$

The solution to (1) applies to a given field, and is based on the assumption that each field can be managed separately. This representation is convenient as it greatly simplifies the modeling of the linkages between economic and bio-physical processes. However, several conditions may cause the management of distinct fields to be inter-related. One consideration discussed by Just *et al.* (1983) is constraints on allocatable fixed inputs such as land or capital. In this case, problem (1) would be embedded in a choice problem for all fields subject to the adding-up constraint on the allocatable fixed inputs (elements of **z**). Whether or not an adding-up restriction is appropriate depends on how farmers utilize machinery and other quasi-fixed inputs. In many cases rental markets are available for machinery and for custom operations such as pesticide and fertilizer applications. In this case, services of capital (e.g., tractor hours) may be interpreted as variable inputs rather than fixed. The same can be said for the total amount of land managed by farmers. Given land rental markets, the total number of acres managed in a growing season may be a choice variable rather than a constraint.

Management of fields also may be inter-related on farms where production and consumption decisions are non-separable (de Janvry *et al.*, 1991). This condition is relevant to subsistence farms whose production is motivated by the consumption needs of the farm household. In this case the farm decision maker's objective function is the maximization of utility of income or consumption and leisure, and farm production from all fields are incorporated into household decisions for utility maximization.

Another factor that may lead into interdependence of management decisions across fields is risk. We can add a stochastic term to each production function and assume that these stochastic elements are jointly distributed across fields. Then under the assumption that farmers are risk averse and choose production activities to maximize expected utility or some other risk-based criterion, it can be shown that production decisions may be inter-related across fields.

The preceding discussion implies that fields may be modelled as being managed independently – at least as a first-order approximation to reality – when farmers are risk-neutral, when they participate in markets for inputs and outputs, and when they have access to rental markets for land and capital inputs. To the degree that these conditions do not hold, more complex models that account for the particular characteristics of farmers may need to be utilized.

The dynamics of crop rotations can be readily incorporated into the above model. For example, the potato / pasture rotation typical of the high-Andes is incorporated by specifying the profit function to include the appropriate costs and returns over the relevant time period for land-use decision making. The production function defined above can be generalized to include a variable indicating if the previous land use was a potato crop or pasture. The static profit function defined above can then be replaced by the present value of profit for all combinations of potato and pasture rotations (i.e., potato / potato, potato / pasture, pasture / potato, and pasture / pasture). The farmer chooses between those combinations each period that provide the highest expected returns.

Expected returns

The purpose of this econometric model is to represent expected returns in the land use component of the simulation model. Perhaps the most obvious approach to econometric model formulation for this purpose would be to use a restricted profit function to represent expected net returns above variable cost. However, there is a major practical limitation to the use of the profit function. Simple, well-behaved functional forms are needed for simulation modeling. The most common functional form used in production modeling is the log-linear or Cobb-Douglas form. When a profit function is specified in log-linear form, however, profit or net return is necessarily restricted to be non-negative. This non-negativity restriction is frequently violated in actual data that represent realized rather than expected returns, rendering the model inapplicable. While flexible functional forms such as the quadratic can be used for a profit function that allow negative net returns, these functional forms are less desirable for simulation because they are parameter intensive and are difficult to constrain so that they are well-behaved (i.e., satisfy convexity properties).

The alternative approach used here is to decompose profit or net returns into revenue and cost components that are modeled in log-linear form. The revenue component of expected returns is represented with the supply function derived from the restricted profit function, and the cost component is represented by the restricted cost function. Using Hotelling's lemma define $\partial\pi(p,w,z,e)/\partial p = y(p,w,z,e)$ as the supply function and $c(y,w,z,e)$ as the cost function. It then follows that by estimating the supply function and the cost function, expected net returns can be derived as $\pi = \pi(p,w,z,e) = py(p,w,z,e) - c(y(p,w,z,e),z,e)$.

In applying this approach, the total quantity of potatoes supplied, for example, is specified as log-linear in pesticide, labor wage, and output price (with linear homogeneity in prices imposed), in field size, quantity of fertilizer applied (assumed determined at the beginning of the production cycle), and a dummy variable indicating the previous use of the field (crop or pasture). This supply function is estimated jointly with a log-linear cost function which is a function of quantity supplied, pesticide, fertilizer, and labor prices, previous crop, and field size. The system is estimated jointly with the first-order conditions for cost minimization to increase estimation efficiency. Fertilizer quantity is taken as a variable determined at the beginning of the growing season so for the simulation model a fertilizer demand equation is estimated in log-linear form.

Expected returns from dairy production is estimated using a similar system of equations for quantity of milk supplied (a function of number of cows, medical expenses, and quantity of feed), and a cost function for labor (a function of quantity of milk produced and the wage rate). In order to simulate estimates of expected returns (the farmer's estimate of returns before production takes place), these supply and cost functions are used to calculate mathematical expectations (i.e., predicted mean values) of quantities produced and cost of production. These expected values are then used to compute an estimate of expected net returns.

Note that in the approach described above, a single output is assumed to be grown on each field. In some cases, however, multiple crops are grown on a single field, i.e., the farmer uses inter-cropping. In this case, the approach described above which utilizes a supply function and cost function is complicated by the existence of the jointly produced outputs. An alternative approach that can be used in this case is to specify and estimate a log-linear revenue function of the form r(p,v,z,e) jointly with a system of factor demand functions of the form v(p,w,z,e).

Pesticide demand functions

Following Antle *et al.* (1994, 1998), the pesticide demand functions for the Carchi potato/pasture case are estimated using a system of equations representing both the quantity applied and the time intervals between applications. The demand equations represent quality-adjusted quantities of fungicides and insecticides, and carbofuran (not quality adjusted). For each type of pesticide, a two-equation reduced-form system is estimated representing quantity and timing of pesticide applications. These log-linear functions depend on input and output prices, field size, fertilizer, application time, and lagged quantity and timing variables to incorporate the dynamics of the sequential applications.

In some if not many applications, detailed data on timing of pesticide applications may not be available. In this case simpler static pesticide demand functions may be used.

Revenue functions

The value of potato production is estimated using a revenue function specified in terms of quantities of pesticides applied during the season, previous crop, fertilizer, and field size. For milk production, the supply function estimated with the cost function is also used to generate a value of milk produced. To simulate the realized value of output, the estimated models are used to predict the mean value of output and estimated error variances for the models are used to construct random components of the output value.

Incorporating spatial soils and climate data into production models

A problem facing empirical production economics research is how to incorporate effects of soils and climate on productivity into economic production models. Production economists have long specified production functions in the general form $q_i = f(\mathbf{v}_i, \mathbf{z}_i, \mathbf{e}_i)$ as discussed above, including variables representing soils and climate. However, in practice the bio-physical factors $\mathbf{e}_i$ are represented in models by using ad hoc indicators of soil quality and climate such as dummy variables for soil types and average rainfall during the growing season. At the same agronomic research developed crop growth simulation models describing agricultural production in the general form $q_i = g(\mathbf{v}_i, \mathbf{e}_i)$. Theoretically, soil and climate conditions define a productivity that farmers expect to obtain before it takes decisions on the usage of variable inputs. This expected productivity is a function of the inherent environmental conditions on a field in combination with a typical or average input use $\bar{\mathbf{v}}_i$. In the present context we will refer to this expected productivity as the inherent productivity of a field. Subsequent, actual productivity is a function of this inherent productivity and management practices. This inherent productivity of the soils and climate in a location can be quantified in the predicted yield of a crop growth simulation model, denoted here as $g(\bar{\mathbf{v}}_i, \mathbf{e}_i)$. Thus, we specify the production process as $q_i = f(\mathbf{v}_i, \mathbf{z}_i, g(\bar{\mathbf{v}}_i, \mathbf{e}_i))$. This specification thus embodies the (testable) hypothesis that production is weakly separable in $\mathbf{e}_i$.

The crop and livestock simulation models are used to estimate the inherent productivity of each field represented in the data. Being a yield estimate, an inherent productivity variable can be multiplied times area in production (or number of animals in the case of livestock production) to obtain an estimate of potential total production on that field (or for the given animal herd). This variable is then incorporated into the various econometric models giving each model a spatially explicit productivity characteristic based on bio-physical factors filtered through crop growth models. This information can be interpreted as representing the information the farmer knows about the potential productivity of the field when land use and management decisions are being made.

5.2 Econometric-Process Simulation Model

Figure 5.1 presents the structure of the econometric-process simulation model (Antle and Capalbo, 2001). A simulation begins by reading data used to characterize price distributions and the fields on which production will be simulated. From the production models parameters are input that define technical efficiency, pesticide management, and pesticide safety practices. Finally, parameters that define the tradeoffs scenarios to be simulated are read into the model. After sampling price distributions for inputs and outputs and drawing an initial planting date from a distribution of observed values, expected returns for potatoes and dairy production are simulated using the econometric supply and cost function models described above. Expected returns are compared, and the activity with the highest expected returns is selected. If potato production is selected, the pesticide application decisions of the farmer are simulated using the system of dynamic factor demand equations. During this simulation, individual pesticide applications and application times (days after planting) are output to external data base files for later use in the leaching simulations. At the end of the pesticide applications, a harvest date is selected and the value of potato production is generated with the revenue function described above.

If dairy production is selected, it is assumed that the dairy cycle lasts 360 days, and the dairy supply function is used to simulate the value of dairy production on the field assuming production begins a fixed number of days after conversion of the field to pasture (this is the time assumed necessary for pasture establishment). The stocking rate on the field is a parameter selected by the user of the model. The values for potato and milk production are output to the data base files.

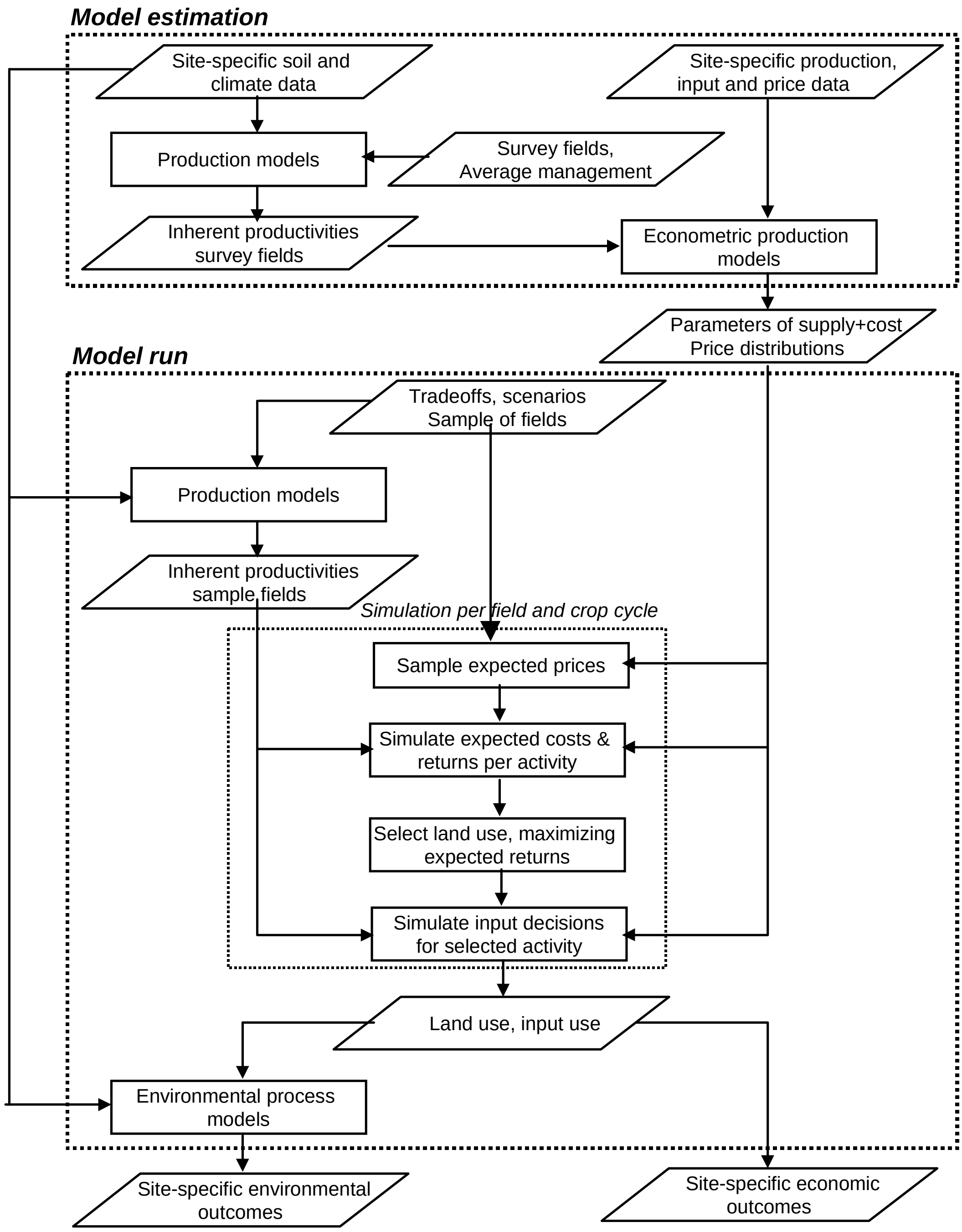


Figure 5.1 Structure of the econometric-process simulation model for Carchi, Ecuador

6 Environmental Process Models

6.1 Introduction

The principal objective of the Tradeoff Analysis Model is to assess tradeoffs between agricultural production and its environmental and health impacts. To assess the environmental impact of agricultural management on a specific field, we will need environmental process models. In the Tradeoff Research Design (Figure 2.1) we show that stakeholders, policy makers and scientists are needed to jointly identify the major sustainability criteria. These sustainability criteria will involve certain environmental processes and as a result require certain environmental process models. In its current version, the Tradeoff Analysis Model is operational for the potato-pasture zone in Carchi, Ecuador. One of the major environmental issues is the intensive use of chemicals to control pests and diseases threatening the potato production (Table 6.1). In Carchi, Ecuador, pesticide leaching is the main environmental issue of pesticide use. Consequently a pesticide leaching model was linked to the Tradeoff Analysis Model. In this chapter we discuss problems of determining the environmental fate of pesticides and adjustments we made to the LEACHP and PEARL models and its incorporation into the Tradeoff Analysis Model.

Table 6.1 Major pesticides used in the potato production, Carchi Study Site (Crissman *et al.*, 1998 [b])

Active ingredient	Total amount applied (kg)	Total No. of applications	Total No. of parcels treated[1]
Fungicides			
Mancozeb	3,111	1,801	304
Sulfur compounds	333	286	99
Propineb	142	146	53
Maneb	115	181	65
Cymoxinal	65	635	178
Copper compounds	29	94	29
Fentinacetate	11	86	36
Insecticides			
Carbofuran	225	687	262
Methamidophos	207	999	265
Profenofos	21	117	62

[1]Total number of survey parcels was 330.

6.2 Pesticide Leaching

Pesticide emissions from agricultural production areas are found to be a major threat for environment and rural populations. In many countries numerous agricultural and environmental policies are directed towards controlling or somehow modifying pesticide use. To monitor the environmental fate of pesticides, complex, mechanistic models have been developed that simulate pesticide movement through the soil. Modeling is an excellent alternative to determine pesticide fate in the soil. In combination with geographical information systems, simulation models are able to quantify the spatial variability in pesticide movement. However, we still face limitations. Although modeling provides a good alternative to monitoring, field data on soil and pesticide characteristics are required for accurate assessments. As a result, policies are often based on simple indicators (Dieter *et al.*, 1997; Goldenman, 1996). The plethora of pesticides and cropping systems makes extensive monitoring of pesticide emissions practically impossible (Wagenet *et al.*, 1998; Di and Aylmore, 1997). General databases with pesticide properties are frequently used for policy purposes (e.g., Wauchope *et al.*, 1992; Hornsby *et al.*, 1995). However, data typically are not site-specific and should therefore be interpreted as a rough indication.

Preliminary results of the project indicate that these general data, originating in most cases from industrialized countries, are not applicable in tropical conditions. Studies for carbofuran in northern Ecuador showed that the mobility is much higher in the volcanic ash soils of Ecuador than one would expect on the basis of these general databases. Stoorvogel *et al.* (1999) observed similar differences in Costa Rica. Degradation half-lifes of Ethoprop in a banana plantation were found to be 2.5-4.5 days whereas the SCS/ARS/CES pesticide properties database gives a soil half-life of 25 days (Wauchope *et al.*, 1992). In this particular case, Ethoprop leaching was much less than expected on the basis of general databases.

Literature shows that relatively simple indicators can be extremely useful to determine pesticide fate in agricultural systems. However, these indicators only function properly if soil and pesticide properties have been quantified under similar agro-ecological conditions. Within the Tradeoff project soil properties have been quantified in detail (see Meyles and Kooistra, 1998 and van Soest, 1998). Measurements of pesticide fate for the specific conditions in Ecuador are on their way.

Simulating pesticide leaching

LEACHP is among a group of several mechanistic simulation models that have been tested under various agro-ecological conditions with good results (Wagenet *et al.*, 1998). In the Tradeoff Analysis Model we make use of LEACHP (Wagenet and

Hutson, 1989) to simulate pesticide movement. Although the use of simulation models strongly reduces the amount of field measurements, the models do require insight in pesticide properties (half life and sorption) as well as soil physical properties.

Data and model availability limit pesticide modeling in most cases to a one-dimensional simulation. To determine the spatial variability in pesticide leaching it is necessary to apply GIS technology and link the one-dimensional leaching models to spatial databases on soils, climate and land use (Corwin *et al.*, 1997). The linkage of a one-dimensional simulation model with a GIS database is relatively straightforward. Simulation models and GIS data are linked through the transfer of data files with model input and model results (Stoorvogel 1995; Corwin *et al.*, 1997). However, in mountainous areas with large differences in topography lateral flow along the slopes significantly limits the applicability of these models. Meerbach (1999) indicated that lateral flow does exist in the Carchi study area. The application of a one-dimensional model is therefore just an indication for pesticide fate.

Leaching studies are usually carried out for a limited number of representative profiles and extrapolated on the basis of soil survey maps to farms, watersheds or even larger regions. Micro variability in soils is well studied and has revealed large variations of soil properties and profile characteristics across short distances. As a result, derived behavior like leaching of agrochemicals may be similarly variable and concentrated in specific niches of the field (Biggar and Nielsen, 1976). Linear aggregation of the results of representative profiles is therefore dangerous and may lead to over- or under-estimations of leaching. At the same time, monitoring studies are expensive and can only be carried out for relatively short periods, whereas weather extremes may result in short, but extremely high leaching. Leaching models permit us to use a limited number of measured soil and pesticide properties and explore spatial and temporal variation in pesticide leaching.

LEACHP simulates water flow in combination with pesticide displacement and degradation in unsaturated or partially saturated layered soil profiles. The model calculates water flow using a finite-difference solution of the Richards' equation:

(1) $$\delta\theta/\delta t = \left\{\delta\left[(\delta H/\delta z)K(\theta)\right]/\delta z\right\} - U(z,t)$$

Where θ is the volumetric water content ($m^3 \cdot m^{-3}$), t is time (day), K is the hydraulic conductivity ($m \cdot day^{-1}$), z is the depth (m), H is hydraulic head (m), composed of the matrix potential ψ, and U is a sink term representing water uptake by plants (day^{-1}). The Richards equation thus states that the change in water content over time at a particular soil depth is composed of the quantity of water in the soil, the conductivity of the soil and the amount of water taken up by plants. For description of the soil hydraulic properties, the Campbell K-θ-ψ equations in LEACHP were replaced by the closed form equations by van Genuchten (1980).

Recently PEARL, a new simulation model for pesticide leaching, was launched by RIVM and Alterra Green World Research (Tiktak *et al.* 2000). The model was calibrated for the local conditions in Ecuador and its results have been compared to the outcomes of LEACHP. Although PEARL results are similar to the results of LEACHP, the Tradeoff Analysis Project decided to continue with PEARL as it can be used in its released form and is fully backstopped by the two institutions.

LEACHSum

Given the fact that pesticide leaching is simulated on the basis of water movement, the equilibrium constant Kd for adsorption/desorption and half-life times, LEACHP and PEARL actually calculate the fraction of the pesticides applied that leach. As a result it is independent of the quantity of pesticides applied. Since in most cases we will perform calculations for a fixed year(s), water movement will be similar. As a result, we have to perform leaching calculations to get the fractions. Since the calculations in LEACHP and PEARL are rather slow, we carried out a large number of calculations for the different soil types, climatic years, and pesticides and derived transfer functions. The transfer functions are simple regression equations between the fraction of a pesticide leached F_{cps} and the total amount of rainfall, R, thickness of the A-horizons, A, and the soil type, S:

(2) $$F_{cps} = f(R_{tot}, A, S)$$

Although the regression equations are determined per soil type they have a linear character with respect to R_{tot} and A.

The implementation of LEACHSum in the Tradeoff Analysis Model

After running the econometric-process simulation model, data are available on pesticide use (type of pesticide, time of application and quantity). Data on the main soil characteristics and the corresponding weather data were already extracted from the GIS database to run the crop growth simulation model. The Tradeoff Analysis Model creates the appropriate input files for the environmental process model. The specific data for an individual field are exported to the LEACHSum input files. In a second step, the Tradeoff Analysis Model calls the executable of the simulation model. The simulation model creates a datafile with the simulation results that is subsequently read by the Tradeoff Analysis Model.

6.3 Other environmental process models

Although in the case of Carchi only a link with pesticide leaching models has been elaborated, linkages with other environmental process models are similarly possible. In another application of the model an interface with the WEPP model to estimate soil erosion is developed. In all cases an interface is required that translates data from the tradeoff model to the environmental process model and back. If simple statistical metamodels are developed, they can also be implemented in the econometric simulation model.

7 Health Models

The purpose of health models in the overall tradeoff analysis framework is to translate data on simulated pesticide applications (outputs from the econometric-process simulation model) into a health indicator for relevant parts of the farm or rural population. For the purposes of the research in Carchi, the quantitative indicator selected was a measure of the neuro-behavioral health of farm workers exposed to pesticides (Cole *et al.*, 1998, Antle *et al.*, 1998).

Two types of simulation models were used to analyze health impacts of pesticides in the original Carchi study. One model was based on a system of equations representing farmers' production decisions and the farmers' health status. In this model, crop productivity was hypothesized to be a function of the farmers' health, and health was hypothesized to be a function of pesticide use and other farmworker characteristics. To implement this approach, we use a log-linear approximation to the cost function,

(1) $\ln C = \alpha_0 + \alpha_1 \ln(Y) + \alpha_2 \ln(Z) + \beta_1 \ln(w_1) + \ldots + \beta_n \ln(w_n) + \gamma I + \varepsilon_1$

where: Y is expected crop yield; Z is the fixed factor of production (field size in this case); the w_i are prices of the variable inputs, fertilizer, labor, and pesticides; I is health status, represented by neuro-behavioral status; and ε_1 is an error term. Applying Shephard's lemma, it follows that $dC/dw_i = x$, where x is the cost-minimizing quantity of the i^{th} input. For the log-linear cost function, Shephard's lemma can be written as:

(2) $\ln(x_i) = \ln(\beta_i) + \ln(C) - \ln(w_i) + \varepsilon_{i\,2}, \; i = 1,\ldots,n$

where the $\varepsilon_{i\,2}$ are error terms.

We specify the health production function as:

(3) $I = \delta_0 + \delta_1 c_1 + \delta_2 c_2 + \delta_3 \ln(x_5) + \varepsilon_3,$

where c_1 and c_2 are measures of the farmer's intelligence not directly affected by pesticide exposure (c_1 is a measure of the ability to associate similar objects, c_2 is a measure of the individual's general knowledge, and both are subtests of the Ecuadorian adaptation of the Weschler adult intelligence score); x_5 is the quantity of carbofuran applied during the season on a particular field; and ε_3 is an error term. Recall that the toxicological literature suggests that carbofuran is the insecticide that is expected to have a significant neurobehavioral effect.

The system of equations (1)-(3) is identified (in the sense of a simultaneous equations system) and can be estimated using nonlinear techniques that account for the endogeneity of cost, input quantities, and health. Note that the conventional way to estimate a log-linear model with first-order conditions is to estimate the factor cost share equation with an additive error term as $w_i x_i / C = \beta_i + \varepsilon_{2i}$. Equation (2) is equivalent to estimating the cost-share equations in the multiplicative error form $w_i x_i / C = \beta_i \exp(\varepsilon_{2i})$. This multiplicative error model is attractive because it is consistent with the log-linear, constant-elasticity specification of factor demand equations with additive errors, and because it fits the data well in this case.

The system of equations (1)-(3) shows that pesticide use affects health, health affects productivity, and productivity affects pesticide use. This type of feedback is not contained in the dynamic factor demand model and the econometric-process simulation model presented in Chapter 5. This is because a model that would capture both the detailed dynamics of pesticide use and the health-productivity relationship would be extremely complex to specify empirically and estimate. In particular, in order to estimate dynamic factor demand functions, the cost function was not estimated directly because doing this for the dynamic specification of the production model is intractable. In the system of equations (1)-(3), on the other hand, we abstract from these dynamics of pesticide decision making to be able to explicitly represent the cost function.

Thus, to be able to use the dynamic economic model presented in Chapter 5, we must abstract from the health-productivity feedback modeled above. The modeling approach that we use to incorporate health into the Tradeoff Analysis Model is therefore constrained to using a single equation like (3) in the same way that the environmental process models are used, without feedbacks from health to productivity.

In the version of equation (3) used in the Carchi analysis, the health effects of pesticides are represented with an equation that predicts the mean neuro-behavioral score (MNBS) for a member of the farm population as a function of pesticide use and potato intake, controlling for individual characteristics. The equation estimated with the least squares method (with t-statistics in parentheses) is:

MNBS = -1.783 – 0.018 (Total number of insecticide applications) +
(-7.33) (-2.98)

0.069 (Information) + 0.167 (Similarities) – 0.035 (Potato intake)
(2.41) (4.00) (-2.05)

These estimates show that neurobehavioral health is decreasing in the total number of insecticide applications, and also in the level of potato intake. A similar relationship was obtained for equation (3) when the full system of equations (1)-(3) was estimated (see Antle *et al.*, 1998).

To implement the health model component, the MNBS equation was incorporated into the SAS-based econometric-process simulation model for the Carchi study. The data on numbers of insecticide applications were derived from the econometric-process model for each field in each growing season to create the variable measuring the total number of insecticide applications. The health model was validated by comparing sample and simulated distributions of the MNBS variable.

8 Tradeoff Analysis Model Software

8.1 Introduction

This chapter introduces users to the use of the Tradeoff Analysis Model (TOA) software. The chapter provides a step-by-step guide to the operation of version 3.1. Key elements of the analysis following the TOA software include:

- Database structure.
- Software installation and operation.
- Parameter estimation.
- Tradeoff and scenario definition.
- Scenario analysis.
- Environmental impact analysis
- Presentation of tradeoffs in graphs and maps.

These elements will be described in the following sections.

8.2 Database structure

Before one can start working with the TOA software, the proper databases need to be established. The databases include geo-information on the natural resources (soil, climate) and field size. In addition survey data is required describing land allocation and land management decisions by farmers. The TOA software does not include disciplinary simulation models (e.g., crop or economic simulation models). It is a shell for the communication between such models. The user must provide these models.

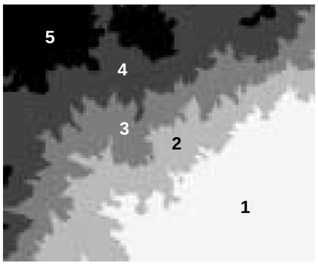
8.2.1. Geo-information

Geo-information is stored in the format developed by ESRI for grid files. However, the GIS module that is provided with the shell also allows for the conversion of IDRISI raster files into this format. The TOA-software does not allow for complex GIS analysis and we therefore recommend users to develop the GIS databases in Arcview, ArcInfo, or IDRISI. What kind of geo-information is required for the operation of the shell?

Weather data: Weather data in the TOA model is used to simulate inherent productivity and the environmental impact of land management (e.g., pesticide leaching, erosion). To describe weather two files are needed to describe the spatial variability and an additional file for each of the climatic zones identified in the map. The structure for Carchi is presented in Figure 8.1 and includes a map with 5 zones identified on the basis of the digital elevation model. Weather data for two stations is available. One station, located in San Gabriel includes minimum and maximum temperature, rainfall, and radiation. The other station (El Voladero) is located in the Páramo and includes only temperature and rainfall. On the basis of those two stations, weather files for each zone are created. Radiation is assumed constant and temperatures and rainfall is interpolated linearly between the two stations.

Soil data: Soil data in the TOA model is used to simulate inherent productivity and the environmental impact of land management. To describe soil variation the same structure as for weather data is followed. Two files describe the spatial variation in soil: the map with soil units and a dBase file with the soil types corresponding codes for the soil units. The site and profile description are subsequently described in two additional dBase files denominated soilprof.dbf and soilhor.dbf respectively. When running the DSSAT models soil.sol files are automatically created as required on the basis of the soil database. The structure of the soil data is shown in Figure 8.2.

Climate.asc



Climate.dbf

CLIM_ID	CLIMZONE
1	1cli
2	2cli
3	3cli
4	4cli
5	5cli

1cli8501.wth

```
*WEATHER DATA : San Gabriel, climatezone 1 (2740-2940)

@INSI      LAT     LONG  ELEV   TAV   AMP REFHT WNDHT
 CISG    0.600  -77.817  2860  12.3   0.8   3.0  10.0
@DATE  SRAD  TMAX  TMIN  RAIN
85001  20.5  16.8   6.4   0.0
85002  22.4  17.4   3.0   0.0
85003  20.6  18.8   7.4   0.0
85004  17.5  16.0   8.2   0.0
85005  20.2  19.0   3.0   0.0
85006   6.1  19.4   2.4   8.0
85007   7.7  15.6   8.8   4.6
```

Figure 8.1 The structure of the weather database for the Tradeoff Analysis Model (only parts of the database files are displayed)

Soil.asc

Soil.dbf

MU_ID	SOIL_ID	S_VALUE
5	5	Df
6	6	Dm
7	7	Dp
8	8	Dv

Profdat.dbf

SOIL_ID	SOILCODE	HOR_ID	HORCODE	SLB
7	Dp	2	A2	62
7	Dp	3	B1	144
7	Dp	4	B2	178
7	Dp	6	B4	200
5	Df	1	A1	35
5	Df	3	B1	83
5	Df	4	B2	163
5	Df	5	B3	200

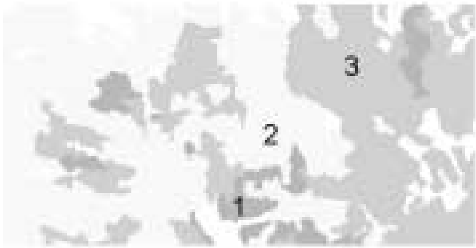
Hordat.dbf

HOR_ID	CODE	SLMH	SLLL	SLSI	SLCF	SLNI	SLHW	SLHB	SCEC
1	A1	-99	0.33	34.4	0	0.44	5.8	4.6	20.8
2	A2	-99	0.25	37.8	0	0.54	5.2	4.5	27.9
3	B1	-99	0.39	25.2	0	0.27	5.8	5.0	32.2
4	B2	-99	0.13	21.3	0	0.05	6.2	4.8	6.1
5	B3	-99	0.44	34.8	0	0.14	5.6	4.7	25.5
6	B4	-99	0.43	31.0	0	0.27	5.5	4.6	25.4

Figure 8.2 The structure of the soil database for the Tradeoff Analysis Model (only parts of the database files are displayed)

Field size data: Field size is an important driving factor behind land management and land allocation decisions. Field size varies throughout the region. If the spatial variability is described by identifying a number of zones, one can specify the specific distribution per region. If data on field size are specified in the settings, the TOA software will sample field sizes. If not specified, one has to deal with field sizes in the economic models. For Carchi, an aerial photo interpretation yielded zones with a similar parcel distribution. On the basis of survey data, a log-normal distribution was used for parcel size in each of the three zones. The structure is shown in Figure 8.3.

Fsize.asc



Fsize.dbf

FSIZE	MEAN	SD
1	-0.40	0.30
2	-0.39	0.37
3	-0.31	0.36

Figure 8.3 Database describing the variation in parcel size for the Carchi study area

Other GIS data: During the tradeoff analysis one has the option to stratify the area on the basis of other GIS data. To avoid missing values for urban areas or natural areas for which no data are available, we created a map indicating the area for which we do have data available. This map is called limit.asc. We added as a condition before sampling fields that parcels should be within the area identified by limit.asc.

8.2.2. Survey data

Database files for the estimation of the econometric-process simulation model vary by model. The shell allows for any structure of database files. A number of elements has to be kept in mind:

- A file is required that contains variables that uniquely identify each field and links the file to the other survey data files. In addition the file needs to have the coordinates of the fields. The headers of the columns containing the coordinates need to correspond with the codes for coordinates as set in the TOA settings.
- In addition a set of other database files can be defined that represent land allocation and land management decisions. Each of these files also requires the necessary identifier variables.

In the case of Carchi, four input database files are created on the basis of the survey data:

- *Field.dbf* data on the fields,
- *Pest.dbf* data on potato management,
- *Cows.dbf* data on pasture (including cattle) management, and
- *Cost.dbf* aggregate data per season, price data on both agricultural inputs and outputs.

Fields are often subdivided and managed differently. In addition, milk production is an important economic activity. Herd management, however, cannot be linked to a field but only to a farm. Therefore, we work with the following identification numbers:

- Farm
- Parcel
- SubParc

Each combination of a farm and parcel is geo-referenced, but sub-parcels, i.e. the often temporary, subdivision of parcels, are not geo-referenced. The sub-parcel corresponds with the “field” as being used in the TOA software.

8.3 Setting up the software

8.3.1 Installation

There are three installation programs on the installation CD of version 3.1:

- Setup_BDE.bat
- Setup_Carchi.bat
- Setup_Encanada.bat

The BDE installation program will install the Borland Database Engine and some minor drivers necessary for the operation of the Tradeoff Analysis Model. The other two installation programs will install the TOA software completely configured with all the appropriate database files for the Carchi and Cajamarca study areas respectively. After the installation of the drivers and the Carchi model (the one described in this manual), you are ready to start working with the Tradeoff Analysis Model. For both applications the Statistical Analysis’s System (SAS) software is required with the econometrics and time series options installed.

8.3.2 Running the software.

Start the Tradeoff.exe file in the c:\to31_Car directory. You will see the opening screen of the Tradeoff Analysis Model (Figure 8.4). By clicking the Continue button, one enters the software and can start working. Although the software is properly configured, it is recommended to review the settings. First one must check the location of the SAS software that is installed independently from the TOA software (Settings – Economic models – General – Statistical Package). After starting up the TOA Model, you will find in the main menu an item denominated “Settings” (Figure 8.5). Here you can setup your specific application. In the following Sections each of the components of the settings will be described.

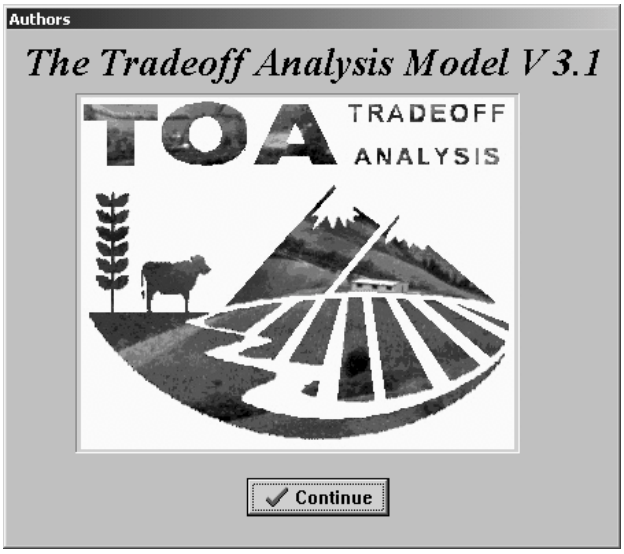


Figure 8.4 Opening screen of the Tradeoff Analysis Model Software.

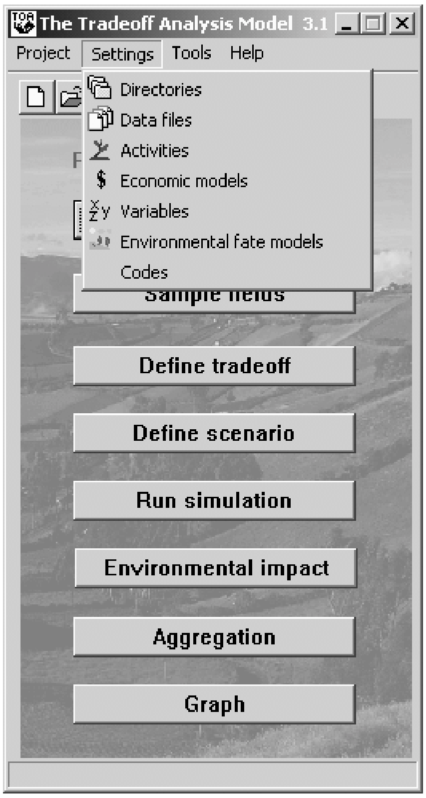


Figure 8.5 Settings menu

8.3.3 Directories and files

Typically one will work with a directory structure as follows:

- C:\
  - TO3
    - Database files
    - GIS data
    - Weather files
    - Soil data
    - Sampled fields
    - Economic models
    - Tradeoff definitions
    - Scenario definitions
    - Results

The directory structure can be defined in the tradeoff shell under Settings – Directories (Figure 8.6). Press the button to change a directory (This guarantees that the directory exists and is available). Note that some of the models (e.g., the DSSAT models) do not allow long directory names or directory names that include spaces. In the following text we will describe the recommended usage of each of these directories.

TO3: The main directory contains the tradeoff program (tradeoff.exe), one or more project files (e.g., carchi.prj), the Settings file (tradeoff.set), and the GIS module (togis.exe). The entire software is composed of one executable (tradeoff.exe). For this program to operate, the Borland Database Engine (BDE) must also be installed. For the proper operation of the model, settings need to be defined (including directory name, database files, models, and variable names). These settings can be stored in project files (files with a prj extension). The TOA Model "remembers" which project file has been used during the last operation by storing the file name in a settings file (tradeoff.set). This project file will be automatically opened when one starts the TOA Model.

Database files: In the database directory, all the databases are stored that are necessary to estimate parameters of the econometric simulation models. One file is needed that contains data on the location of the survey fields. This file (in dBase format) includes one or more identification numbers for that particular field and the field coordinates. The column names for the identification numbers should correspond with the names as they have been identified in the economic models. The column names for the X and Y coordinates should correspond with the names as they have been identified in the project settings (see Setting – Miscellaneous – Code – "Code for X-coordinate in field files" and "Code for Y-coordinate in field files"). The location of this survey field file is specified under Setting – Files – Other files – Survey fields (although it is possible to store the file in other directories we recommend for reasons of consistency that the file is stored in the database directory.

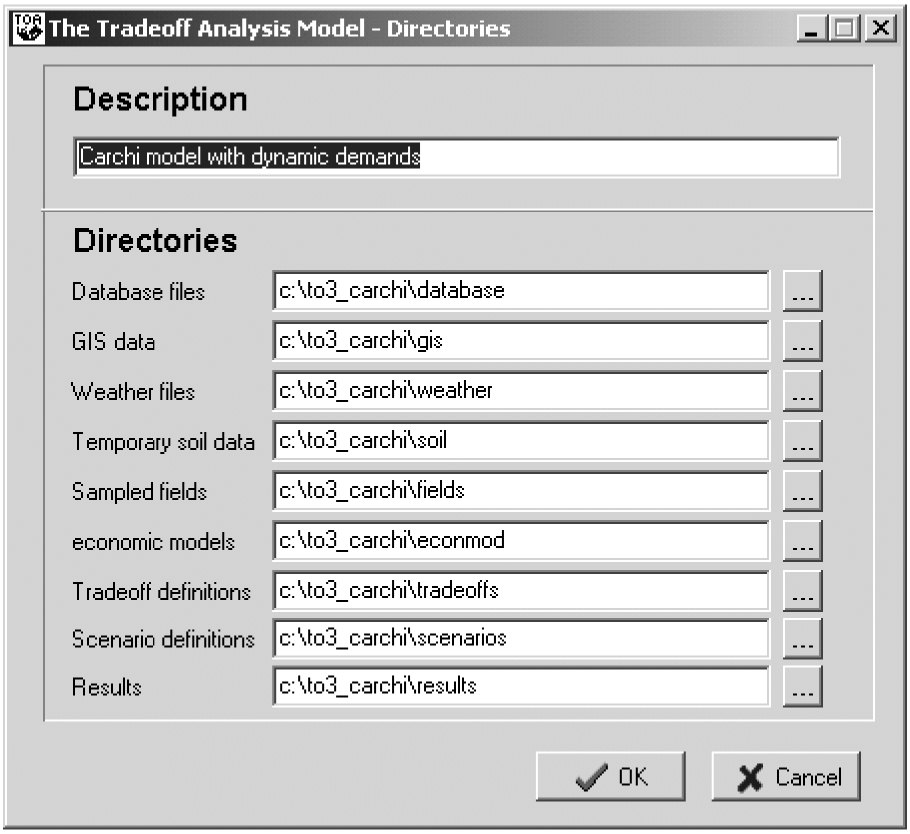


Figure 8.6 Setting Directories in the Tradeoff Analysis Model Software.

GIS data: The GIS data are briefly described in Section 8.2.1. They include the GIS maps (with .asc extension) and the corresponding dBase files as depicted in Figure 1.1-1.3.

Weather files: In this directory the weather files in DSSAT format are stored. DSSAT uses a naming convention for its weather files that should be followed (Figure 8.7). The filename is composed out of a 4-character code for the weather station followed by the year (2-digit) and the number of the file (2-digit). The 4-character codes should be included in the *climate.dbf* file in the GIS directory.

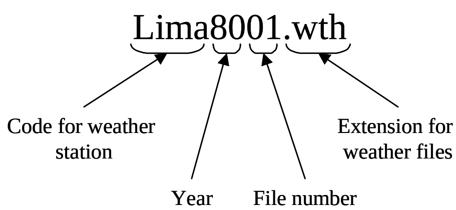


Figure 8.7: DSSAT naming convention for weather files.

Temporary soil data: Currently, the "soil data" directory is only used to temporarily store soil data descriptions for the DSSAT model, i.e., the *soil.sol* file

Sampled fields: The TOA model allows users to carry out the analysis for survey fields but also for fields that have been sampled from the overall population of fields in the region. Sets of fields are described in dBase files that contain the ids for the fields, the coordinates, and the inherent productivities of the different fields.

Economic models: To implement the econometric-process simulation model, tow sets of parameters are estimated: parameters of price distributions, and parameters of econometric production models. In the current version of the TOA, all economic parameter estimation is executed by programs written in SAS and are stored in this "economic models" directory.

Tradeoff definitions: Tradeoff curves represent the joint distribution of economic, environmental or health indicators and how they respond to changes in prices or other parameters. In the tradeoff definition, one defines how e.g. input and/or output prices are being varied to construct the tradeoff curve. Each tradeoff definition is stored in a dBase file. The columns represent an id for the specific conditions and subsequently different price variables. Each row in the file represents specific price conditions with the percent shift in the distribution of a specific variable (100= no change; 50= a 50% decrease; 150= a 50% increase etc.).

Scenario definitions: The econometric-process simulation model is based on various estimated parameters. Running the simulation model with the base parameters gives results that reflect the conditions in the survey data. By changing these variables one can simulate changes in the socio-economic conditions and/or the introduction of alternative technologies. In the settings, one can identify which variables one would like to be able to change in the scenario definition. A scenario definition is a four-column dBase file representing the variable, a description of that variable, a value indicating a new value or a percent change and an indicator whether the value is a new value (0) or a percent change (1). Each scenario will be a separate scenario file in the scenario definitions directory.

Results: All results from the econometric-process simulation model will be written in the results directory. In the current versions of the econometric-process simulation models, the results are composed of one file representing the values for a variety of indicators for each field, tradeoff point and replication. Other files are created that describe input use for the different fields under the different conditions. The latter files are used as input for the environmental impact models.

8.3.4 Data files settings

Before the TOA model can be run, one has to define a number of files that are necessary for running the model. These files can be defined in the 'Settings – Files' item. The data file definition includes:

- Economic data files: these are the files in dBase format necessary to run the economic models
- Maps: All the maps that will be used to determine the growing conditions on the different fields or the environmental impact of agricultural management. In addition, one may include spatial conditions to stratify the area.
- Weather data: Reference to an earlier defined map, the corresponding data files and the names of the columns in the database files describing spatial and temporal variation in weather conditions
- Soil data: Reference to an earlier defined map, the corresponding data files and the names of the columns in the database files describing spatial variation in soil conditions
- Field size data: Reference to an earlier defined map and the corresponding data file describing spatial variation in field size
- Survey field data: the database describing the location and size of the survey fields.

Database files: Under the "Data files" tab under settings you will be able to define a range of data files (Figure 8.8). Each data file is defined by a unique code, a short description and the file name. Note that the filename does not include the directory as all files are located in the data files directory. The code is used as a reference to the SAS models. Users can include in their SAS programs any database file. The typical code in a SAS program to make reference to a database file is:

```
FILENAME field 'c:\TO3_CARCHI\DATABASE\COST.dbf';
```

in which FILENAME is a statement linking a file reference name to physical name of an external file.
field is the file reference name (FILEREF) that is temporarily assigned to a database file, and
'c:\TO3_CARCHI\DATABASE\COST.dbf' is the name of the external file.

Before running a SAS program, the TOA model scans through the SAS code to locate the procedure statement "FILENAME." The TOA Model finds the FILEREF and writes the corresponding filename.

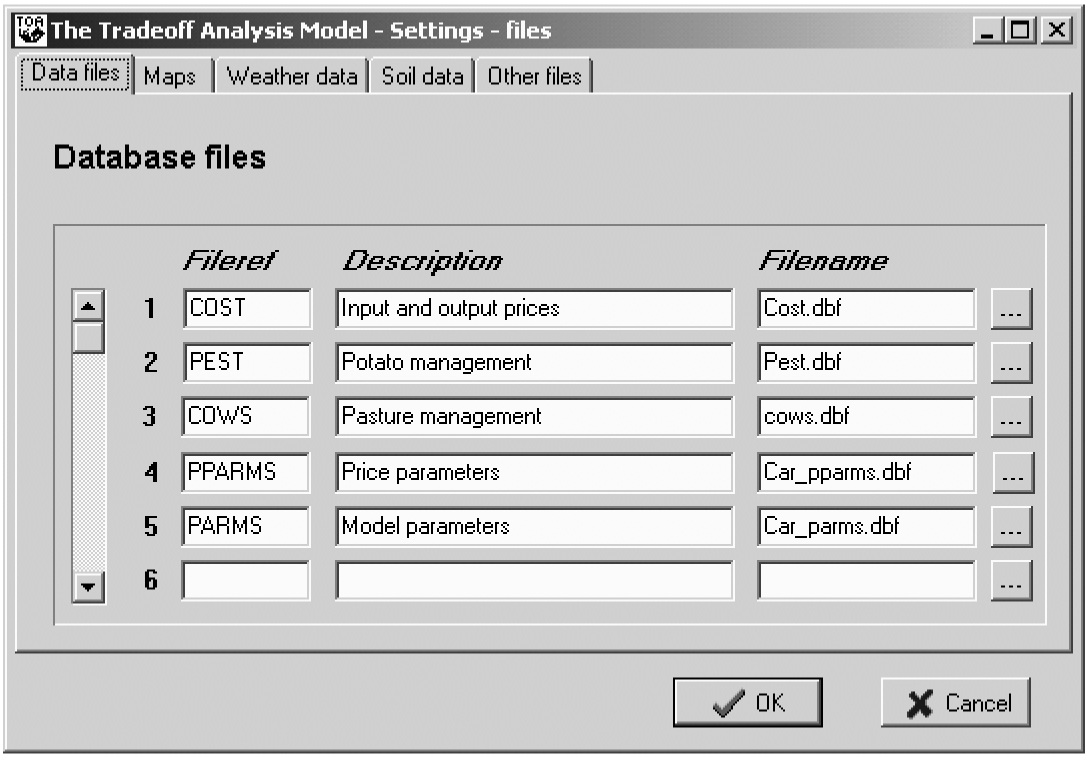


Figure 8.8 Defining database files

Maps: Various maps can be identified for further use in the tradeoff analysis model (Figure 8.9). A map with soil data and climatic data are obligatory. Other maps can be used to stratify the area for specific analysis. Each map is identified by a code, a short description, and a filename. All maps are in a raster format as defined by ESRI with extension ".asc".

Weather data: Weather data are described as illustrated in Figure 8.10: a file reference for a map with the climatic zones, a database file that contains the codes for the different weather stations representing each zone, and subsequently the weather files for the respective weather stations. In the settings one has to define the file reference code for the map, the filename for the database file and the column names for the variable linking the database to the map and the column that contains the codes of the different weather stations (Figure 8.10). As soon as the database file is selected the software will automatically read the column headers. Subsequently, the user can select the columns from the drop-down list.

Note that one does not have to identify the filenames of the DSSAT weather files. The strict naming convention by DSSAT and the definition of the directory in which the files are located make further selection redundant.

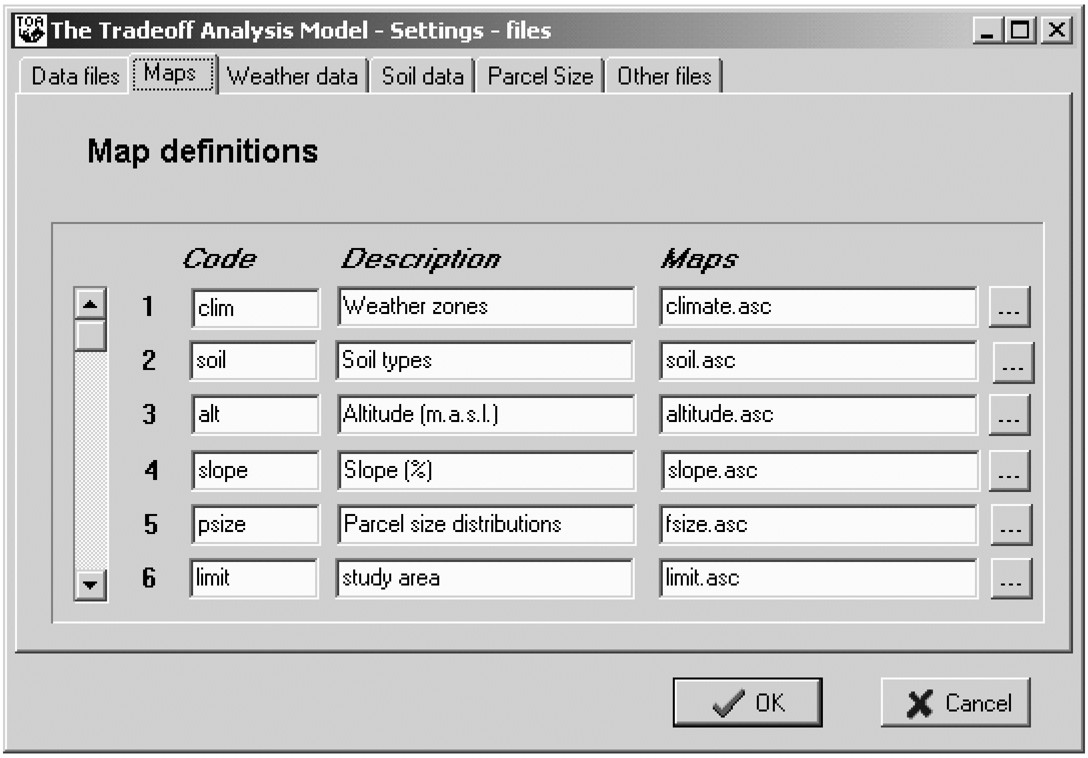


Figure 8.9 Defining maps

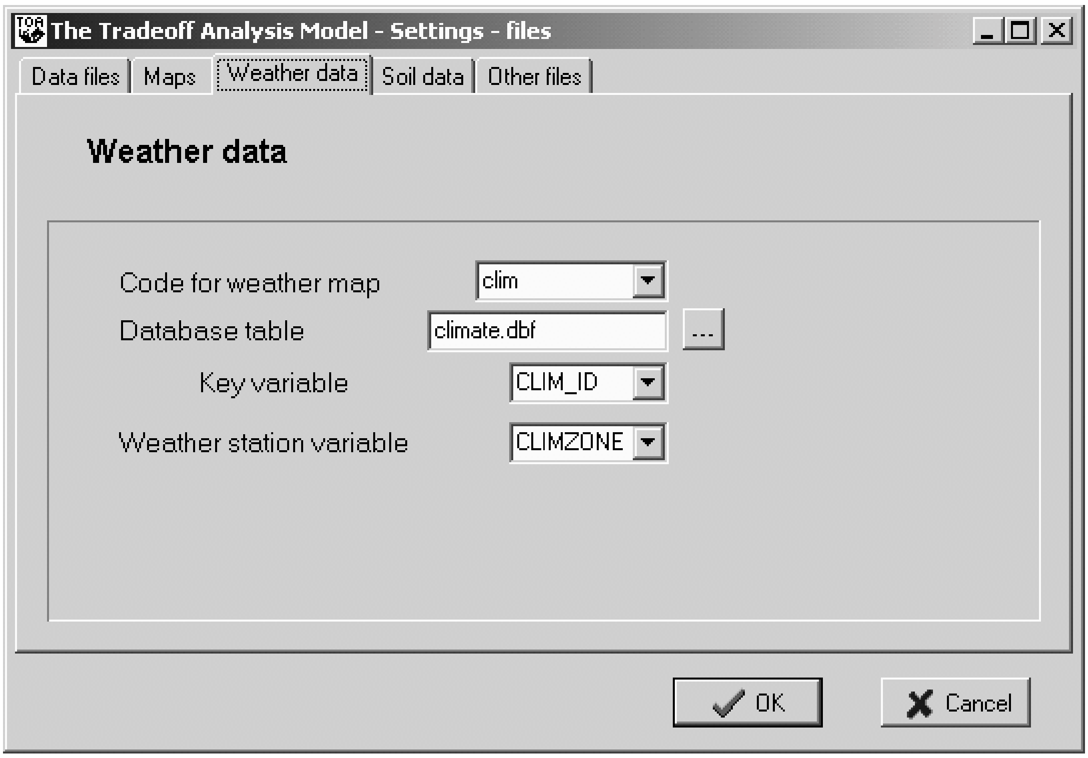


Figure 8.10 Defining weather data

Soil data: Soil data are defined in a page similar to the one for weather data (Figure 8.11). One defines the name of the map by its file reference code, the name of the database file with the columns linking the file to the map and the different soil types and the subsequent files containing site and horizon information. For the two latter files, column names follow the guidelines of DSSAT. Again, if a database file is selected automatically the column names are being read.

Survey fields file: The only other file that has to be defined is the file with the survey fields. This file is located in the “fields” directory and contains the required identification numbers (ids) and the location (x and y coordinates) of all survey fields (Figure 8.12). For further details on this file see Section 8.2.2.

8.3.5 Activities

The tradeoff analysis model can handle any number of user-specified production activities. In the tradeoff analysis the econometric-process simulation model chooses between the different activities for each of the fields under specific economic conditions after which specific components of land management will be simulated. Each activity is described by a reference code, a description, and a reference to the crop growth simulation model that can be used to calculate the inherent productivity (Figure 8.13). The inherent productivity is used by the model to make a selection between different activities and subsequent land management decisions.

8.3.6 Economic models

Land use and management decisions are simulated using econometric-process models programmed in SAS. For the models to function properly one has to identify the name and location of the SAS program (typically the SAS.EXE file), the name of the simulation model (located in the ‘economic models’-directory), and one or several models to estimate the model parameters of the simulation model (all these models are also located in the ‘economic models’-directory) (Figure 8.14 and 8.15).

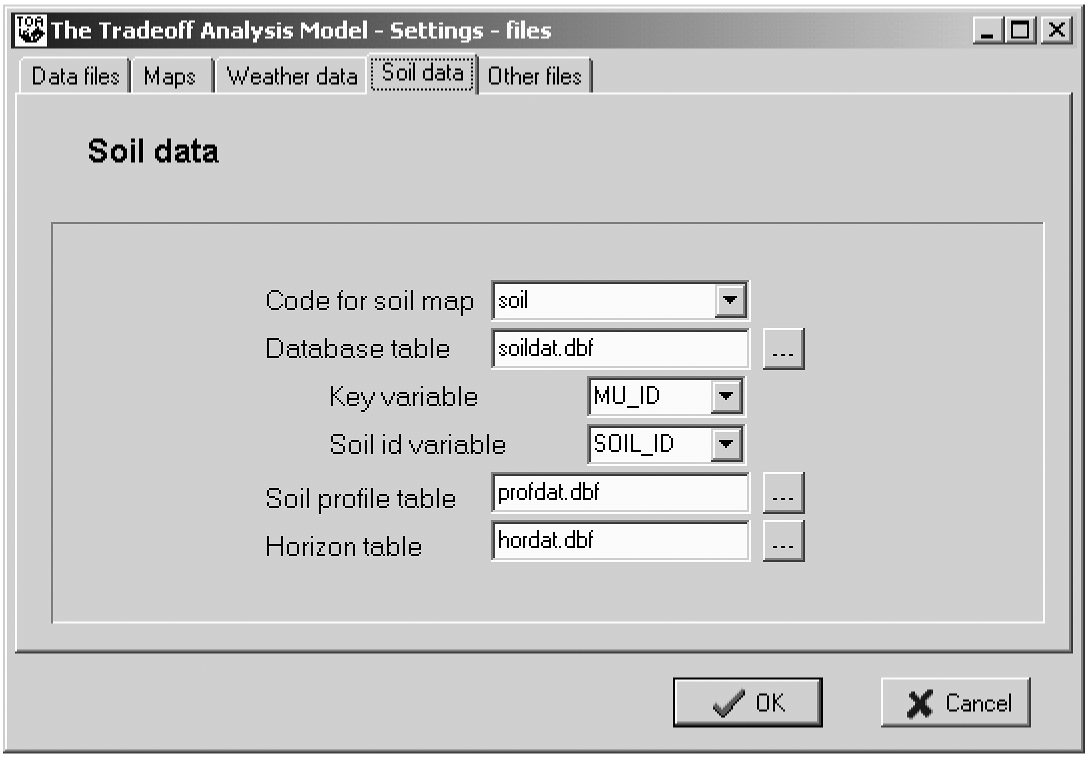


Figure 8.11 Defining soil data

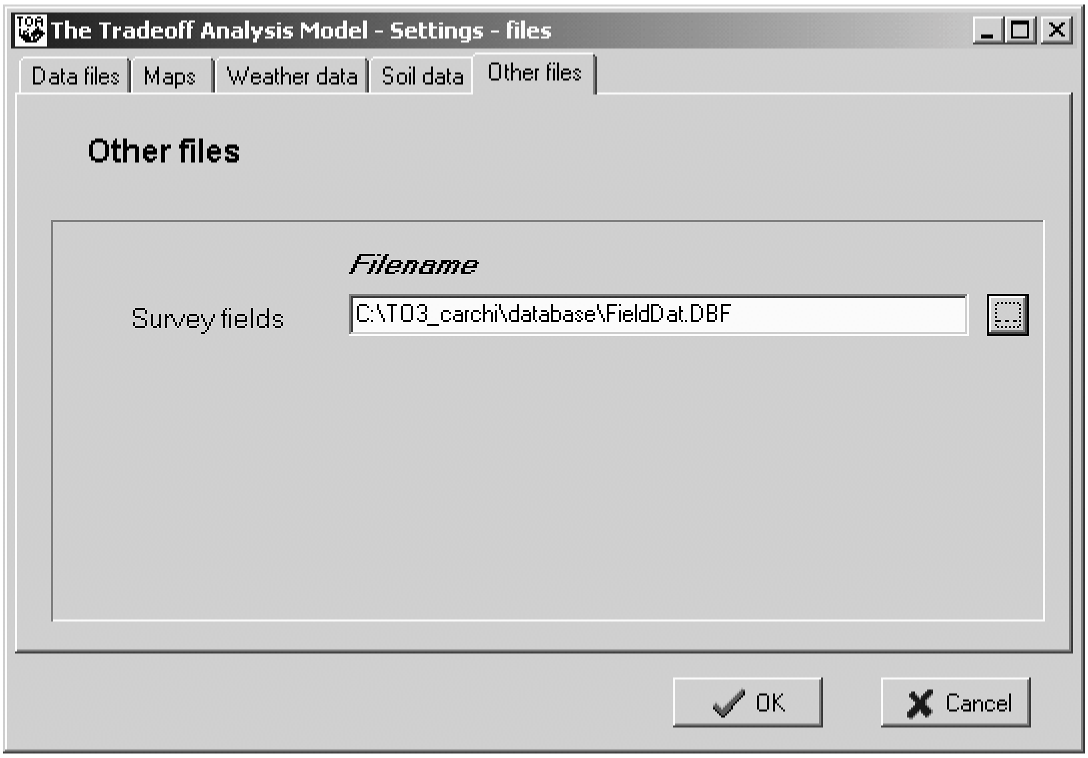


Figure 8.12 Definition of survey fields

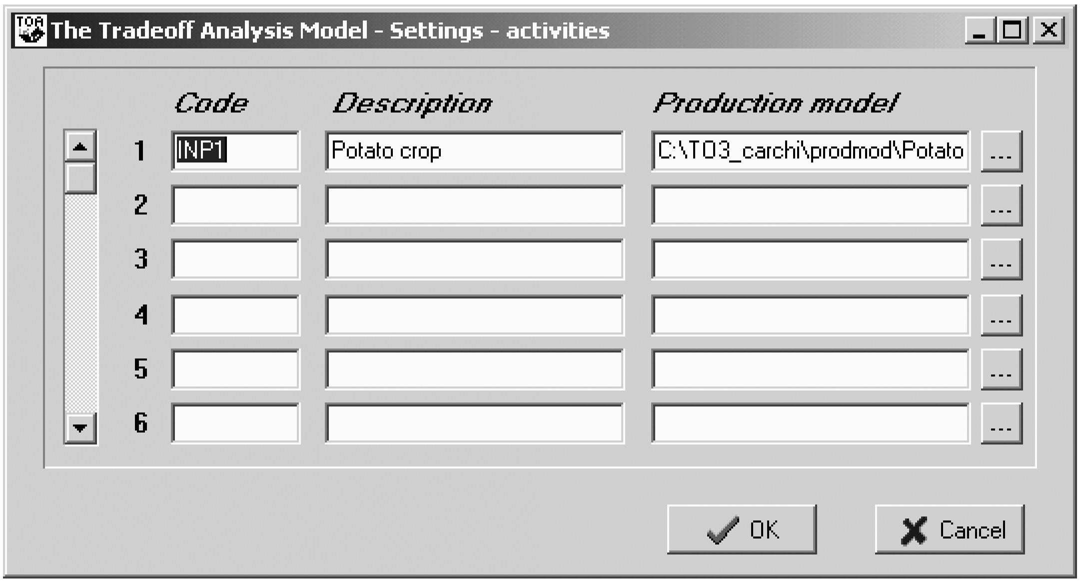


Figure 8.13 Definition of activities

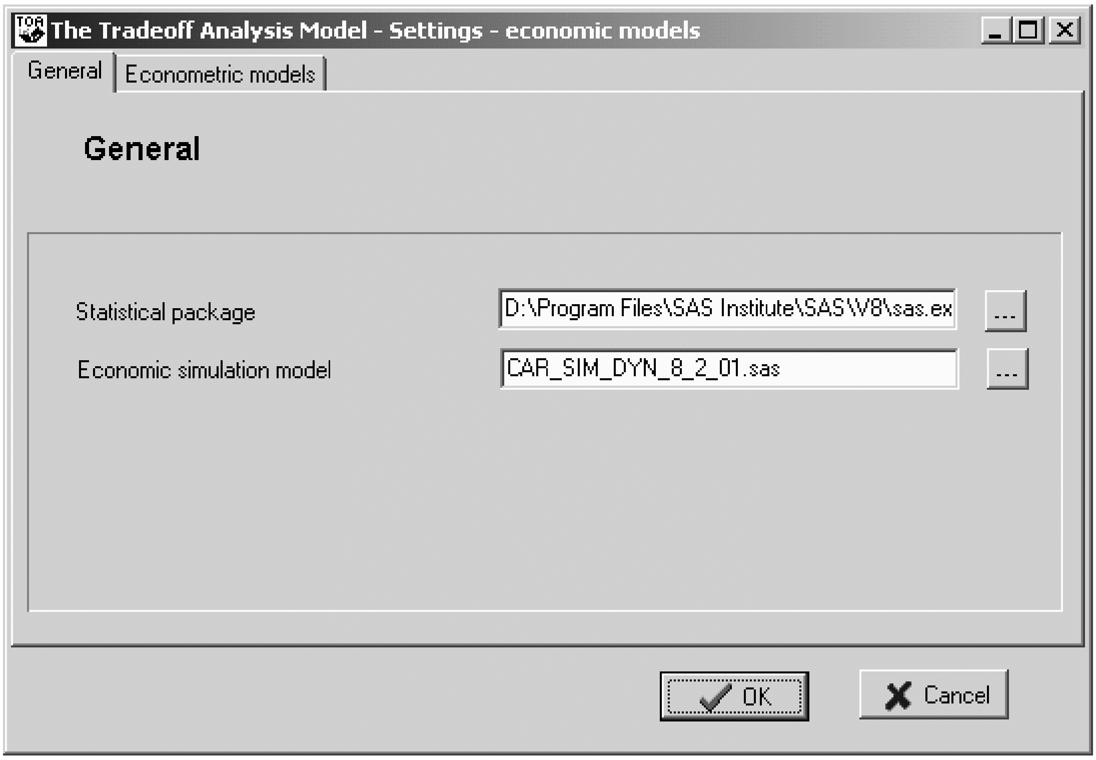


Figure 8.14 Definition of statistical model and simulation model

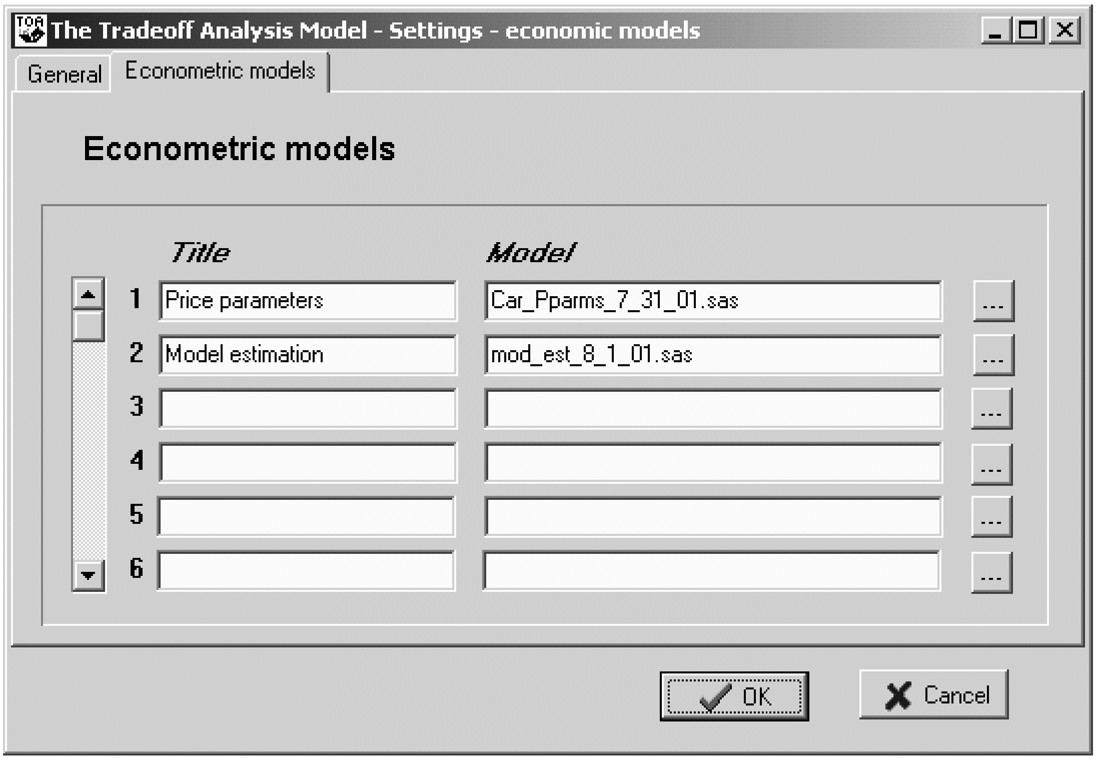


Figure 8.15 Definition of econometric models.

8.3.7 Variables

Under the variable settings in the TOA software one can define

- the abbreviations for all the variables (Figure 8.16),
- the parameters used for the definition of tradeoffs (Figure 8.17), and
- the parameters used for the definition of scenarios (Figure 8.18).

All the basic databases that have been established contain a large number of variables. Under variables one can explain the abbreviations for the variable names. This table (stored in dBase format) is linked to the TOA database viewer. Double clicking on one of the columns will give the description given in the abbreviation table.

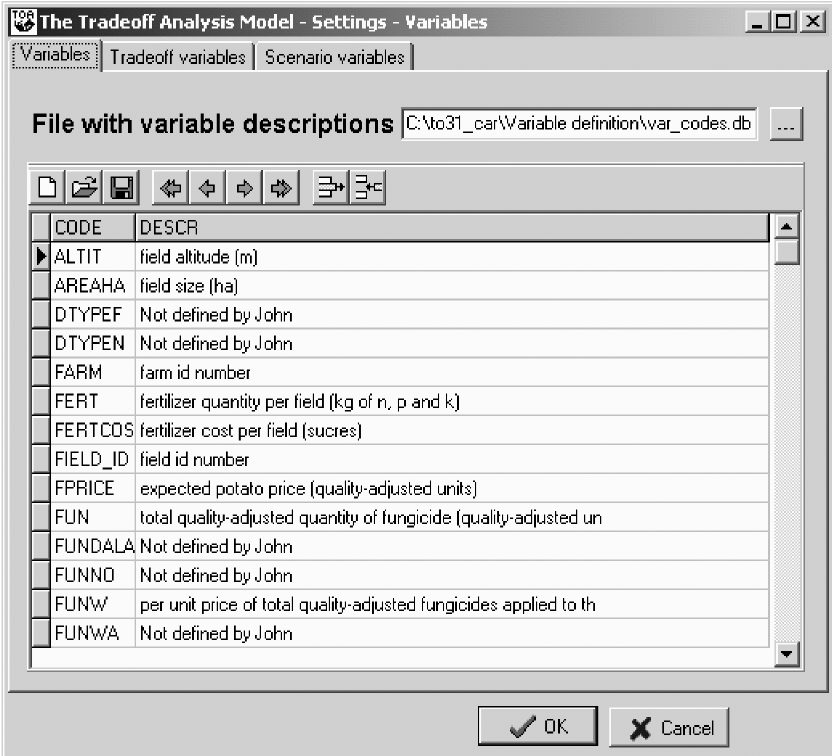


Figure 8.16 Definition of variable names

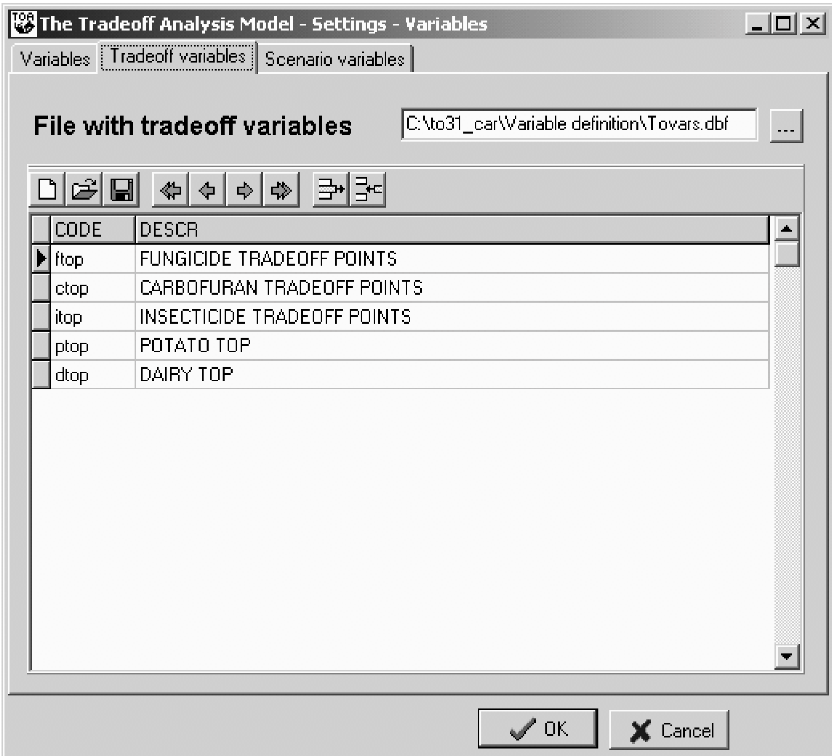


Figure 8.17 Definition of Tradeoff variables

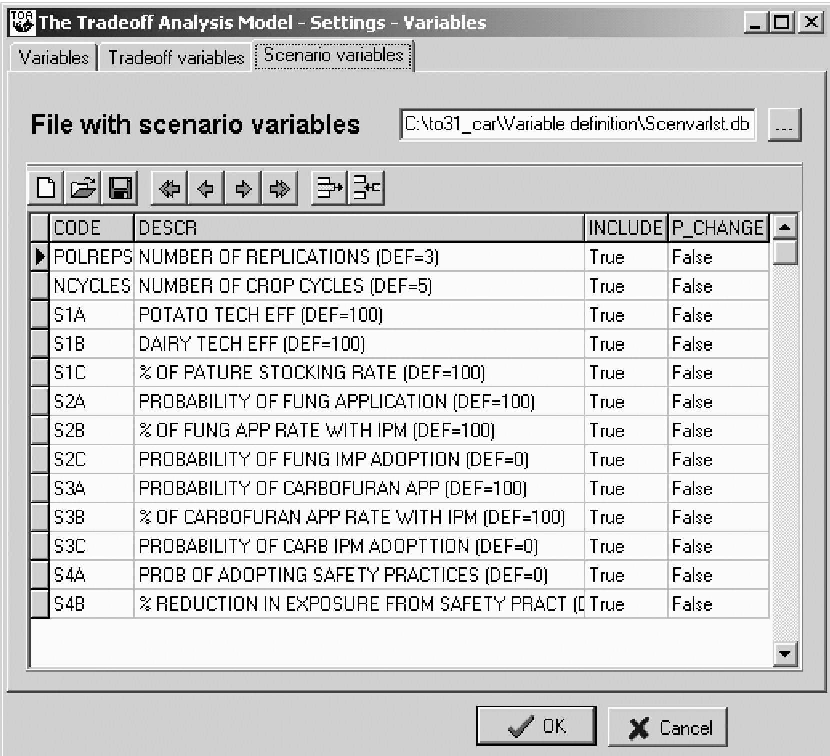


Figure 8.18 Definition of scenario variables

Tradeoff curves are constructed by varying one or more parameters while holding other parameters constant. The economic simulation model reads the files that define the tradeoff points. For example, in the Carchi econometric-process simulation model one has the following SAS code:

```
/*
TOP DEFINITIONS:
  FTOP = FUNGICIDE PRICE
  CTOP = CARBOFURAN PRICE
  ITOP = METHAMIDOPHOS AND OTHER INSECTICIDES
  PTOP = POTATOES
  DTOP = DAIRY
*/

FILENAME trd 'c:\TO3_CARCHI\TRADEOFFS\TODEF1.dbf';
PROC DBF DB4=TRD OUT=TRADE;
*calculate number of tradeoff points;
proc means n noprint DATA=TRADE; var ftop; output out=ntop n=nt;
/* Begin tradeoff loop */
do t=1 to nt;
tno=t;
* read obs. from tradeoff file;
set trade point=t;
 |
 |
 |
end; stop;          /* End of Tradeoffs loop  */
```

In the above code (and in the rest of the code), the variable names are used. If one changes the variable names in the settings, it is necessary to change the simulation model accordingly.

The last group of variables that has to be defined are the scenario variables. Within the TOA Model, scenarios are changes in the model parameters as a result of policies or alternative technologies. In this part, one can identify a list of variables that occur in the simulation model, and indicate whether one would like to be able to change them in the scenarios. In addition, one can specify new values or percent changes to the base values.

3.8 Environmental fate models

Environmental fate models are used to simulate the environmental impacts of the land allocation and management decisions. The output of the econometric-process simulation model describes crop management that forms the basis for the simulation of environmental fate. In many cases, environmental fate models are external models that make use of their own formats for data input and output. Before one can link such a model to the shell an interface needs to be developed that allows for communication between them. Currently two of such interfaces have been developed. One executes a metamodel based on the PEARL model for the calculation of pesticide leaching in the Carchi study area, the other executes the WEPP model for estimation of erosion. In the settings one has to define the name of the interface program. Before calling the interface program, the TOA software will write the project file (now named TO31.PRJ) in the same directory enable the interface to use the same settings. The user defines the environmental fate models in the settings menu (Figure 8.19).

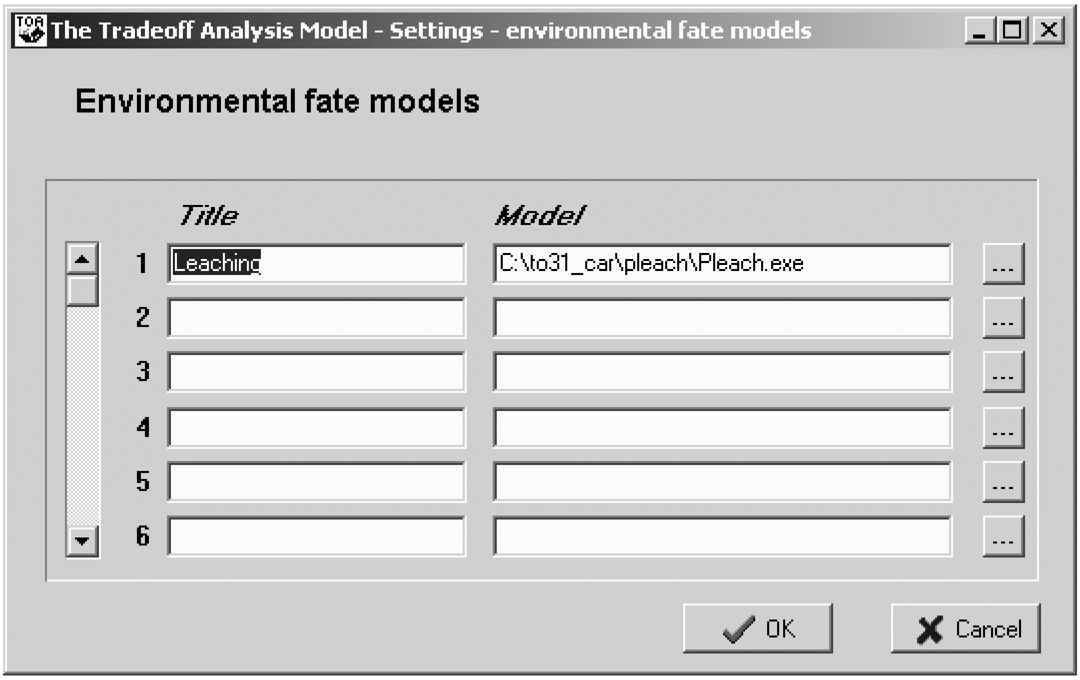


Figure 8.19 Definition of environmental fate models

3.9 Codes

Finally, one has to identify a number of column headings and file reference codes that have not been identified in the above.

Two file reference codes need to be identified for the file containing the data (including the inherent productivities) for the sampled fields (Figure 8.20). In addition, the file reference code for the tradeoff definition is needed.

Five different variable codes are still required (Figure 8.21). These variable codes correspond to the headers in the dBase files, but need to correspond also with the codes in the simulation programs.

The econometric-process simulation model makes use of a variety of input files, but in addition writes its output to one or several output files. In the last tab page of the code-setting menu, one has to enter the file reference codes for the output files (Figure 8.22). These need to correspond to the FILEREF's in the econometric-process simulation model. The output filenames will be set at:

'simulation code'+FILEREF+'.dbf'.

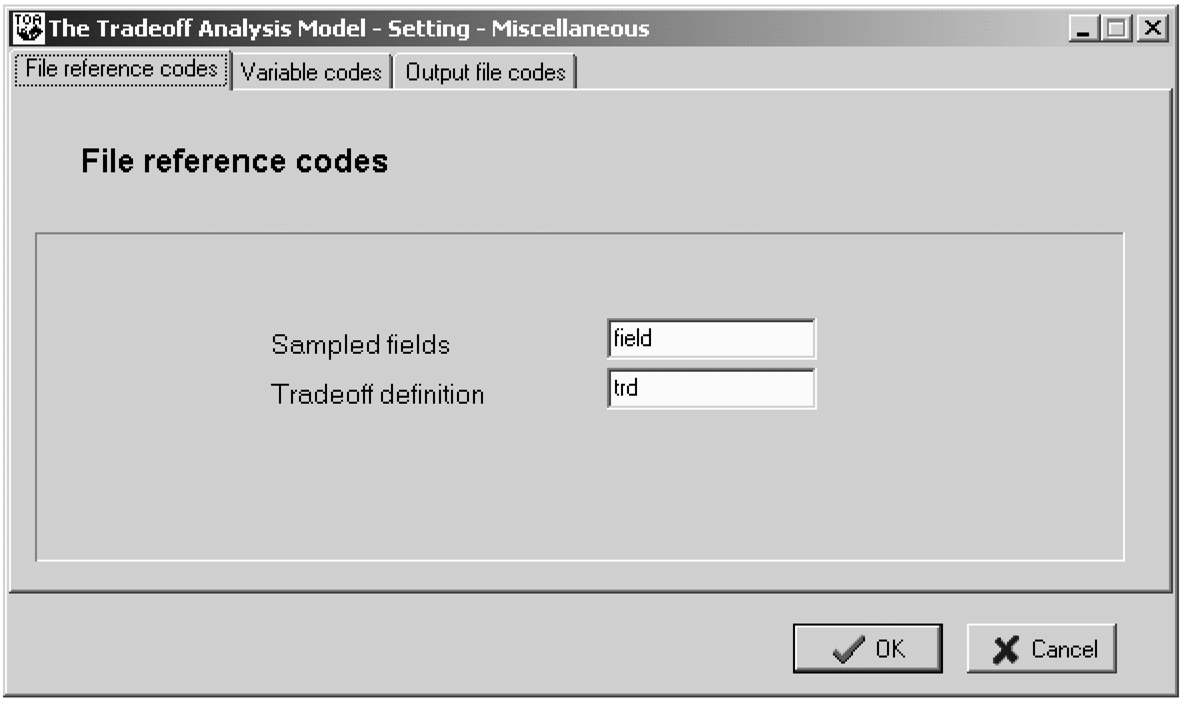


Figure 8.20 Definition of file reference codes

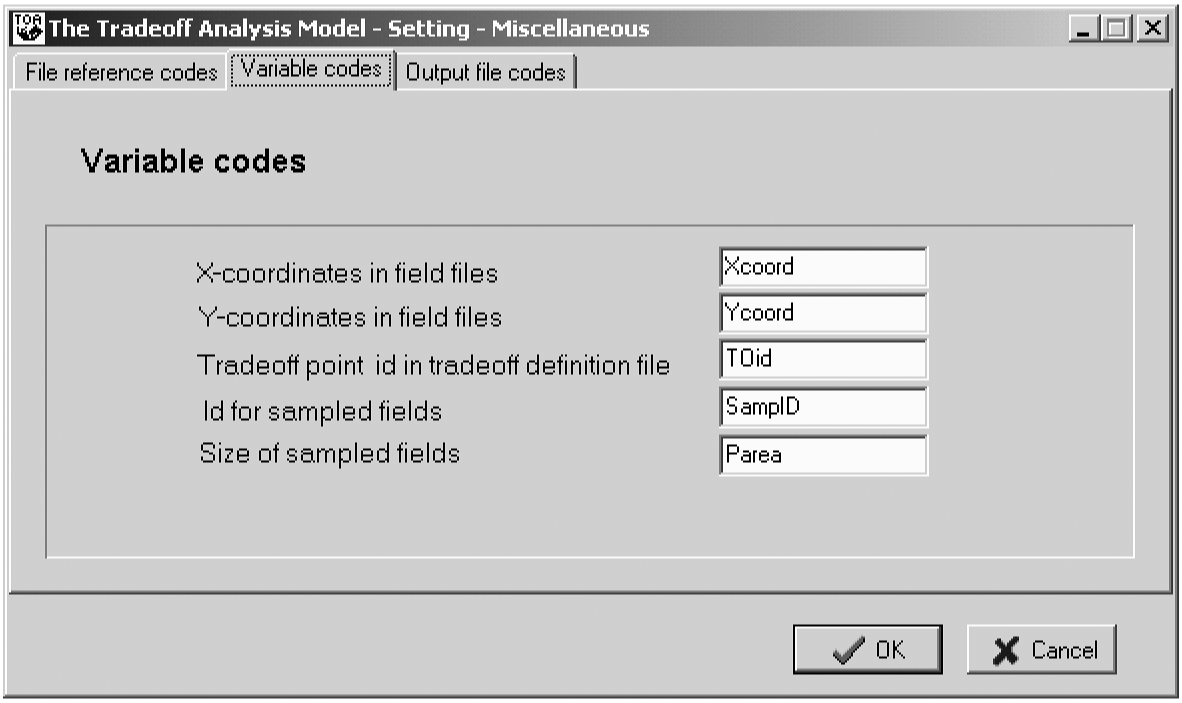


Figure 8.21 Definition of variable codes

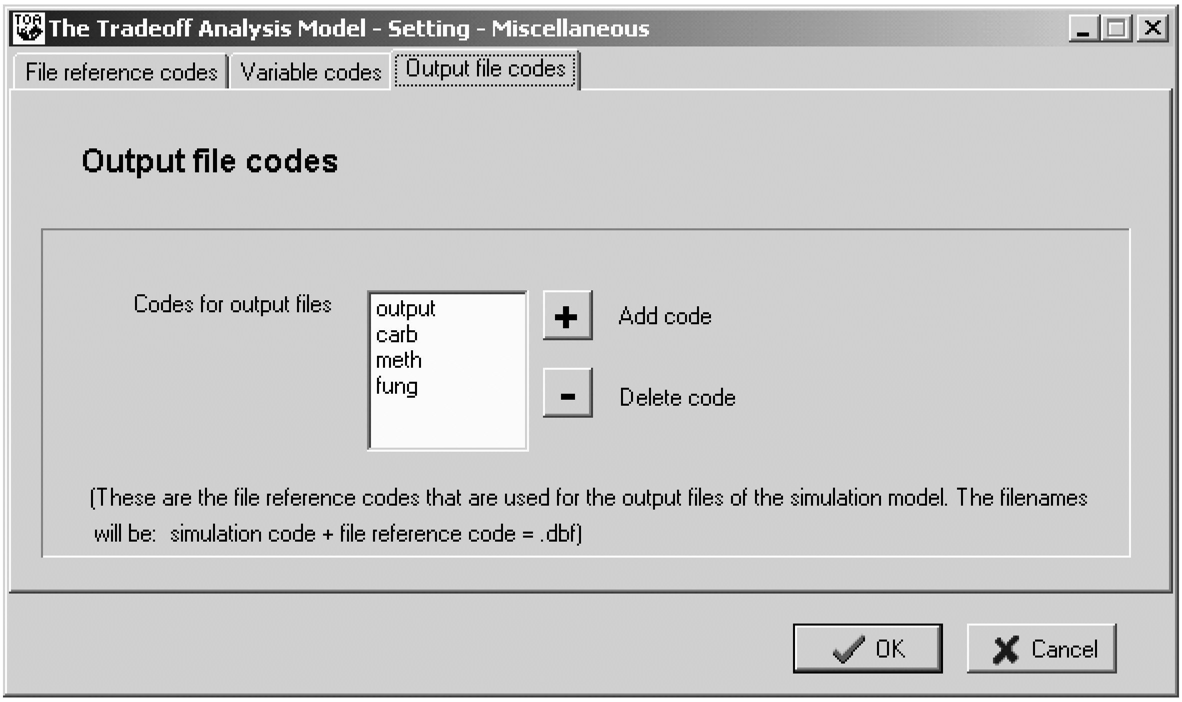


Figure 8.22 Definition of output file codes

8.4 Estimating Economic Model Parameters

The econometric models use the inherent productivities as explanatory variables in parameter estimation. It is therefore necessary to run the DSSAT models for each of the activities for each field in the data used to estimate the econometric models (Figure 8.23). The activities and the respective models are specified in the 'settings-activities' menu. To create the file with the inherent productivities one has to select the activities and indicate a filename for the model output. The output file will be a copy of the survey-fields file with extra columns for the inherent productivities. The headers of the new columns correspond with the codes for the different activities. If one checks the 'View output when finished' button, the model will show the output file in its dBase viewer.

After the calculation of the inherent productivities, the econometric model parameters are estimated (Figure 8.24). Note that the file containing the inherent productivities must be specified in the database files (Settings – Data files).

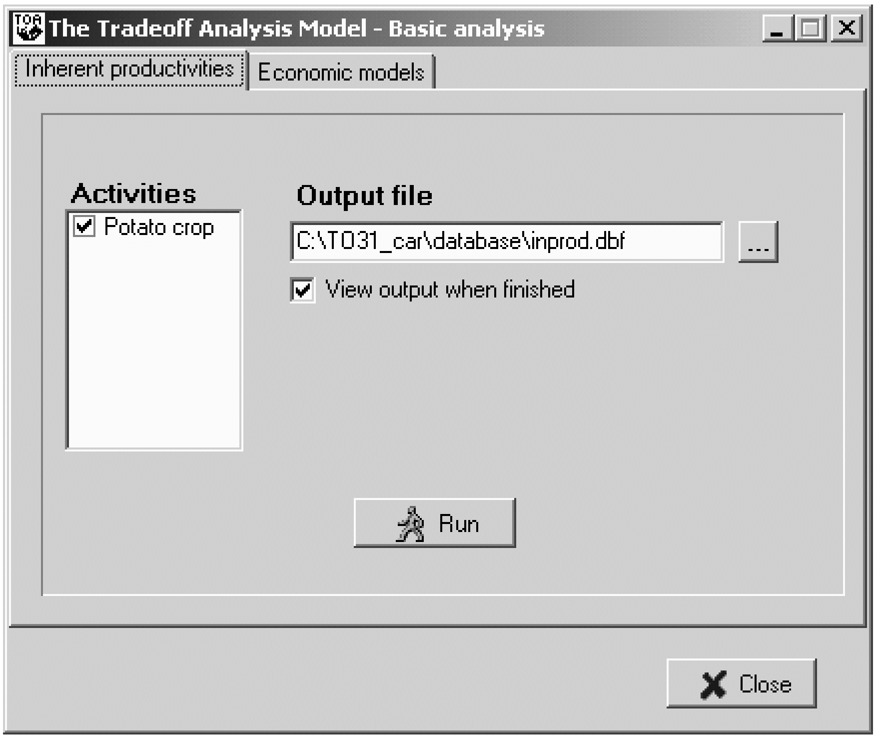


Figure 8.23 Calculating the inherent productivity for the survey fields.

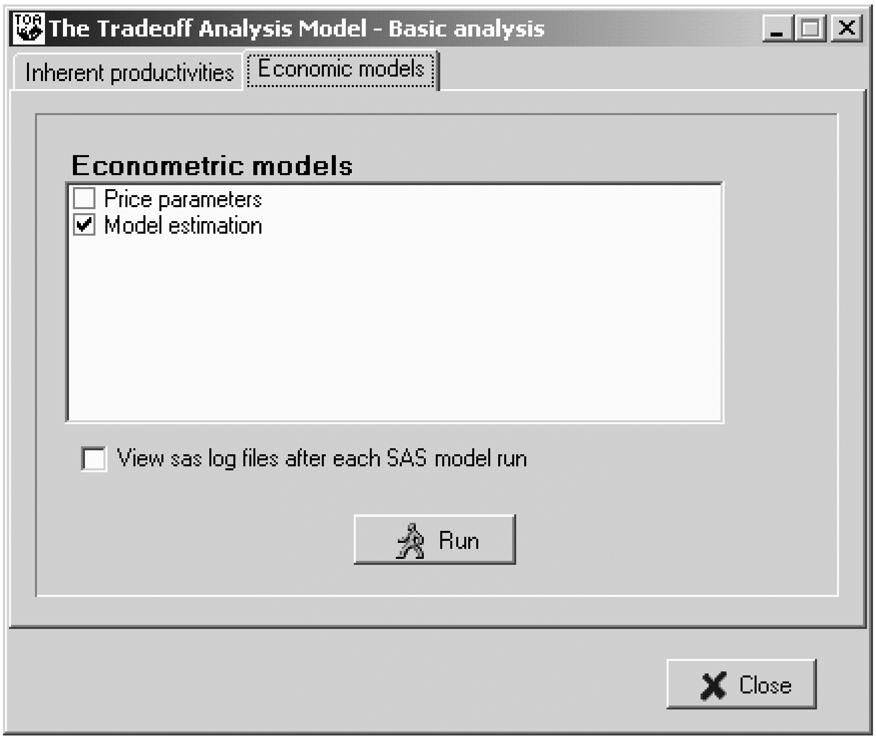


Figure 8.24 Estimating the parameters of the economic simulation models

8.5 Sample Fields

Simulation runs can be carried out for the survey fields or from a random sample drawn from the region represented by GIS data (Figure 8.25). If fields are sampled a number of steps are taken:

1. A location is randomly drawn within the study area (in other words X- and Y-coordinates are drawn from within the limits of the study area).
2. Check whether this particular location fulfills the spatial conditions as defined by the user. If not, a new location will have to be drawn. The spatial conditions allows the user to construct stratified random samples for simulation.
3. The location is added to the file with a unique id and if requested the values of specific maps.
4. If the user specified data for the distribution of field sizes (in 'setting – data files – field size'), a field size will be drawn and an extra column will be added to the file. The name of that column is specified under 'setting – codes – variable codes – field size'.
5. Finally, the inherent productivities for all the activities that have been checked is simulated.
6. If the total number of fields requested by the user is reached, the file will be closed, if not a next location will be sampled.

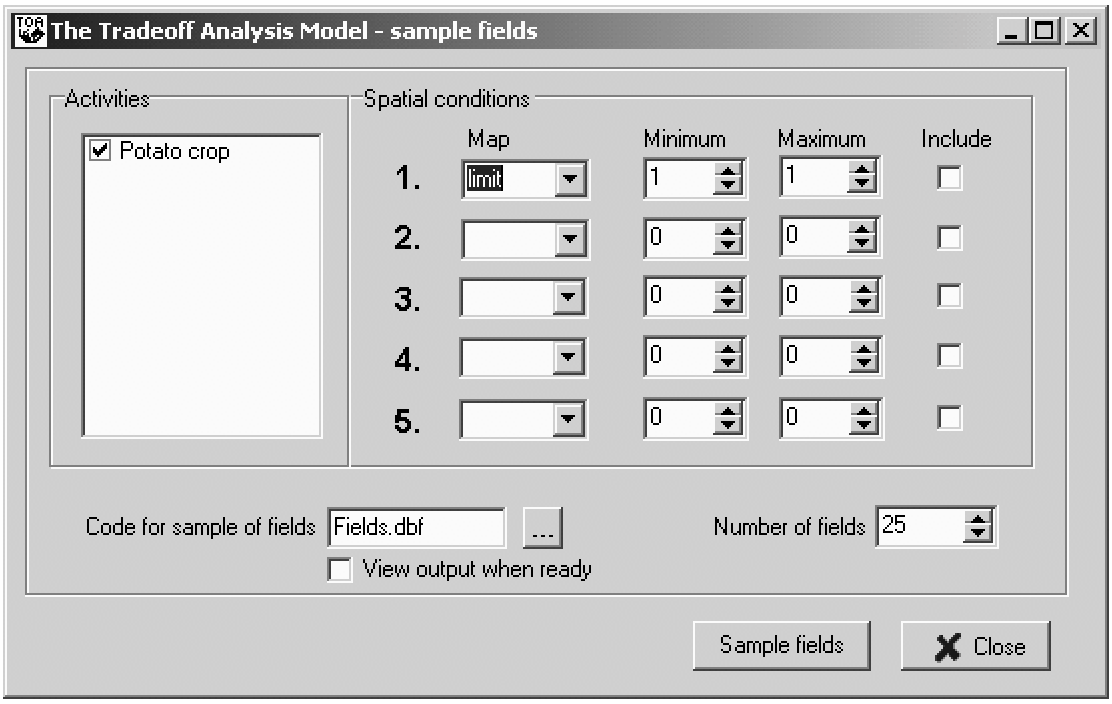


Figure 8.25 Sampling fields (including the calculation of their corresponding inherent productivities)

A number of notes about this menu:

- For the spatial conditions, maps must be specified in the settings menu (‘Settings – Data files – Maps’).
- When a map is selected the minimum and maximum values of that map are determined automatically.
- To view the output check the ‘View output when ready’ check box.
- The filename for the sample of fields can be changed by pressing the  button. This file name must correspond to the file reference code as defined under ‘Settings – Codes – File Reference Codes – Sampled fields’.

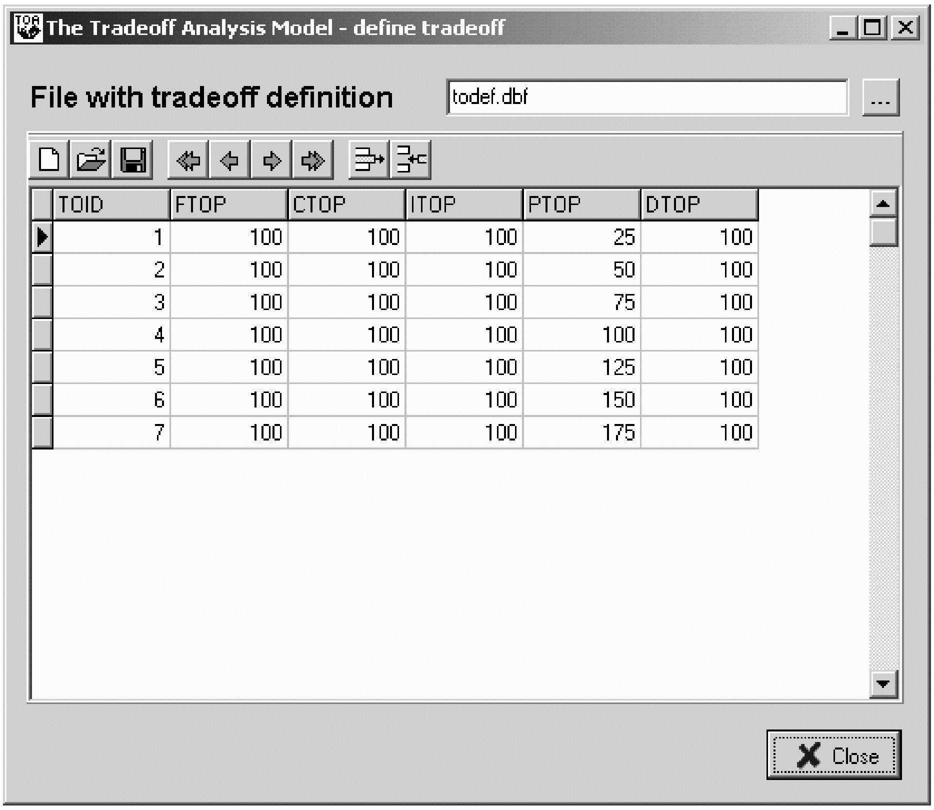
8.6 Defining Tradeoffs

The definition of tradeoffs is based on the parameters defined in the variable definition (‘Settings – Variables – Tradeoff variables’; Figure 8.26). Each row in the tradeoffs file corresponds with a tradeoff point. Each tradeoff point has a unique identifier defined under ‘Settings – Codes – Variable codes – Tradeoff point id’. Subsequently a change to the variables defined in the tradeoff definition file can be given. Default value is 100, indicating no change. A value of, for example, 80 indicates a 20% decrease, whereas a value of 120 indicates a 20% increase.

In the example of Figure 8.26, only the potato prices (PTOP) varied between the tradeoff points. The 4th tradeoff point corresponds to the situation observed in the survey.

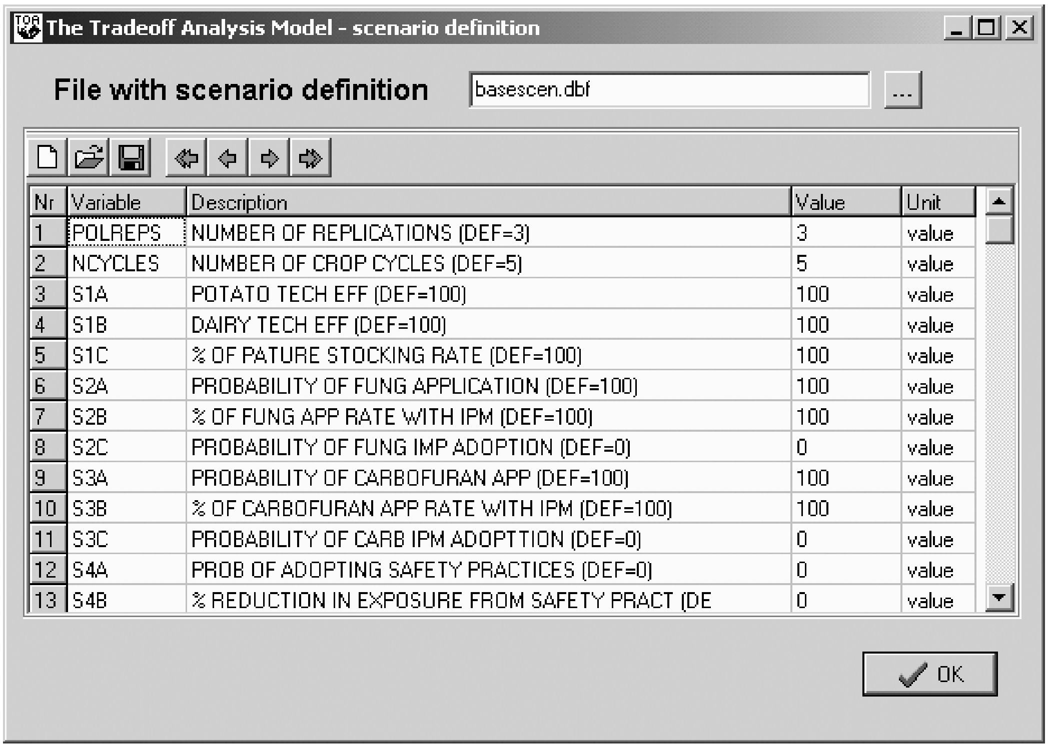
8.7 Defining Scenarios

The definition of scenarios is based on the parameters defined in the variable definition (‘Settings – Variables – Scenario variables’; Figure 8.27). Each row in the scenario file corresponds with a variable. The user already indicated whether the variable is changed in absolute terms or in relative (percent) terms. This is indicated in the last column by the unit (value versus %). It is essential that the user has insight in the definition of these variables in the economic simulation model.



TOID	FTOP	CTOP	ITOP	PTOP	DTOP
1	100	100	100	25	100
2	100	100	100	50	100
3	100	100	100	75	100
4	100	100	100	100	100
5	100	100	100	125	100
6	100	100	100	150	100
7	100	100	100	175	100

Figure 8.26 The definition of the tradeoff curve



Nr	Variable	Description	Value	Unit
1	POLREPS	NUMBER OF REPLICATIONS (DEF=3)	3	value
2	NCYCLES	NUMBER OF CROP CYCLES (DEF=5)	5	value
3	S1A	POTATO TECH EFF (DEF=100)	100	value
4	S1B	DAIRY TECH EFF (DEF=100)	100	value
5	S1C	% OF PATURE STOCKING RATE (DEF=100)	100	value
6	S2A	PROBABILITY OF FUNG APPLICATION (DEF=100)	100	value
7	S2B	% OF FUNG APP RATE WITH IPM (DEF=100)	100	value
8	S2C	PROBABILITY OF FUNG IMP ADOPTION (DEF=0)	0	value
9	S3A	PROBABILITY OF CARBOFURAN APP (DEF=100)	100	value
10	S3B	% OF CARBOFURAN APP RATE WITH IPM (DEF=100)	100	value
11	S3C	PROBABILITY OF CARB IPM ADOPTTION (DEF=0)	0	value
12	S4A	PROB OF ADOPTING SAFETY PRACTICES (DEF=0)	0	value
13	S4B	% REDUCTION IN EXPOSURE FROM SAFETY PRACT (DE	0	value

Figure 8.27 The definition of a scenario.

8.8 Running the Simulation Model

The economic model has been identified under ‘settings – economic models – general – Econometric-process simulation model’. You will see the name of the simulation model on the status bar of the model run window (Figure 8.28). The names of the last files for sampled fields, tradeoff definition and the scenario definition are loaded automatically. With the drop-down boxes, the user can easily select another file that does exist in the appropriate directory. The code for the simulation run is a three-character code that will precede the output file names. If one prefers to see the SAS log file, check the ‘View SAS log file after model run’ check box. The simulation run will take place after pressing the run button.

When the run button is pressed the following steps will be taken by the tradeoff analysis model:

1. The econometric-process simulation model is copied to the TOA program directory and will be named *temp.sas*.
2. The copy of the simulation model will scanned for the reserved word ‘FILENAME’. File reference codes have been defined for:
    a. Input files (‘Settings – Data files – Database files’),
    b. Sampled fields (‘Settings – Codes – File reference codes’),
    c. Tradeoff definition file (‘Settings – Codes – File reference codes’), and
    d. Output files (Based on codes for output files (‘Settings – Codes – Output file codes’).
3. Each of the input files is copied to the TOA program directory with names temp1.dbf→tempN.dbf (With N being the number of database files).
4. The temporary file names are written to the simulation model (temp.sas).
5. All the temporary input files are scanned for variable names that occur in the scenario file. If scenario variables do occur the variables are adapted accordingly.
6. The simulation model is run (through the SAS program).

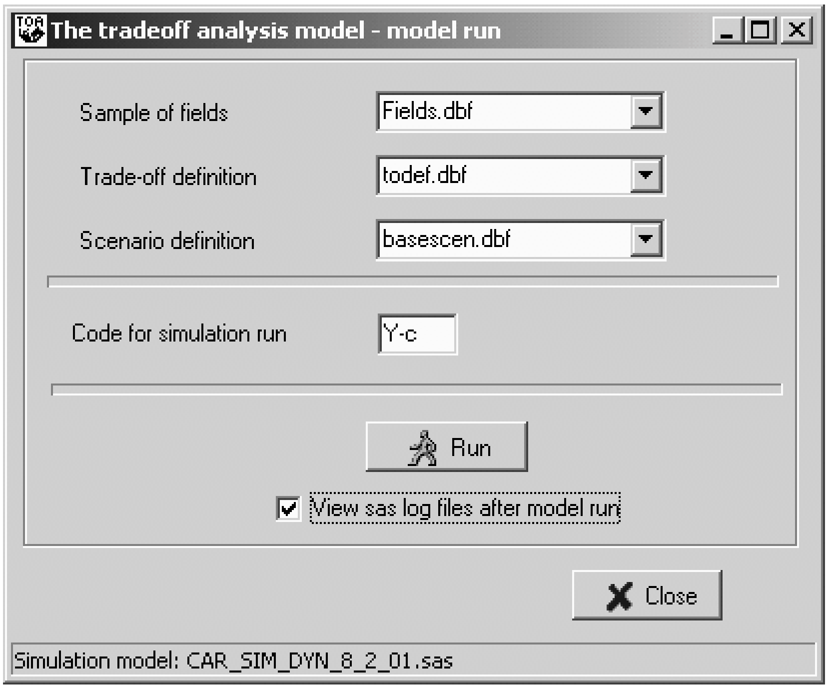


Figure 8.28 Running the simulation model

8.9 Environmental Fate Models

Environmental fate models are run through an interface module that is in most cases specific for the model (Figure 8.29). Before calling the interface module, the TOA software write the project file to the directory containing the interface module. This enables the interface to find soil and weather data and the directory structure of the project. Each interface module is designed in such a way that it copies the output file of the econometric-process simulation model and adds a column to it with the appropriate output of the environmental fate model. In some cases, the environmental fate model will be run, but in other cases, more simple meta-models based on the original environmental fate model will be used. Note that the number of simulation runs is rather large and as a result it may be a slow process to carry out simulation runs.

Running the environmental fate models is rather straightforward. One simply has to select one of the interface models as they are defined in the settings ('Settings – environmental fate model').

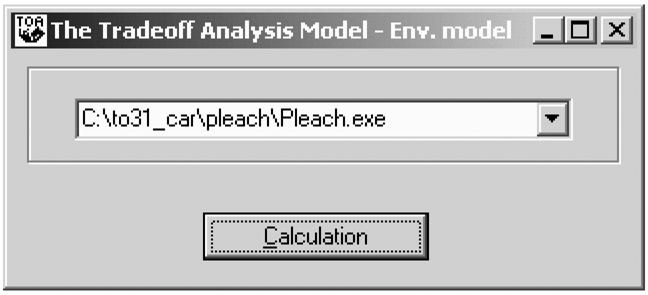


Figure 8.29 Running the environmental process model.

8.10 Aggregation

After running the simulation model has run the output file contains a very large number of records: (# of fields) * (# of crop cycles) * (# of repetitions) * (# of tradeoff points). This would result in a enormous scatter of points in the tradeoff plot. Users may therefore aggregate the results (Figure 8.30). The actually aggregation is done by writing a little SAS batch file that carries out the aggregation. In the TOA software users have to identify the names of the database files (both input and output) and the columns over which they would like to aggregate. Aggregation will take place over those variables that are checked. An example, if one would check the variables for tradeoff point and sample field id, one would get a file with (# of fields) * (# of tradeoff points) records with the average values for each of the parameters per field and tradeoff point.

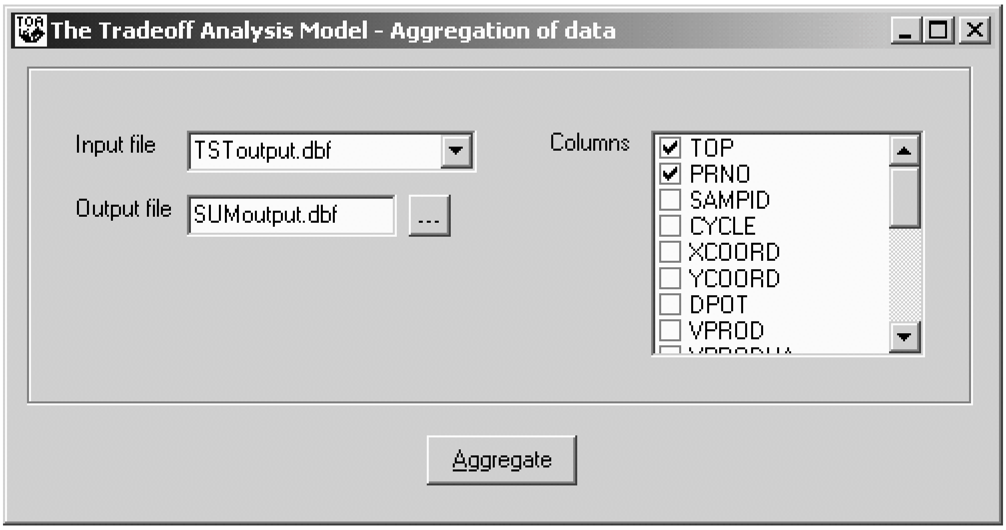


Figure 8.30 Aggregation of simulation results

The following steps are taken after pressing the Aggregate-button:

1. A temporary SAS batch file is created, denominated temp.sas in the TAO program directory that looks as follows:

```
FILENAME filename 'c: \ to31_car \ results \ TSToutput.dbf';
FILENAME db_out 'c: \ to31_car \ results \ SUMoutput.dbf';
PROC DBF DB4=filename OUT=filename;data a; set filename;
proc sort; by  TOP PRNO;
proc means MEAN noprint; by  TOP PRNO; var  SAMPID CYCLE XCOORD YCOORD
DPOT VPROD VPRODHA TPROF TPROFHA INP1 YIELD QMANCT QGTOT
QMETHT TINNO TNGQA MNBSA HRISKA;
output out=outfile mean= SAMPID CYCLE XCOORD YCOORD DPOT VPROD
VPRODHA TPROF TPROFHA INP1 YIELD QMANCT QGTOT QMETHT TINNO
TNGQA MNBSA HRISKA;
data b; set outfile;
keep  TOP PRNO SAMPID CYCLE XCOORD YCOORD DPOT VPROD VPRODHA
TPROF TPROFHA INP1 YIELD QMANCT QGTOT QMETHT TINNO TNGQA
MNBSA HRISKA;
format  SAMPID CYCLE XCOORD YCOORD DPOT VPROD VPRODHA TPROF
TPROFHA INP1 YIELD QMANCT QGTOT QMETHT TINNO TNGQA MNBSA
HRISKA 14.5;
proc dbf db4=db_out data=b;
run;
```

2. The above SAS batch file is executed.

8.11 Graphing Your Results

An important form of viewing your results is to display them as graphs. To view your results as graphs, one has to select one or several data files (Figure 8.31). Note that the variables you are going to use should occur in each of the database files. One can add names to the different file names and enter a title of the graph. By clicking on the colored box before each filename one can set the color of that particular file. By selecting more than one file, the TOA model allows users to compare the results of different scenarios. If all the data are set, the graph is viewed by pressing the graph button (Figure 8.32).

The grapher is based on the commercial TEEchart software. Press the -button to enter the menu for adapting the graph setup. There one will find also an extensive help function that explains more about TeeChart.

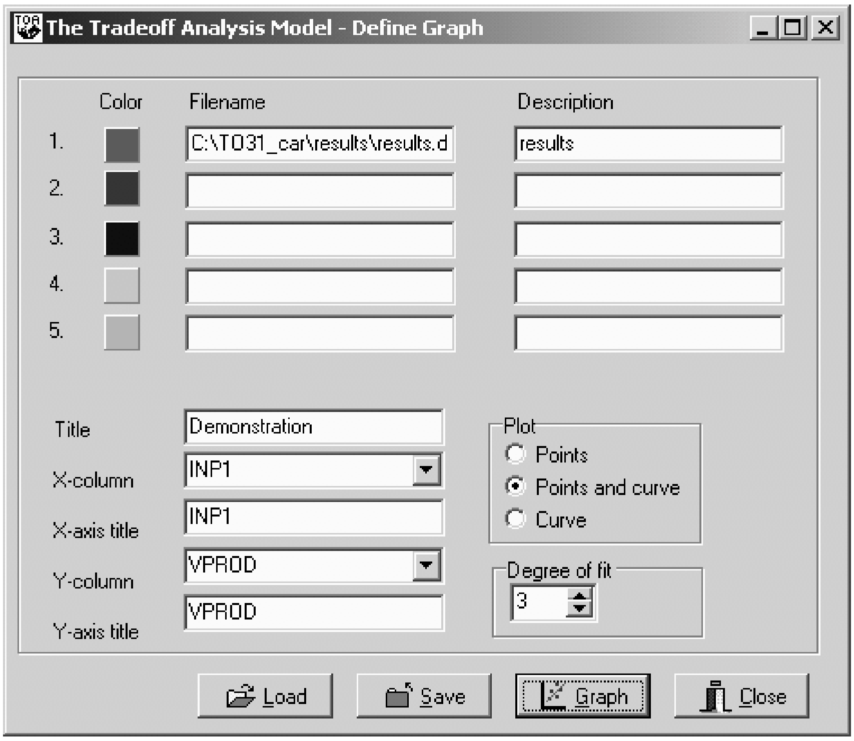


Figure 8.31 Definition of graph.

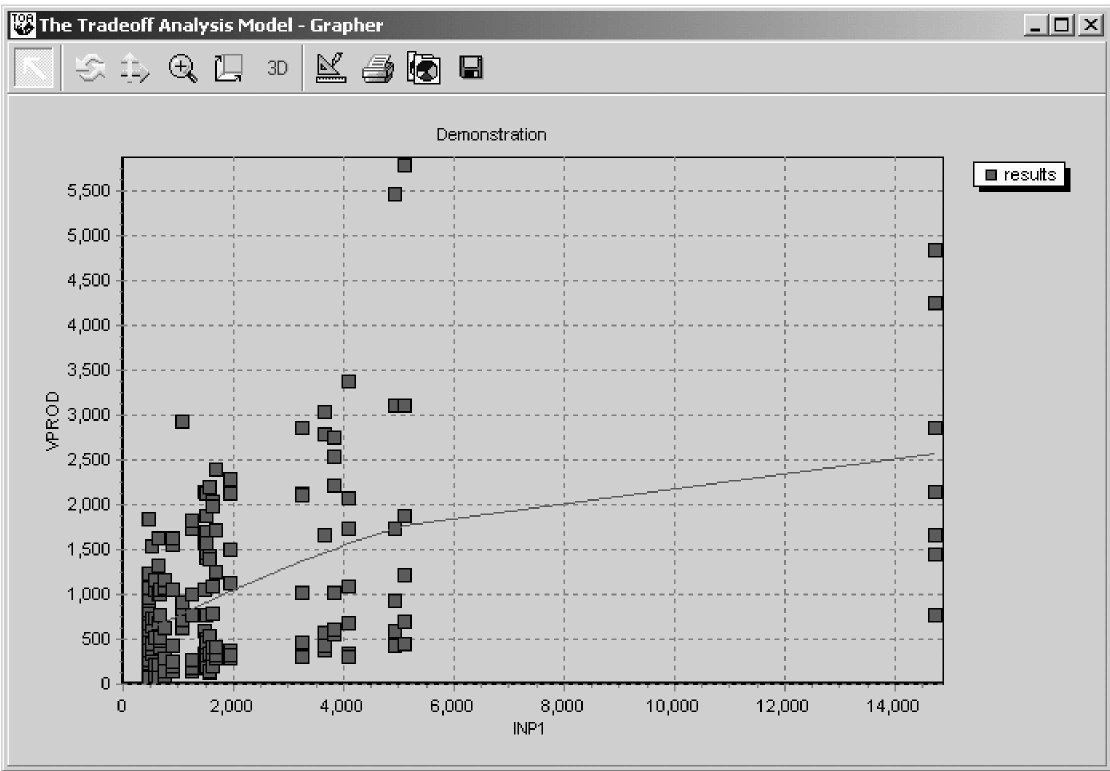


Figure 8.32 Graph viewer

9 An application of the Tradeoff Analysis Model

The Carchi province in northern Ecuador is typical of the northern humid páramo Andes. The production system on the steep Andean hillsides is focused on the production of potatoes and milk. In an early stage of the project, stakeholder meetings were held and especially the excessive use of pesticides was mentioned as a key parameter related to both environmental effects as well as human health. Pesticide use was assumed to have a significant environmental impact as well as health impacts to both potato producers and consumers. In this section, we will show some examples of the analysis of tradeoffs and the interaction between different indicators for productivity, pesticide use and tillage erosion.

9.1 Model Development

A two-year dynamic survey on 188 farmers' fields provided us information about the way farmers take decisions. In addition, data were collected on the natural resources in the study area. For the survey fields we calculated the inherent potato productivity. The inherent productivity is defined as the production a farmer can expect to obtain on his field with an average management. The inherent productivity plays an important role in the econometric production models as it is assumed that the production farmers expect strongly influences their decisions with respect to land allocation and land management. Subsequently, econometric production models were estimated on the basis of the survey data and the inherent productivities.

9.2 Simulation

A total of 100 fields were sampled from the area for the simulation runs. Sampling was done randomly for the whole study area (excluding build up areas). For each of the fields a field size was drawn from a statistical distribution and the inherent potato production was simulated using the SUBSTOR-potato model (from the DSSAT suite of models) (Figure 9.1). Subsequently the econometric process simulation model is used to simulate land allocation and land management decisions for 5 subsequent crop cycles. After the simulation, the results are summarized in a number of variables representing, for example, input use, production, revenues, and net returns. One can graphically show the joint distributions between those variables. For the Carchi study area pesticide leaching was indicated as an important environmental issue. A detailed study to the process of pesticide leaching allows us to simulate pesticide leaching (Stoorvogel *et al.*, 2001) on the basis of input use and the natural resource database. This enables us to show the relationship between production variables and pesticide leaching. In the examples we will focus on carbofuran which is the single most widely used insecticide applied to control the Andean Weevil (*Premnotypes vorax*).

Land allocation and land management decisions are strongly influenced by the markets for agricultural inputs and outputs. The Tradeoff Analysis Model is able to construct tradeoffs between different indicators while changing, for example, price regimes. In practice, this means that the simulation is repeated while shifting the price distributions. Figure 9.2 shows the effect of varying potato prices on the joint distribution of net returns and carbofuran leaching. For visualization purposes the data have been aggregated by calculating the mean for each of the tradeoff points and crop cycles. The changing environmental conditions have a large impact on the simulation results. These spatial trends can also be visualized as shown in Figure 9.3.

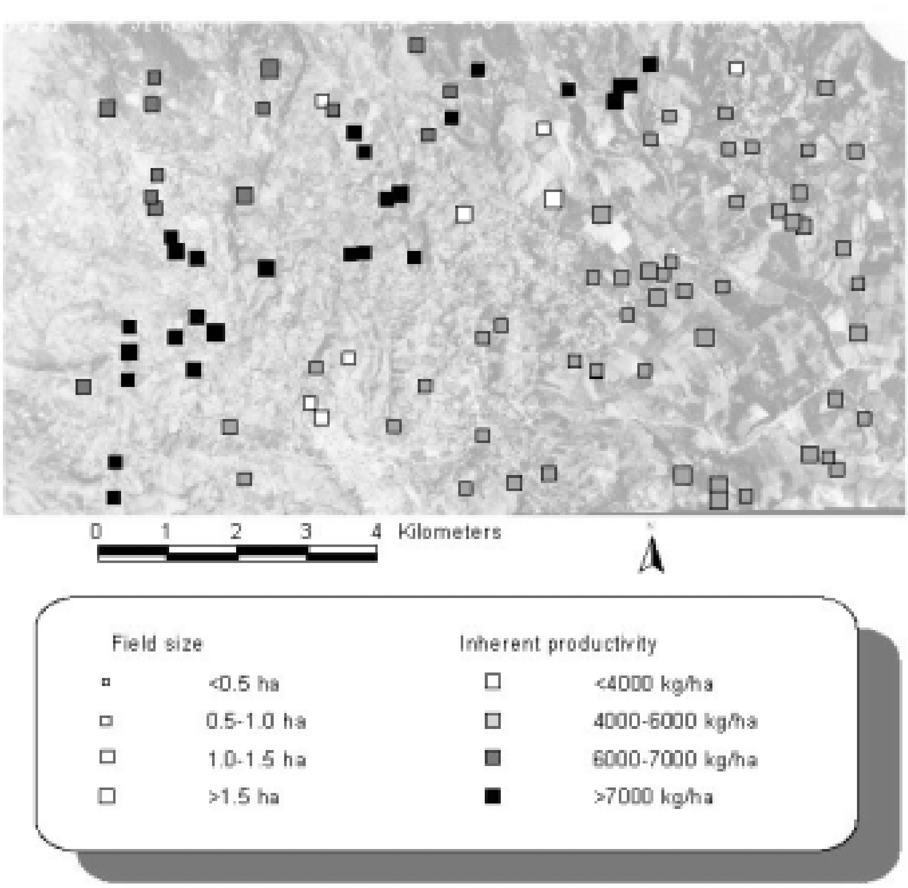


Figure 9.1 The location, field size and the inherent potato production of the sampled fields in the San Gabriel region of Carchi Province, Ecuador.

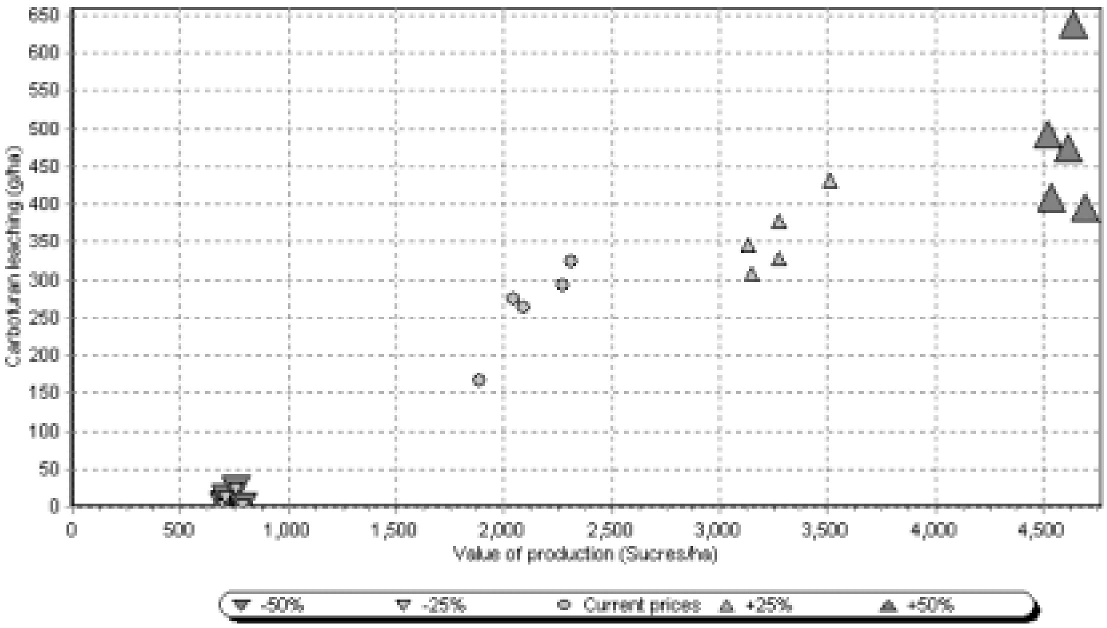


Figure 9.2 The relation between net returns and Carbofuran leaching under different potato price regimes.

9.3 Scenarios

After running the base scenario, we can define scenarios that represent the effect of certain changes in the socio-economic environment (possibly initiated by policy interventions) and the introduction of alternative technologies. To illustrate the potential of the Tradeoff Analysis Model, the impact of an alternative integrated pest management technology (IPM) on the tradeoff curve will be analysed. First, the implication of the scenario needs to be translated into changes of the model parameters. In many cases, a proper translation can only be carried out using field experiments. An IPM technology may for example result in a lower probability that Carbofuran will be applied at a certain crop development stage. In addition, we may indicate that a certain percentage of the farmers will actually adopt the alternative technology. Figure 9.4 shows the implication of the alternative IPM technology on the tradeoff curve.

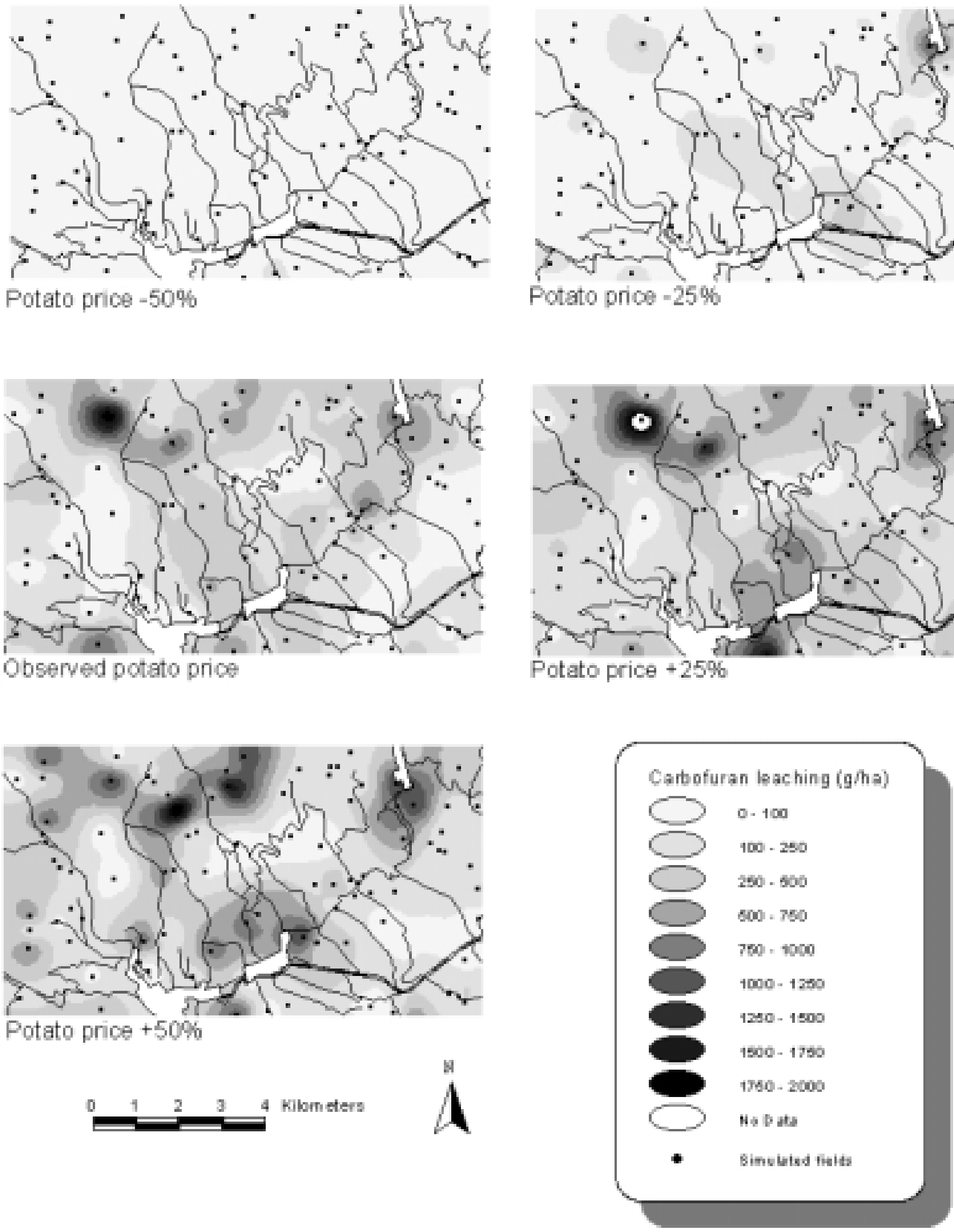


Figure 9.3 The spatial variation in carbofuran leaching under different potato price regimes in the Carchi study area.

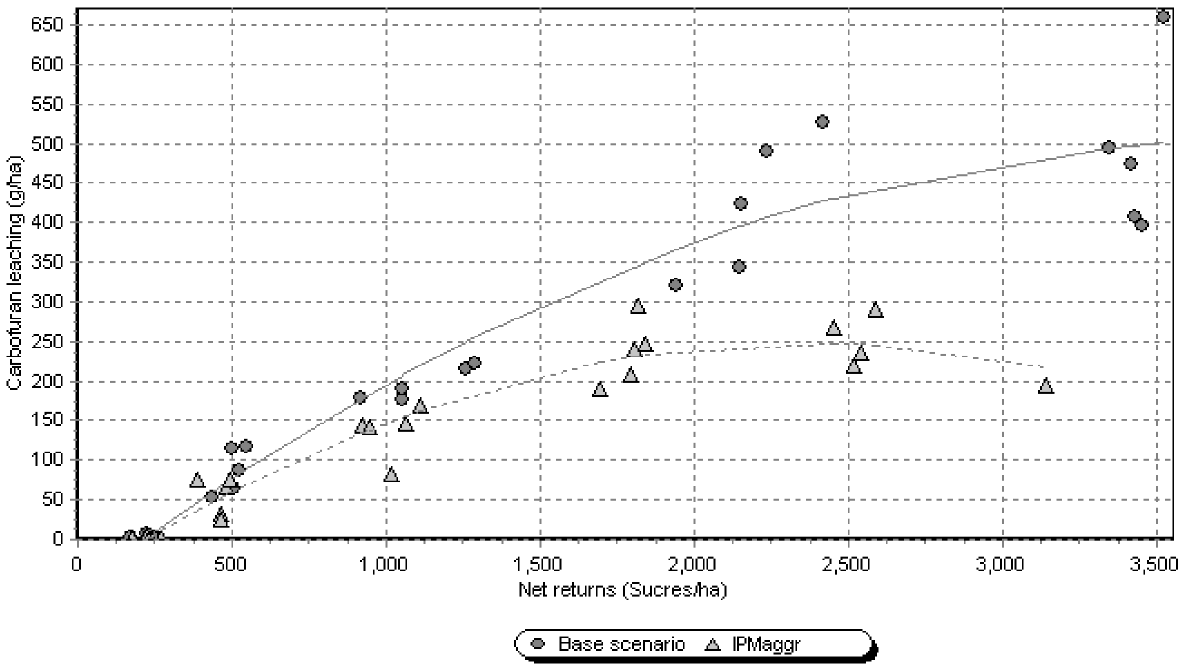


Figure 9.4 The effect of the introduction of an alternative IPM technology on the tradeoff curve between carbofuran leaching and net returns.

An alternative scenario can be used to evaluate the effect of changes in the biophysical environment. These may be due to natural disasters (e.g., large floods or volcanic eruptions) or due to more gradual processes like tillage erosion. Veen (1999) analysed the process of tillage erosion in the Carchi area and found that in many farmers' fields large movement of soil material takes (and has taken) place resulting in a complete lack of top soil material on the higher parts of many fields. As a result tillage erosion may lead to lower productivities of farmers fields and, in addition, to an increase in pesticide leaching due to a reduction of the pesticide retention capacity of the soil. These changes in the natural environment can also be reflected in adaptations of model parameters and the effect on the tradeoff curve can be simulated (Figure 9.5). Research organizations and policy makers can use to information to decide whether they find the observed shift in the tradeoff curve important enough to support the development of alternative technologies that result in a reduction of tillage erosion.

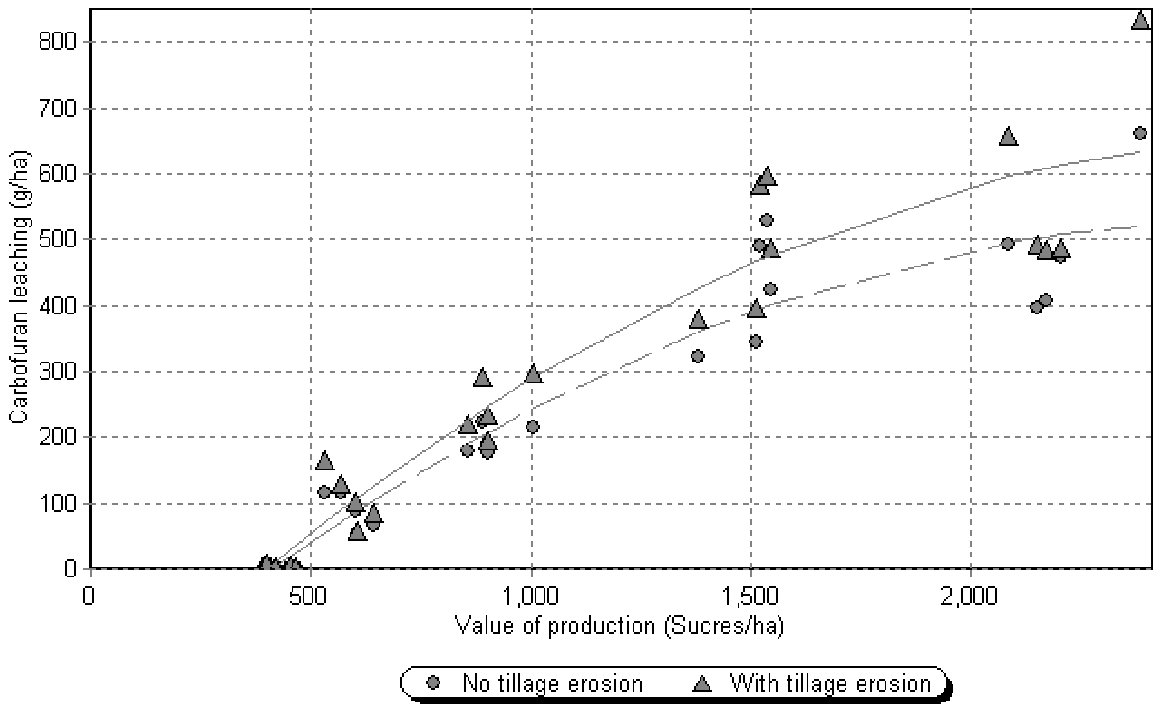


Figure 9.5 The effect of tillage erosion on the tradeoff curve between the value of production and carbofuran leaching.

References

Antle, J.M., and S.M. Capalbo, 2001. Econometric-process models for integrated assessment of agricultural production systems. American Journal of Agricultural Economics 83(2): 389-401.

Antle, J.M., S.M. Capalbo, and C.C. Crissman, 1994. Econometric production models with endogenous input timing: an application to Ecuadorian potato production. Journal of Agricultural and Resource Economics 19: 1-18.

Antle, J.M., C.C. Crissman, and S.M. Capalbo, 1998. Tradeoffs in policy analysis: conceptual foundations and disciplinary integration. In C.C. Crissman, J.M. Antle, and S.M. Capalbo, (eds.). Economic, environmental, and health tradeoffs in agriculture: pesticides and the sustainability of Andean potato production. Kluwer Academic Publishers, Boston, pp. 21-40.

Antle, J.M., and J. Stoorvogel, 1999. Models for integrated assessment of sustainable land use and soil quality. Paper presented at the conference on Land Degradation and Sustainable Agriculture, Wageningen Agricultural University, June.

Ayensu, E., D. van R. Claasen, M. Collins, A. Dearing, L. Fresco, M. Gadgil, H. Gitay, G. Glaser, C. Juma, J. Krebs, R. Lenton, J. Lubchenco, J.A. McNeely, H.A. Mooney, P. Pinstrup-Andersen, M. Ramos, P. Raven. W.V. Reid, C. Samper, J. Sarukhán, P. Schei. J.G. Tundisi, R.T. Watson, X. Guanhua, and A.H. Zakri, 1999. International ecosystem assessment. Science 286 (22 October): 685-686.

Baigorria, G., W. Bowen, and J.J. Stoorvogel. 2001. Estimating the spatial variability of weather in mountain environments. Program Report 1999-2000. International Potato Center, Lima, Peru, pp. 371-378.

Belzer, R.B., 1999. HACCP principles for regulatory analysis. In L. Unnevehr, (ed.). The economics of HACCP: studies of costs and benefits. Eagan Press, St Paul, MN.

Biggar, J.W., and D.R. Nielsen, 1976. The spatial variability of the leaching characteristics of the field soil. Water Resources Research 12: 78-84.

Boote, K.J., J.W. Jones, and N.B. Pickering, 1996. Potential uses and limitations of crop models. Agronomy Journal 88:704-716.

Bouma, J., 1998. Introduction. In J.J. Stoorvogel, J. Bouma, and W.T. Bowen (eds.). Information technology as a tool to assess land use options in space and time. Proceedings of an international workshop Lima, September 28-October 4, 1997. Quantitative Approaches in Systems Analysis No. 16. The C.T. de Wit Graduate School for Production Ecology and DLO Research Institute for Agrobiology and soil fertility, Wageningen, The Netherlands, pp. 1-11.

Bouma, J., A. Kuyvenhoven, B.A.M. Bouman, J.C. Luyten, and H.G. Zandstra (eds.), 1995. Eco-regional approaches for sustainable land use and food production. Dordrecht, the Netherlands: Kluwer Academic Publishers.

Bouman, B.A.M, H.G.P. Jansen, R.A. Schipper, A. Nieuwenhuyse, H. Hengsdijk, and J. Bouma, J., 1999. A framework for integrated biophysical and economic land use analysis at different scales. Agriculture, Ecosystems and Environment 75: 55-73.

Bowen, W., H. Cabrera, V. Barrera, and G. Baigorria, 1999[a]. Simulating the response of potato to applied nitrogen. CIP Program Report 1997-1998. International Potato Center, Lima, Peru: pp. 381-386.

Bowen, W., G. Baigorria, V. Barrera, J. Cordova, P. Muck, and R. Pastor, 1999[b]. A process-based model (WEPP) for simulating erosion in the Andes. CIP Program Report 1997-1998. International Potato Center, Lima, Peru: pp. 403-408.

Cole, C.C., F. Carpio, J.A. Julian, and N. León, 1998. Health impacts of pesticide use in Carchi farm populations. In C.C. Crissman, J.M. Antle, and S.M. Capalbo, (eds.). Economic, environmental, and health tradeoffs in agriculture: pesticides and the sustainability of Andean potato production. Kluwer Academic Publishers, Boston, pp. 209-230.

CONDESAN, 1999. Memorias de CONDESAN 1999. Consorcio para el Desarrollo Sostenible de la Ecorregión Andina, Lima, Peru. Available at http://www.condesan.org/memoria/memo99.htm.

Consultative Group for International Agricultural Research (CGIAR), 1993. The eco-regional approach to research in the CGIAR. Report of the TAC/Center Directors Working Group, Technical Advisory Committee Secretariat, FAO, Rome.

Consultative Group for International Agricultural Research (CGIAR), 1995. Report of the task force on eco-regional approaches to research. Mid-term meeting, Nairobi, Kenya, 22-26 May.

Corwin, D.L., P.J. Vaughan, and K. Loague, 1997. Modeling nonpoint source pollutants in the Vados Zone with GIS. Environment, Science and Technology 31: 2157-2175.

Crissman, C.C., J.M. Antle, and S.M. Capalbo (eds.), 1998[a]. Economic, environmental, and health tradeoffs in agriculture: pesticides and the sustainability of Andean potato production. Kluwer Academic Publishers, Boston. 281 p.

Crissman, C.C., P. Espinosa, C.E.H. Ducrot, D.C. Cole, and F. Carpio, 1998[b]. The case study site: physical, health, and potato farming systems in Carchi province. In C.C. Crissman, J.M. Antle, and S.M. Capalbo (eds.). Economic, Environmental, and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production. Kluwer Academic Publishers, Boston. pp 85-120

de Janvry, A., M. Fafchamps, and E. Sadoulet, 1991. Peasant household behavior with missing markets: some paradoxes explained. Economic Journal 101(409): 1400-1417.

de Koning, G.H.J., P.H. Verburg, and A. Veldkamp, and L.O. Fresco, 1999. Multi-scale modelling of land use change dynamics in Ecuador. Agricultural Systems 61: 77-93.

Dercon, G., 2001. Tillage erosion assessment in the Austro Ecuatoriano. PhD Thesis, Catholic University, Leuven, Belgium.

Di, H.J., and L.A.G. Aylmore, 1997. Modeling the probabilities of groundwater contamination by pesticides. Soil Science Society of America Journal 61: 17-23.

Dieter, H.H., A. Grohmann, and D. Thompson, 1997. Specific contributions of politics, economics, and toxicology in setting socially consensual limit values. Environmental Management 21: 505-515.

Godwin, D.C., and U. Singh, 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In G.Y. Tsuji, G. Hoogenboom, and P.K.Thornton (eds.). Understanding options for agricultural production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 55-77.

Goldenman, G., 1996. Elaboration on possible arguments and objectives of an additional EC policy on plant protection products, Study for Phase 2 of the project on Possibilities for future EC environmental policy on plant protection products. Oppenheimer Wolff & Donnely, Brussels.

Hoanh, C.T., R.P. Roetter, D.M. Jansen, P.K. Aggarwal, F.P. Lansigan, N.X. Lai, A.A. Bakar, and A. Tawang, 1998. Generalizing SysNet methodologies for land use planning at the sub-national level. In: R.P. Roetter, C.T. Hoanh, N.V. Luat, M.K. van Ittersum, and H.H. van Laar (eds.). Exchange of methodologies in land use planning. SysNet Research Paper Series No. 1, IRRI, Los Baños, Philippines, pp. 41-56.

Hoosbeek, M.R., and R. Bryant, 1992. Towards quantitative modeling of pedogenesis - a review. Geoderma 55: 183-210.

Hornsby, A.G., R.D. Wauchope, and A.E. Herner, 1995. Pesticide properties in the environment, Springer-Verlag, New York.

Hunt, L.A., and K.J. Boote, 1998. Data for model operation, calibration, and evaluation. In G.Y. Tsuji, G. Hoogenboom, and P.K.Thornton (eds.). Understanding options for agricultural production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 9-39.

Jones, J.W., G. Tsuji, G. Hoogenboom, L.A. Hunt, P.K. Thornton, P.W. Wilkens, D.T. Imamura, W.T. Bowen, and U. Singh, 1998. Decision support system for agrotechnology transfer: DSSAT v3. In G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton (eds.). Understanding options for agricultural production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 157-177.

Just, R.E., D. Zilberman, and E. Hochman, 1983. Estimation of multicrop production functions. American Journal of Agricultural Economics 65: 770-80.

Krueger, A.O., 1992. The political economy of agricultural pricing policies, volume 5: a synthesis of the political economy in developing countries. The Johns Hopkins University Press, Baltimore.

Lemon, M., 1999. Exploring environmental change using an integrative method. Gordon and Breach Science Publishers, Amsterdam.

Meerbach, D., 1999. Water flow and solute transport in soils in the region of San Gabriel, Ecuador. MSc Thesis, Wageningen Agricultural University.

Meyles, E., and L. Kooistra, 1998. A novel method to describe spatial soil variability: a case study for a potato-pasture area in the northern Andes of Ecuador. MSc Thesis, Wageningen Agricultural University.

Ministerio de Agricultura y Ganaderia (MAG) and Office de la Recherche Scientifique et Technique Outre Mer (ORSTOM), 1980. Mapas de Suelos. MAG-ORSTROM, Quito, Ecuador.

Organization for Economic cooperation and Development (OECD), 1994. The use of environmental indicators for agricultural policy analysis. OECD Joint Working Party of the Committee for Agriculture and the Environment Committee. Paris.

Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge, and A. Bakema, 1989. Simulation of ecophysical processes of growth in several annual crops. Simulation Monograph Series, PUDOC, Wageningen, The Netherlands and IRRI, Los Banos.

Rabbinge, R., 1995. Eco-regional approaches: Why, what, and how. In J. Bouma, A. Kuyvenhoven, B.A.M. Bouman, J.C. Luyten, and H.G. Zandstra (eds.). Eco-regional approaaches for sustainable land use and food production. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp 3-11.

Ritchie, J.T., 1998. Soil water balance and plant water stress. In G.Y. Tsuji, G. Hoogenboom, and P.K.Thornton (eds.). Understanding options for agricultural production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 41-54.

Ritchie, J.T., T.S. Griffin, and B.S. Johnson, 1995. SUBSTOR: functional model of potato growth, development and yield. In: P. Kabat, B. Marshall, B.J. van den Broek, A. Vos, and H. van Keulen (Eds.). Modelling and parametrication of the soil-plant-atmosphere system. Wageningen Pers, Wageningen, The Netherlands. pp. 401-435.

Stoorvogel, J.J., 1995. Geographical information systems as a tool to explore land characteristics and land use, with reference to Costa Rica, Ph.D. Thesis, Wageningen Agricultural University, Wageningen.

Stoorvogel, J.J., R. Jaramillo, R. Merino, and S. Kosten, 2001. Destino de plaguicidas, contaminación en suelos y agues. In: C. Crissman, and P. Espinosa (eds.). Impactos del uso de plaguicidas en la producción, salud, y medioambiente en Carchi: Un compendio de investigaciones y respuestas multidiciplinarios. Ediciones Abya-Yala, Quito, Ecuador. (In press)

Stoorvogel, J.J., L. Kooistra, and J. Bouma, 1999. Spatial and temporal variation in iematocide leaching, management implication for a Costa Rican banana plantation. In D.W. Corwin, K. Loague and T.R. Ellsworth (eds.). Assessment of non-point source pollution in the vadose zone. Geophysical monograph 108, AGU. pp 281- 289.

Tiktak, A., F. van den Berg, J.J.T.I. Boesten, D. van Kraalingen, M. Leistra, and A.M.A. van der Linden, 2000. Manual of FOCUS PEARL version 1.1.1. RIVM report 711401008, Alterra Report 28, RIVM, Bilthoven, The Netherlands.

Turkelboom, F., J. Poesen, I. Ohler, and S. Ongprasert, 1999. Reassessment of tillage erosion rates by manual tillage on steep slopes in northern Thailand. Soil and Tillage Research 51: 245-259.

U.S. Department of Agriculture (USDA), 1994. Agricultural resources and environment indicators. Agricultural Handbook No. 705, USDA, Economic

Research Service, Natural Resources and Environment Division, Washington, DC.
van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44: 892-898.
van Ittersum, M.K., R. Rabbinge, and H.C. van Latesteijn, 1998. Exploratory land use studies and their role in strategic policy making. Agricultural Systems 58: 309-330.
van Keulen, H., A. Kuyvenhoven, and R. Ruben, 1998. Sustainable land use and food security in developing countries: DLV's approach to policy support. Agricultural Systems 58: 285-307.
van Soest, F., 1998. A method for downscaling Soil Information from regional to catena level. MSc Thesis, Wageningen Agricultural University.
Veen, M., 1999. The development of land use and land management, and their effect upon soils in processes of mechanical erosion and compaction. A case study for a potato-production area in the northern Andes of Ecuador. MSc Thesis, Wageningen University, The Netherlands.
Wagenet, R.J., J. Bouma, and J.L. Hutson, 1998. Conceptual and methodological aspects of assessing pesticide environmental impact in developing areas. In C.C. Crissman, J.M. Antle, and S.M. Capalbo (eds.). Economic, Environmental, and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 41-63.
Wagenet, R.J., and J.L. Hutson, 1989. Leaching estimation and chemistry model: a process based model of water and solute movement, transformations, plant uptake, and chemical reactions in the unsaturated zone. Continuum, Vol 2 (version 2). Ithaca, NY: Centre of Environmental Research, Cornell University.
Wauchope, R.D., T.M. Butler, A.G. Hornsby, P.W.M. Augusteijn-Beckers, and J.P. Burt, 1992. The SCS/ARS/CES pesticide properties database: Select values for environmental decision making, Review of Environmental Contamination and Toxicology 123: 1-164.
Whisler, F.D., B. Acock, D.N. Baker, R.E. Fye, H.F. Hodges, J.R. Lambert, H.E. Lemmon, J.M. McKinion, and V.R. Reddy, 1986. Crop simulation models in agronomic systems. Advances in Agronomy 40: 141-208.
Wiebe, K.D., and R. Meinzen-Dick, 1998. Property rights as policy tools for sustainable development. Land Use Policy 15: 203-215.