A multi-agent model linked to a GIS to explore the relationship between crop diversification and the risk of land degradation in northern Thailand highlands

G. Trébuil, F. Bousquet, B. Ekasingh, C. Baron, C. Le Page

Integrated watershed management implies a collective management of the land reconciling ecological dynamics and social processes to ensure a viable and equitable use of renewable resources and to mitigate conflicts. Based on the integration of existing knowledge from different sources and disciplines, this chapter describes the construction of a spatially explicit multi-agent model to analyze the poorly understood interaction between the risk of land degradation and crop diversification and agricultural commercialization of heterogeneous household-based farming systems in a highland Akha village catchment of upper northern Thailand. In this region, cash cropping on sloping land is commonly blamed by lowlanders for aggravating land degradation. But on-farm agronomic surveys led to the hypothesis that this interaction is far more complex and could be further examined by using an integrative model to explore simultaneously the interaction between the agronomic and socioeconomic components of the system. The simulated behavior of the different model entities is based on previous field observations and measurements. This agronomic simulator represents actual farmers' cropping practices at the field level under different slope and climatic conditions. The social dynamics are taken into account through the representation of three main types of households identified through a farm survey. They have contrasting historical backgrounds, are managing different amounts of resources, and correspond to a gradient of integration into commercial agriculture. Because key agroecological and socioeconomic processes need to be simulated at different pertinent scales, this multi-agent model is loosely linked to a geographic information system (GIS) displaying the distribution of three complementary spatial entities in the catchment. Following a presentation of the selected integrative modeling approach, the model conceptualization, its architecture, and modeling sequences are described. An analysis of the results of several sets of simulations is also presented. They were performed to explore the relationships between soil erosion and the variability of rainfall distribution, farmers' crop production practices, and different types of farms. Finally, the use of such a multi-agent model with stakeholders for collective learning and improved communication purposes is discussed.

Introduction

Scientists working in the field of integrated watershed management (IWM) with local communities need to understand and represent the interactions among ecological, social, and economic dynamics in such complex agroecosystems. Such a representation can be used to identify more viable and equitable use of renewable resources, and to mitigate resource-use conflicts among different groups of stakeholders. In such a context, complexity is created by the heterogeneity (over space) and variability (over time) of landscapes and society. It is also generated by the diversity of interacting processes that are taking place among different natural and human entities. In the field of integrated natural resource management (INRM), understanding the effects of interactions between natural and social dynamics is of paramount importance. Ecological dynamics are made of interwoven biophysical processes, involving different renewable resources, such as soil, water, and vegetative cover, at various spatial and temporal scales. The set of socioeconomic processes to be considered involves an array of individual or collective stakeholders. These range from different types of individual farming households displaying specific socioeconomic objectives, strategies, and related agronomic practices to local communities managing the collective exploitation of land resources at the catchment level, and development-oriented or policy-making institutions operating at higher regional or national levels of organization. A prior understanding of these interacting dynamics, their co-viability, and their effects on both the state of the renewable resources and the status of heterogeneous farming communities is a prerequisite for researchers to assist stakeholders in mitigating conflicts and facilitating negotiated settlements over the use of renewable resources. Doran (2001) explained that descriptive and integrative models are useful tools to stimulate cooperative ecosystem management. Models proposing representations of the complex system to be managed collectively can be used to stimulate communication among stakeholders (the on-farm researcher being one of these) and the creation of acceptable rules for regulating land use through the application of resource management tools selected by local users (d'Aquino et al 2002, Etienne et al 2003).

The current land-use dynamics of montane northern Thailand are characterized by a rapid diversification of cropping systems. Horticultural production for different markets is playing a key role in these agricultural dynamics. This crop diversification accompanies the integration of highland farming households into commercial production and the market economy for goods, labor, and capital. These profound rural transformations are powered by strong driving forces such as the ramification of the communication infrastructure, population migrations, a stronger presence of state institutions in the highlands, and national policies dealing with access to land resources and environmental protection of headwaters in the context of a closing land frontier (Trébuil et al 2000).

Because most highlanders' fields are located on steep slopes, with angles reaching up to 60%, the risk of severe land degradation, particularly through soil erosion by concentrated runoff, is strong during the wet season, from May to October, in such highly heterogeneous and variable catchments (Turkelboom 1999). An overall understanding and representation of farmers' diverse production practices and decision-making processes regarding land use is needed to elucidate the much debated relationship between crop diversification-commercialization and the risk of land degradation on sloping lands. This can be based on the integration of existing knowledge from different sources and disciplines obtained over several years of on-farm research. Such an understanding is a prerequisite to the identification and assessment with the concerned stakeholders of various possible land-use scenarios to mitigate the risk of land degradation problems. It is urgent to find ways to make progress in this area with all concerned highlanders to improve their relations with the lowlanders who are blaming them for environmental destruction in a socially tense atmosphere.

The risk of increased land degradation is becoming a major issue in this ecologically and socially fragile montane environment. An increasing number and types of individual or collective stakeholders are presently (inter)acting in sloping land agriculture with different land-use strategies. The local agricultural system already displays an extensive socioeconomic differentiation among farming households at the village level. Over the past two decades, intensive efforts focusing on the introduction of soil and water conservation techniques had little impact in farmers' fields. This underlines the need for improving researchers' understanding of farmers' actual circumstances, practices and diverse farming strategies (Turkelboom et al 1996). It also calls for new coordination mechanisms among stakeholders (including researchers) to facilitate the emergence of a more ecologically sustainable and socially equitable type of highland agricultural development.

To move forward in this direction, this article describes the use of a multi-agent modeling approach to examine the poorly understood interaction between crop diversification and the risk of soil erosion at the catchment level in diversifying smallholdings of Chiang Rai Province in upper northern Thailand. The objective is to use this model to better assess how far soil erosion in steep-land agricultural production is influenced by climatic variability, current farmers' practices, the increased differentiation among local farming households observed during previous field surveys, and the recent evolution toward a more market-oriented and horticultural crop-based agricultural system.

The specific objectives of this case study were threefold:

1. To integrate existing agroecological and socioeconomic knowledge on crop diversification and commercialization and the risk of soil erosion gathered at the field, farm, and catchment levels into a spatially explicit model;
2. To represent the diversity of the farming community and farmers' decision-making processes driving land-use changes at the village catchment level; and
3. To achieve this by adopting a methodological approach based on the construction and testing of a multi-agent system (MAS) linked to a GIS to provide a dynamic representation of diverse cropping and farming systems in a highly heterogeneous and variable biophysical environment.

Following a presentation of the study site and of the characteristics of the selected integrative modeling approach, the model conceptualization and its architecture are described. The modeling sequences, agents, and methods are introduced before presenting the results of simulations performed to explore the relationships between soil erosion and the variability of rainfall distribution, farmers' crop production practices, and different types of farms in this catchment. Finally, the proposed use of such a model with stakeholders for collective learning and improved communication and coordination purposes is discussed.

The study site and field surveys

For the past two decades, crop diversification and commercialization have been going on in the highland Akha village of Mae Salaep in Mae Fah Luang District of Chiang Rai Province in upper northern Thailand. Over time, the expansion of farmland on sloping land was more and more limited by the environmental protection measures enforced in this area. Fallow periods are presently very short (generally 1 or 2 years long) and, every year, more fields become permanently cultivated. While the area under upland rice, the traditional zero-input subsistence crop, is already very limited, maize is a very popular low-input, low-commercial-value cash crop. Rice terraces are limited to the valley bottoms, which are mainly owned by a minority of early settlers. For the past 15 years, horticultural production has been expanding in this former opium-growing area. In the early 1990s, ginger was the most important high-input, high-value vegetable crop, while lychee orchards and, more recently, small plantations of Assam tea are expanding on the farmland surrounding the village.

Mae Salaep village was previously a pilot site under an important Thai-Australian highland agricultural development project. This project provided detailed information on land allocation in the village catchment in 1990 to support an analysis of recent trends in land-use changes between 1990 and 1998, and the construction of a small GIS (Trébuil et al 2000). A field office of the Department of Public Welfare (DPW, now an agency under the new Ministry of Social Development and Human Security), the main Royal Thai government development organization in charge of highlanders, was also established in Mae Salaep. A DPW officer participated in a farm survey carried out in the mid-1990s to characterize the differentiation among local farming households based on their socioeconomic objectives, amount of resources available, and related agricultural production strategies. The construction of a simple farmer typology displayed the respective combination of different cropping systems in each main category of household-based production systems (Trébuil et al 1997).

In the neighboring Akha village of Pakasukchai, which presents biophysical, agronomic, and socioeconomic conditions similar to those observed in Mae Salaep, data were intensively collected over a period of two years (that is to say, four cropping seasons) to assess the risk of soil erosion by concentrated runoff under very diverse conditions in farmers' fields. A very extensive range of slope, climatic, and actual farmer cropping circumstances was observed intensively in this on-farm soil erosion survey and its results are reported elsewhere (Turkelboom and Trébuil 1998, Turkelboom 1999). In particular, this on-farm erosion survey produced precise knowledge on the relationship between climatic conditions and soil erosion processes on steep land. In particular, a series of key thresholds for erosion risk according to cropping history, slope angle and length, and soil coverage were identified.

This comprehensive body of knowledge was gathered from different sources (indigenous farmer practices and scientific analyses) and disciplines (agronomy, soil science, agroclimatology, agricultural economics, geography). It was also acquired at complementary scales ranging from small intrafield observation stations displaying homogeneous slopes to entire farmer fields, different types of farms (seen as sets of cropped fields and fallows managed by a single decision-making unit for crop production), and the entire village catchment. The selected modeling approach aimed at integrating this knowledge into a spatially explicit MAS model.

Design of an integrative modeling approach

At the initial meeting, a group of CGIAR researchers working in the field of INRM said that the models used in such research needed an increased capacity to integrate social and bioeconomic information beyond the common representations of biophysical and agroecological dynamics (CGIAR 1999). At their following meeting in Penang, they added that modeling activities "should proceed iteratively by successive approximations (…) of system dynamics (… and) in close interaction with stakeholders, who, along with the modelers, use the models for scenario planning" (CGIAR 2000). Izac and Sanchez (2000) stated that the understanding of a complex agroecological system implies the understanding of interactions among different hierarchical levels of organization. To put these recommendations into practice, we decided to use an agent-based modeling approach for land use in a village catchment considered as a complex system. Therefore, the emphasis will be on its entities and hierarchical relationships, its multilevel organization, its behavior, and the interactions among its agents and their common environment (Bousquet et al 2001). Because, later on, we plan to use the model in a participatory way with stakeholders, it was important to construct a dynamic, open, and adaptive tool having the flexibility to be modified according to the content of the feedback received from users. Because of the topic of this application, we also wanted to be able to run simulations based on different temporal scales, that is, on a day-to-day basis to analyze the effects of a given allocation of various crops in the catchment fields (as shown in an example below), or on a year-to-year basis to explore and assess longer-term scenarios (this is not illustrated in this article).

Choice of a multi-agent systems approach for knowledge integration

Models are commonly used to deal with the increased complexity and rapidity of changes in agricultural systems. Quite often, they also constitute a tool to facilitate and focus discussions among stakeholders on the relationships between causes and effects of their practices on the ecological and social dynamics of their common agroecosystems. In this case study, an integrative and dynamic approach is needed to understand the distribution of the risk of soil erosion at the catchment level because different cropping systems present different susceptibilities to land degradation (Turkelboom 1999). Meanwhile, the choice of a given crop combination by a farming household depends on its economic orientation and its recent history (Trébuil et al 1997). Therefore, the model should be able to represent the individual behavior of the heterogeneous set of Akha farming units exploiting the catchment, and their respective or aggregated impacts on soil erosion at this level.

In the recent past, significant progress has been made in the field of modeling and simulating societies in interaction with their environments (Epstein and Axtell 1996, Gilbert and Troitzsch 1999). Many research teams are now relying on agent-based modeling (ABM) for the representation and analysis of land-use and land-cover change (Parker et al 2002). ABM approaches such as multi-agent systems (MAS), which are based on the principles of distribution and interaction, can be used to create virtual societies and their relationships with a given environment (Ferber 1999). MAS and simulations are being increasingly used to represent complex distributed systems and explore interactions between ecological and socioeconomic dynamics arising from multiple uses of the land by multiple users (Bousquet et al 1999, Bousquet et al 2001). Modelers use these methods and tools to create computer representations of dynamics observed in the field. Therefore, field work and systems modeling need to be seen as two mutually supporting activities that are closely interlinked in an iterative way.

Recent examples have demonstrated the effectiveness of these models to support interdisciplinary research and to provide dynamic, spatial, and temporal representations of the system under study. In the Senegal valley, Barreteau and Bousquet (2000) built the SHADOC model to simulate the management of irrigation based on the individual behavior of a heterogeneous society of water users having contrasting socioeconomic objectives and strategies regarding agricultural production. More recently, Bécu et al (2003) conceived the CATCHSCAPE model to simulate water management based on farmers' individual decisions at the small catchment scale in northern Thailand. Other similar case studies recently developed in Southeast Asia are presented in this volume. When used with stakeholders, very dynamic and open MAS modeling and simulation tools seem particularly useful to facilitate the emergence of a common agreement on a shared representation of the system to be managed. Subsequently, they also facilitate the identification and assessment of possible future scenarios with all concerned parties. In such a context, they can be useful to support the selection of socially and ecologically acceptable courses of action regarding land management by facilitating stakeholders' interactions (Röling 1996).

In a MAS model, an agent is a computerized autonomous entity that is able to act locally in response to stimuli from its environment or to communication with other agents (Bousquet et al 1999). The Mae Salaep model needs to provide an agent-based representation of the village catchment in which different interacting entities with specific behavior perceive, partially and differently according to their respective amount of resources, their common environment and act on it. The focus is on the interaction between the resource dynamics and its exploitation by different agents pursuing various socioeconomic objectives and adopting different crop production strategies to achieve them. The consequences of their agricultural production practices and collective behavior for the risk of land degradation in their common environment are assessed through a bottom-up aggregation of their effects on the resource base from the field to the farm, and then the village catchment level.

The Mae Salaep MAS model was built by using the CORMAS (common-pool resources and multi-agent systems) platform under the VISUALWORKS environment. This simulation platform has been specifically conceived to apply the MAS approach in the field of collective management of renewable resources (for more details about this simulation tool, see Le Page and Bommel's contribution in this volume). CORMAS provides users with a choice of different types of entities to create situated and/or communicating agents with their specific sets of attributes, methods, and interactions. It also facilitates implementation of the control of simulation dynamics and proposes several kinds of visual interfaces (spatial grids, graphs, communication diagrams) to observe simulations and analyze their results. Particularly, its spatial grid allows users to display different viewpoints regarding the resource management problem under consideration. Technical procedures are also available for linking the CORMAS environment with a GIS to make use of its data files.

Linking multi-agent systems with GIS to represent multi-scale land management dynamics

There is an increasing body of literature on spatially explicit simulation models using GIS in connection with ABM techniques to dynamically simulate evolutionary, ecological, and social phenomena in complex systems (Gimblett 2002). An original characteristic of the Mae Salaep MAS model is its built-in linkage with GIS maps in a vector mode providing a spatially explicit representation of land resources in the catchment. This MAS model is an importing input variable and data from several layers of the GIS are used to manage multiple spatial entities and to characterize the initial states of these different spatial components before running the model. This MAS-GIS linkage allows the model to handle dynamically three interconnected spatial entities: small intrafield homogeneous units, which are portions of fields showing regular slope angle and orientation delimited in the GIS, full farmers' fields usually displaying complex slopes, especially in the case of large ones, and the whole catchment (Fig. 1).

GIS data files created with the Arc Info software package and corresponding to actual maps of the catchment at different scales were transferred into the CORMAS environment. These GIS data files are used by the model in the following ways:

- To allocate fields to farms (field location, number of fields, and field size),
- To delimit small intrafield homogeneous units, and
- To provide the spatial distribution of data regarding slope angle and length at the catchment level.

This procedure allows the use of the most relevant layer of information and scale for each important process to be simulated, as shown in Table 1. For example, following each storm exceeding 10 mm (this being the minimum volume of a storm to create new erosion symptoms according to field observations), the risk of soil erosion by concentrated runoff is first assessed at the most relevant micro level of the small homogeneous units before being aggregated to the level of the whole farmer field made up of several of such units.

This integrative MAS-GIS modeling approach was used to represent into a single model farmer and scientific knowledge on land management obtained at complementary spatial and social levels of organization, as well as time scales (single rain event, crop cycle, crop succession, long-term trends in land-use changes).

Model description

This model proposes a dynamic representation of the catchment as a complex totality characterized by a biophysical setting exploited by different types of farmers.

Modeling assumptions

The Mae Salaep model is based on the following main assumptions made to simplify the modeling of agronomic and socioeconomic processes linked to the interaction between soil erosion risk and agricultural diversification:

- Field position in the landscape: the model locates paddy fields in the valley bottom and takes into account the fact that they usually belong to the families of early settlers who are presently managing the largest and most diverse types of agricultural production systems. Young families and recent settlers have access only to steeper fields located on the upper slopes.
- Crop choice in relation to farm types: in the model, farmers can choose among the whole range of main annual crops being grown in this village such as upland or wetland rice, maize, beans, or vegetables. But each type of farm manages a crop combination corresponding to its specific strategic orientation and corresponding amount of (land and financial) resources available. Small farms generally managed by young villagers (type A) grow mainly short-duration cash crops, while the large ones (type C) display a diverse selection of crops, including wetland rice. Medium-sized and more conservative holdings (type B) tend to focus on staple crops, such as upland rice and maize, and low-input, low-risk ones.
- Crop successions: bunded and terraced paddies located at lower elevation can be double-cropped with rice in the wet season, followed by soybean in the early and cool part of the dry season, while a single crop of upland rice, maize, beans, or vegetables is grown on sloping fields during the wet season if they are not fallowed.
- Farmer typology and farm dynamics: the ability of a given holding to switch to another category of farm following a series of good or bad economic results, or the retirement of the family head at 55, is not activated in the version of the model used to illustrate this article. Similarly, interactions with markets, especially farmers' reaction to price fluctuations for high-value cash crops, are not displayed in this mainly agronomic version.
- Climatic data: simulations use the rainfall distribution provided by the chronological series of daily pluviometric data recorded in neighboring Mae Chan District for 1976-2002. Turkelboom (1999) has shown that this data set can be used to represent rainfall in the local highlands if small storms, which are more frequent at higher elevation, can be ignored. This is the case in our study because the same author also showed that, under the local soil conditions, a storm of more than 10 mm is needed to create new erosion symptoms in sloping fields.
- No cumulative effect of soil erosion from field to field along the slope is taken into account by the model. This is because the catchment is made up of a patchwork of small fields usually separated by fallows or hedges. Turkelboom (1999) showed that, in some three-quarters of the actual field situations, the plots could be considered as hydrologically isolated. As a consequence, for each storm of more than 10 mm, the model estimates a level of soil erosion for each homogeneous unit in a given field and then aggregates these erosion indices at the whole-field level based on the respective size of each homogeneous unit.
- A single succession of well-ordered cultivation practices (or "itinerary of techniques") is associated with a given crop and is applied across all the farms. This is because only slight differences among farmers were observed during the preliminary on-farm surveys. A given duration of the critical period during which the field is susceptible to soil erosion by concentrated runoff is associated with each main kind of cropping system (kind of crop and its associated itinerary of techniques). This varies from 120 days for upland rice, the most susceptible crop, to 38 day for beans and cabbage, and 44 days for maize (Turkelboom 1999).
- Fallow effect on the risk of soil erosion: in this version of the model, fields are cultivated for 2 years and then fallowed for 1 year. Turkelboom (1999) found that fields cropped just after a fallow displayed strong aggregates that are more resistant to soil erosion than second-year fields. This effect of fallowing on the risk of soil erosion is taken into account in the model, with newly cleared fields eroding less than the second-year ones (see below in Table 2).

Model entities

The selection of research objects and their corresponding entities represented in the model denotes the degree of system complexity taken into account. These entities and their linkages are displayed in Figure 2. Four different categories of agents were modeled under the CORMAS environment:

1. Situated agents having spatial references in the watershed such as homogeneous units, farmers' fields, etc.
2. Passive objects such as crops, crop successions, successions of farmers' practices for a given crop, series of daily rainfall distribution, etc.
3. Communicating agents being able to receive messages: these are the village entity and three main types of farmers displaying contrasting socioeconomic objectives and cropping strategies, amounts of available resources, and degrees of integration into the market economy. The farm-level agents are autonomous and the results of their agricultural practices in their respective fields are pooled at the village catchment level. There is some communication among the different types of farmers through access to land.
4. Spatial entities located on the grid: an original characteristic of this MAS model is its built-in linkage with GIS maps of the catchemnt. This MAS-GIS link allows the model to handle dynamically two complementary spatial entities: farmer fields subjected to a homogeneous type of crop management are split into smaller homogeneous units regarding their slope conditions and are characterized by their size, slope angle, and length.

Spatial representation and entities. The representation of the Mae Salaep catchment takes into account the different levels of organization and relevant spatial units needed to simulate the land management dynamics. They constitute classes in object-oriented language (see below in Fig. 2). Spatial units are characterized by their actual boundaries. Agricultural land use is represented by the allocation of a given crop to each of the farmers' fields delineated in the catchment.

- Whole farmers' fields are used by the model to manage farmers' crop production practices and crop population dynamics, especially the duration from sowing to a soil coverage of 50% beyond which no more erosion symptoms were observed in the on-farm survey. The farmers' fields are homogeneously cropped by their owners and constitute the essential spatial entity for managing agronomic information and decisions such as crop allocation, cropping calendars, crop population dynamics, activation of successive farmers' practices for a given crop, etc.
- Small intrafield homogeneous units with regular slopes are used by the model to assess the effects of farmers' practices on the risk of soil erosion over the cropping season, according to various rainfall distributions and a series of slope angle and length thresholds identified during the previous on-farm erosion survey (see below in Table 2). The homogeneous unit is used by the MAS model to assess the risk of soil erosion after each significant rain (rainfall > 10 mm).
- As in reality, the village entity main role is to regulate the beginning and end of the crop year and consequently the timing of farmers' cultivation practices. It is also at the village catchment level that the daily results of the assessment of soil erosion in each homogeneous unit and field are pooled.

This linkage among complementary spatial entities allows researchers to run simulations taking into account multiple levels of organization and several specific spatial functions. In this way, the most pertinent layer of information at the most relevant scale is used for each important biophysical or socio-agronomic process to be simulated.

Social agents. The preliminary farm survey showed that farmers' objectives and cropping strategies are contrasted. Therefore, the social heterogeneity among the local farming community is represented by three different main types of households with contrasting resource availability (particularly quantity and quality of land) and agricultural production strategies (Trébuil et al 1997):

- Type A: small holdings on upper steep slopes, managed by relatively young farmers who are very much involved in the production of annual cash crops such as maize, vegetables, beans, etc.
- Type B: medium-sized farms characterized by a rather conservative management strategy; upland rice and maize production dominate in these fields.
- Type C: larger, very diversified, and relatively well-off farming units managed by early settlers on prime, less steep land with access to water for paddy rice production and capital for establishing perennial plantations (lychee, tea).

In the agronomic version of the model presented in this article, interactions are limited to access to farmland. The model allocates annual crops to the available fields at the whole-farm level depending on the farmer's strategy and related choice of a combination of crops.

Passive entities. These are made of various elements in the farm environment that are needed to simulate land-use and soil degradation dynamics: the fields, the various crops and their successions, the inventories of techniques associated with each crop, and the historical series of daily rainfall data for Mae Chan District. Specific attributes, procedures, and interacting rules are also programmed for these passive agents.

Model structure

The model structure is shown in Figure 2 as a simplified class diagram using the Unified Modeling Language (UML). It displays the different model entities and agents, as well as their hierarchy and relationships. For example, each plot instance is attributed to a given farmer managing several of them. Just under the name of each model entity, a box indicates its own set of attributes while, just below, another box lists the various methods associated with this entity and linked to its evolution during simulations.

Sequential flow of information during simulation

Soil erosion dynamics. The model relies on a series of thresholds for slope angle and length, soil coverage, and cropping history to assess the level and severity of soil erosion risk after each rain with a total volume of more than 10 mm, the minimum amount of rain needed to generate new erosion symptoms in local fields. They are shown in Table 2 and detailed information on these thresholds can be found in Turkelboom and Trébuil (1998) and Turkelboom (1999). In particular, the thresholds dealing with slope angle and length take into account the nonlinear characteristics of soil losses at the site depending on the dominating type of soil erosion process (gully erosion, plow layer erosion, rill networks, etc.) occurring in different slope conditions.

The village decides the start of the crop year in March, at the end of the dry season, by allowing farmers to allocate their crops to their different fields and to begin their land preparation practices according to the itinerary of techniques programmed for each kind of selected crop. As soon as the wet season begins, if a potentially damaging rain event occurs, the soil coverage (which is modified by the timing of farmers' practices such as plowing and weeding) and slope conditions of each homogeneous unit in each field are checked on a daily basis according to the recent crop management practices performed by farmers. If the model finds that soil erosion occurred during this storm, it estimates a level of damage severity and a given amount of soil loss based on the thresholds shown in Table 2. Then, the amount of erosion damage for this field is updated. This procedure repeats itself until the end of the wet season.

Farmer decision-making processes. The simplified UML sequence diagram presented in Figure 3 displays the chronology of the model operations when it reads the instructions. This sequence diagram shows the objectives of the successive sets of instructions and procedures. For each key step, it displays the interactions between various objects and agents of the system, their activities, and changing states. At the initialization stage, the model reads a set of GIS files to create the spatial units (small homogeneous units and whole fields), passive objects, and social entities (number of farmers per main type and the village made up of 48 households). Afterward, it allocates the fields to the different farmer categories according to their number in each category. Then, for each field, the erosion counter registering the amount and the frequency of erosion damage is initialized and set at nil. Next, farmers are asked to allocate their crop combinations among their different fields in agreement with their respective strategies. The village agent decides to start the cropping year and "sends" the farmers to their fields at the beginning of the wet season. The control of the simulation can be set up according to a daily or a yearly time scale.

Outputs and indicators

The dynamics of the simulated system can be visualized and analyzed thanks to a selection of indicators. In this chapter, we will focus on the risk of soil erosion quantified by the cumulative assessment made for each spatial unit after every eroding storm. At the end of a simulation, the model can display the spatial distribution of erosion damage for each field or each farming unit in the village watershed. Based on given distributions of the village's 48 farming units among the three main types and crop allocations to their respective fields, this indicator allows us to assess the effects of climatic variability on soil erosion damage due to unpredictable rainfall distribution. Later on, it could be used to assess the environmental effects of new land-use scenarios proposed by stakeholders. The same indicator can also be used to compare the impact of different types of crop allocations on the risk of soil erosion and total soil loss during the wet season, for example, after the introduction of more perennial crops in this catchment. The respective contribution of the different types of farming units to the total erosion damage can also be evaluated through this indicator.

Beyond this environmental indicator, the outputs of the complete version of the model will also be able to display graphs to observe changes over time in the social distribution of the farming community and the related economic status of the household types. Such changes depend on the local rules for inheriting the land from old farmers and on the economic results of farmers' cash-cropping activities. This kind of socioeconomic indicator could be very useful to answer the question "Who benefits?" when assessing alternative land-use scenarios proposed by local actors.

Model verification and calibration

A verification of the coded modules was performed to ensure their coherence with the conceptual model represented in UML diagrams (Figs. 2, 3). For several of these modules, the simulations were stopped during execution and the modeler used the CORMAS debugger to check those lines of code and to verify that they operated in agreement with his expectations.

Several simple tests were performed to verify that the model was behaving logically and realistically according to experts. For example, the module dealing with farmer decision-making was followed step-by-step under different conditions.

The actions of several key agents, such as farmers' practices and their effects on soil erosion dynamics under given rainfall conditions, were observed during simulations to check the coherence between their behavior and the modeler's expectations.

Most of the model calibration relied on expert knowledge and the published results of previous on-farm experiments and surveys.

Model validation: respective roles of experts and stakeholders to assess the simulated behavior of the system

A general two-step approach is being used for validating this model. Following expert assessments of the results of simulations, further improvements and validation of the model will be carried out with potential users among the local stakeholders (Bousquet et al 2001).

Expert validation. An internal and formal validation of the model was done by the project modeler to check the relationships among variables. Sensitivity tests were performed on selected key variables such as rainfall distribution, farmer actions, and soil erosion and analysis to assess the reactions of the modeled system when its values vary. Because of the large number of parameters included in the model, a full exploration was not feasible. Analyses of the simulation results under a variety of input parameter settings were carried out to verify that the outputs were reasonable in comparison with the system dynamics understanding based on field studies. Several examples are provided below.

Participatory validation. In agreement with our INRM approach, it is essential that the model be found acceptable by the stakeholders so that it can be used to facilitate communication among them. It is necessary to verify that, in the eyes of its potential users, the model is transparent enough, and that its key assumptions and hypotheses can be accepted. Therefore, suitable procedures for model validation to be put in place must make its contents explicit, and users must be able to verify the coherence between the observation and the simulation of dynamic events. To do so, this MAS model needs to be simplified, by retaining only key interactions, and transformed into a less complex tool, such as a role-playing game to be tested with stakeholders. To limit the "black box" effect, such a simpler gaming tool can help local actors to familiarize themselves with the way the MAS model is working. It can also show them how it relates to the real world in which they act (Trébuil et al 2002).

We anticipate that this step will generate new knowledge on actors' strategies and decision-making processes that will imply modifications of the original MAS-GIS model, while increasing its credibility and legitimacy. Because the role-playing game has a dual role (validation of the proposed representation of the system and production of new knowledge to improve it), a back-and-forth process between this interactive tool and the MAS model is an original feature of the companion modeling approach. As soon as the stakeholders become familiar with the rules and the outputs of the role-playing game, a similar version of the MAS model incorporating their contribution on the representation of the system could be used with them. Their knowledge of the functioning rules of the model will allow them to criticize the simulation results and, later on, to use a modified version of this tool to explore the effects of various scenarios of land-use changes.

Exploration of simulated scenarios

In this article, each scenario is run for a period of 1 year only. Because random functions are included in the program (for example, to determine the amount of soil loss corresponding to the three levels of severity of erosion displayed in Table 2), it is necessary to repeat the simulation of each scenario to assess the variability of the results. At the end of each simulation, the dynamics of total erosion at the catchment level is plotted on graphs for further analysis. The final amount of soil loss can also be displayed on maps to study its spatial distribution.

Simulation of a baseline scenario and soil erosion dynamics

The baseline scenario simulates the farming conditions regarding the production of annual crops in the Mae Salaep catchment as observed during field research in the mid- and late 1990s. Figure 4 displays the allocation of various annual crops to farmers' fields at the beginning of the wet season

(A) and the spatial distribution of the simulated total soil loss at the end of the year. Such an output allows the identification of "hot spots" for the risk of soil erosion in the catchment and their characterization (slope conditions, crop grown, and type of farmer managing these susceptible fields).

For a given year, Figure 5 displays the dynamics of soil erosion in relation to rainfall distribution in 1987, soil coverage by weeds and crop canopies, and farmers' practices. Soil loss increases very significantly at land preparation and at first and second weeding stages at around 100, 140, and 185 days, respectively. After that, the total soil cover remains above the critical threshold of 50% in most of the fields and, consequently, total soil loss increases only marginally until the end of the crop year.

Effect of variable rainfall distribution on soil loss

The soil erosion created by the same baseline scenario of crop allocation was simulated for each of the 27 successive years of the 1976-2002 period. Figure 6 shows that the important variability of rainfall distribution across years (the annual total of rainfall varied from 1,097 to 2,257 mm in 1992 and 2001, respectively) and its interaction with the timing of farmers' practices in their fields led to a very extensive range of total soil loss at the catchment level at the end of the cropping season. This total amount of soil loss varied between 12.1 and 51.1 t ha^{-1} in 1995 and 1993, respectively. Such variability explains the limited success of classic input-output and small plot-based agronomic research procedures to understand the effects of various factors and field conditions on soil loss. A detailed monitoring of soil surface states in relation to rainfall distribution is necessary to be able to explain the total amount of soil loss observed at the end of the crop year.

Effect of different crop allocations to fields on total soil loss

For a given climatic year, we run simulations with 30 different kinds of crop allocation to farmers' fields to assess the effect of crop choice on the total amount of soil loss in the catchment. Figure 7 shows the results of these simulations for the 1987 crop year. The total amount of soil loss at the end of the year varies from 23.9 to 40.8 ton ha^{-1}. This confirms the importance of the spatial allocation of the different annual crops in the landscape to mitigate the risk of soil erosion. For example, in Mae Salaep village, most of the farmers say that, when they can, they try to avoid growing upland rice (the crop most susceptible to soil erosion) on very steep slopes.

Effect of farm type on soil loss

Based on the simulation of the baseline scenario of crop allocation for 27 years (1976-2002), Figure 8 shows the respective mean and standard deviation values of total soil loss per cultivated hectare for the three main types of farming households identified in Mae Salaep. With a mean soil loss of 66.8 t ha^{-1}, which is almost twice as large as the estimations for type B and C farms, the very small-scale type A farms show their higher ecological vulnerability. But with only two or three fields, usually located on steep upper slopes, the total amount of soil loss created at the whole-farm level by these smallholdings is less than in the case of larger type B and C farms.

This result shows that, later on, much attention will have to be given to the already extensive social differentiation among the farming households when identifying and assessing alternative land-use scenarios with Mae Salaep villagers. In particular, it will be essential to ensure that the most resource-poor smallholdings will also be able to meet the necessary conditions to implement the most promising practices if they wish to do so.

Conclusions and perspectives on model use

This simulation model provides a spatial representation of the effects on the risk of land degradation of farmers' actual practices and decision-making related to the selection of annual crops and their allocation to their various fields. We found that the selected MAS-GIS modeling approach has the capacity and flexibility to represent and integrate different kinds of (qualitative as well as quantitative) knowledge across sources (indigenous and scientific ones) and to display interconnected dynamics operating at multiple levels of organization. We do not plan to use this model to predict changes or to better control the simulated agroecosystem. Our aim is to focus on understanding key interactions and on using this tool in a communication and negotiation support approach with local stakeholders.

Such a representation helps to understand dynamically the functioning of a complex agricultural system such as a highland village watershed. If this holistic representation of the system can be validated and shared in a participatory companion modeling process, it could be used as a coordination and negotiation support tool among stakeholders to assess scenarios of possible futures and to support collective learning and management of their common environment. Such a common representation of the system to be collectively managed can also be used with stakeholders to define appropriate indicators and monitoring procedures or information systems.

Further work is needed to allow a more dynamic management of the model spatial entities by the farmers. In particular, they should be able to change the size of the cropped field when they switch from a traditional and self-subsistence crop to a market-oriented and more labor-intensive one. The latter type of crop is usually grown in smaller fields, with shorter slope lengths and, as a consequence, a lower susceptibility to soil erosion. This could be done by introducing the possibility to split large fields into their homogeneous units, for example. More work is also needed to take key economic processes into account, such as price fluctuations for horticultural crops and the more and more common articulation between on-farm and off-farm employment.

Following further validation of this model by experts and Mae Salaep villagers, we plan to use this model to simulate possible future scenarios for highland agriculture in the villages where intensive field data collection was conducted. To be useful, these scenarios should be jointly defined and assessed with the concerned players. Based on recent interactions with them, they could deal with the expansion of perennial crops (mainly lychee and green tea) in this catchment to improve soil coverage during the wet season. Before being able to do so, there is a need to go back to the field to update the list of crops managed by the model to include perennial ones and to collect information on farmers' decision-making procedures regarding market price fluctuations of horticultural crops and labor management between on-farm and off-farm opportunities. This will create a reciprocal learning process between stakeholders and researchers, which is a key characteristic of companion modeling. We think that this "learning by modeling" approach provides an operational way for INRM researchers to closely articulate their field and modeling activities. In many situations characterized by a general policy framework encouraging the decentralization of resource management, it can help to prioritize, plan, implement, and assess research work with diverse stakeholders to accompany and support their projects.

Acknowledgments

The preparation of this article benefited from collaborative research activities carried out with academic and development-oriented partners. The authors would like to thank F. Turkelboom from ICARDA, the Multiple Cropping Center of Chiang Mai University, the Department of Public Welfare of Thailand, and the farming communities of Pakasukjai and Mae Salaep villages in Mae Chan and Mae Fah Luang districts of Chiang Rai Province.

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Notes

Authors addresses: G Trebuil, F Bousquet, C LePage, CU-Cirad Commod Project, Faculty of science, Chulalongkorn University, Bangkok, Thailand, and GREEN Research Unit, Tera Department, Cirad, Montpellier, France: guy.trebuil@cirad.fr, francois.bousquet@cirad.fr; B Ekasingh, Department of Agricultural Economics, Faculty of Agriculture, Chiang Mai University, Thailand; C Baron, GEOTROP Laboratory, Amis Department, Cirad, Montpellier, France.

Fig. 1. Spatial levels of organization in Mae Salaep catchment: homogenous units to assess soil erosion, and farmers' fields to simulate cultivation practices and to represent the different crop combinations selected by the main types of farms.

Fig. 2. Class diagram of the Mae Salaep model showing its main entities inherited from four types of CORMAS entities (these are the upper classes shown at the top of the figure).

Fig. 3. Simplified UML sequence diagram of the Mae Salaep model displaying the sequence of different procedures run during a time path. Each model class is represented as a vertical line and its activation occurs when there is a rectangle on the line. Objects communicate by exchanging messages corresponding to the horizontal arrows from their senders to their receivers.

Fig. 4. Simulated allocation of farmers' fields to annual crops at the beginning of the baseline scenario (A) and simulated distribution of soil erosion (t ha^{-1}, B) in Mae Salaep catchment.

Fig. 5. Dynamics of soil erosion at the catchment level for rainfall distribution in 1987.

Fig. 6. Simulated results of the effects of rainfall variability (1976-2002) on soil erosion for a baseline scenario of land allocation to annual crops in Mae Salaep catchment.

Fig. 7. Effect of 30 different kinds of crop allocations to farmers' fields on total soil erosion at the catchment level for the 1987 crop year.

Fig. 8. Simulation results of 27 years (1976-2002) displaying the respective contributions of the three main types of farming households to soil erosion per land unit in Mae Salaep catchment.

Fig. 1.

A. Homogenous units

B. Farmers' fields

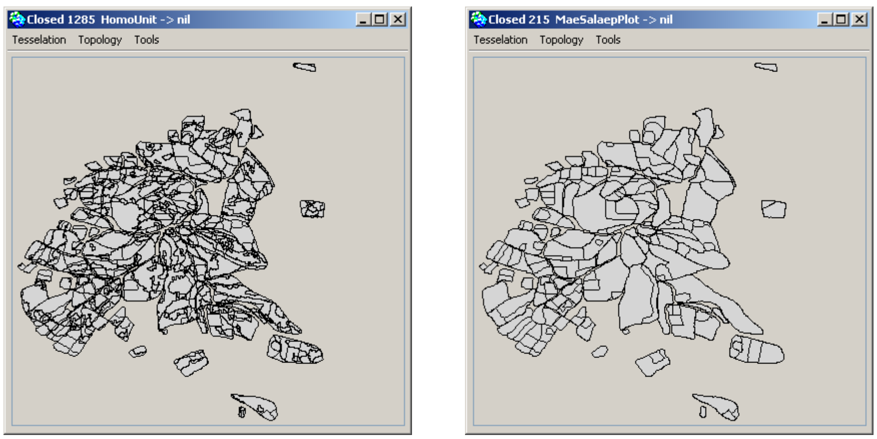


Fig 2.

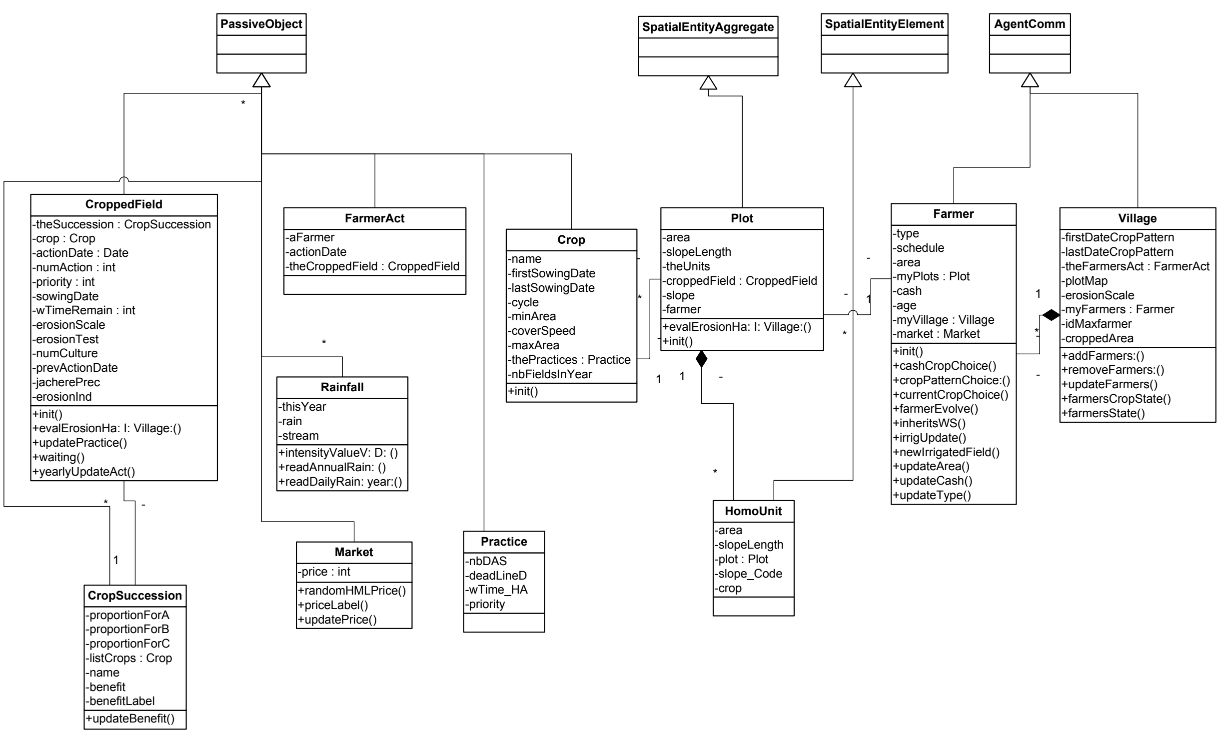


Fig. 3.

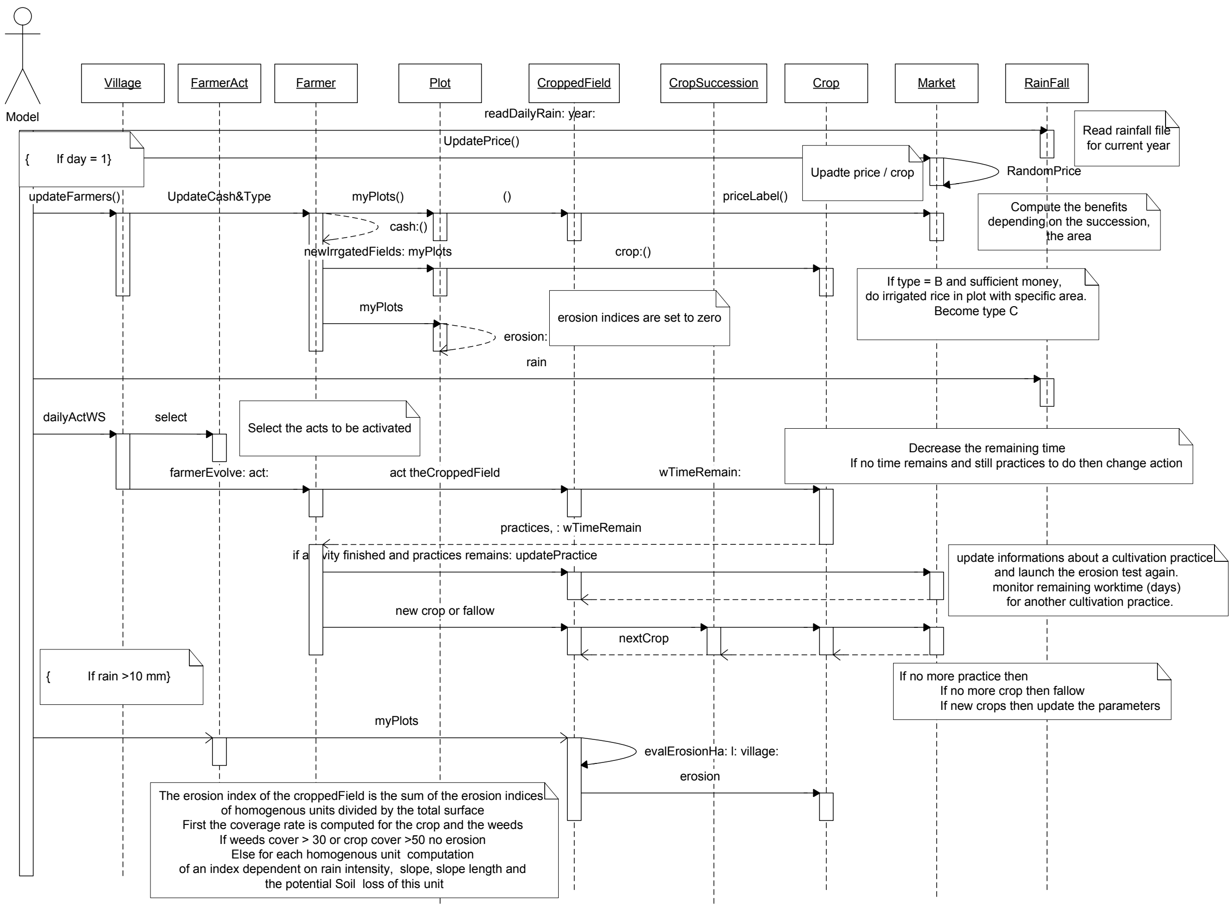


Fig. 4.

■ Maize

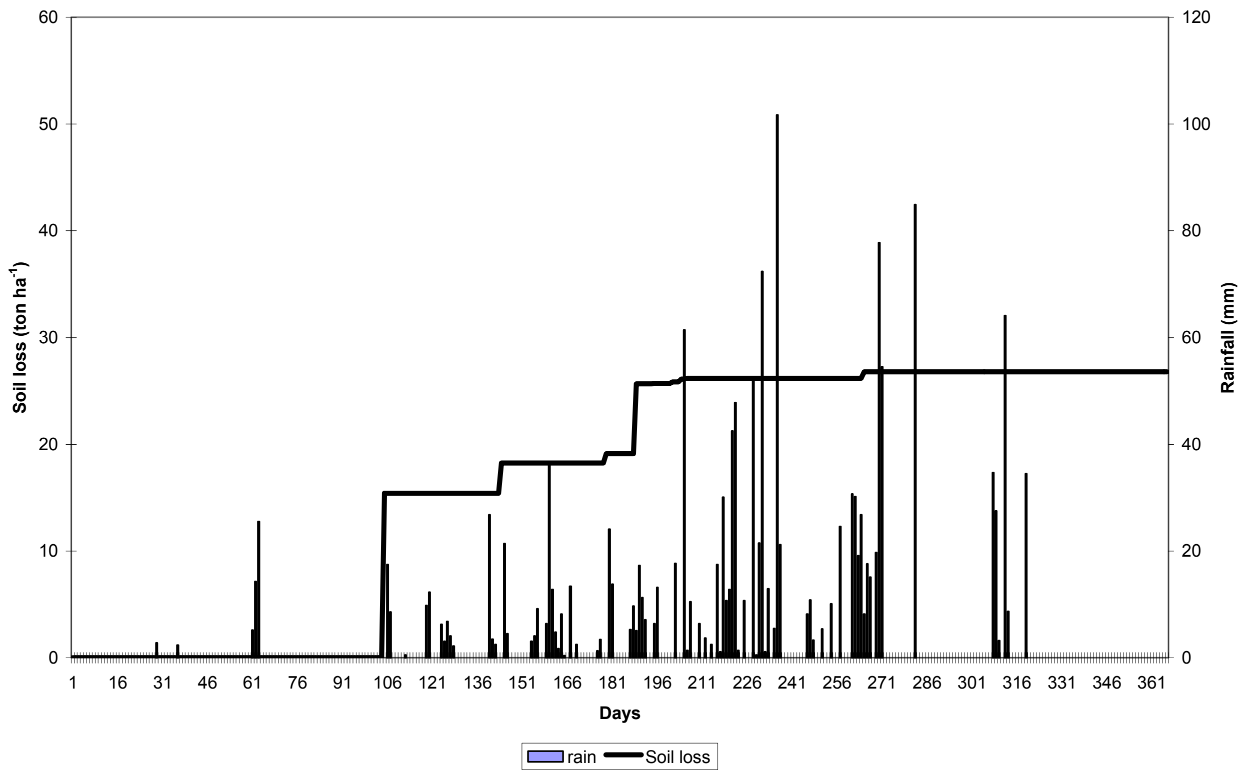
■ Upland rice

■ Vegetables

□ Fallow

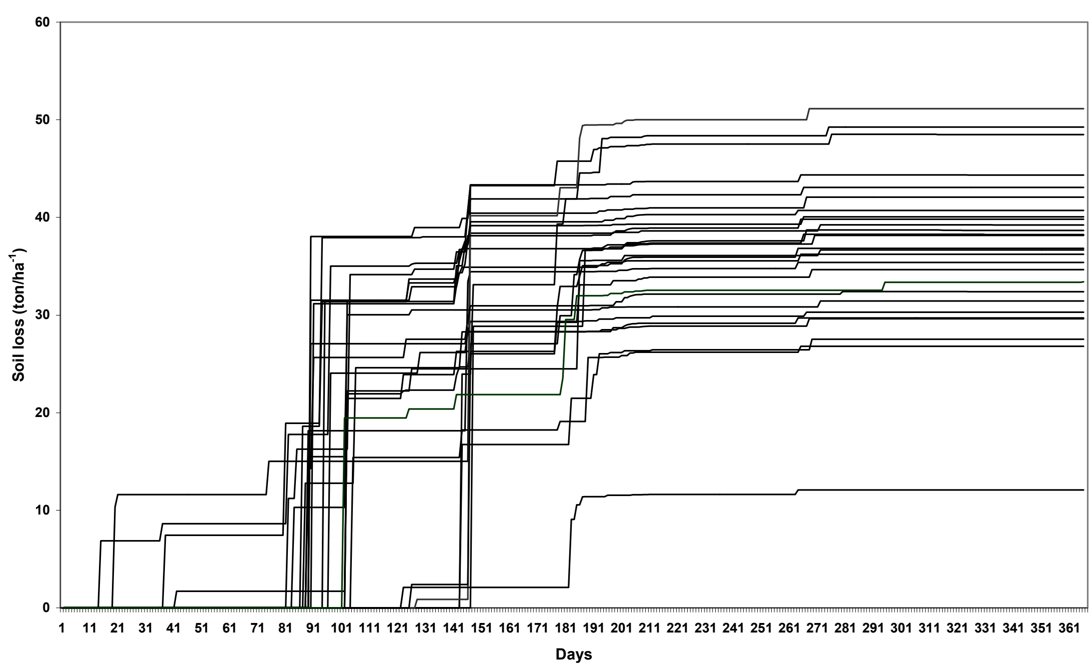
Relative index: the darker the plot the higher the soil erosion

Fig. 5.



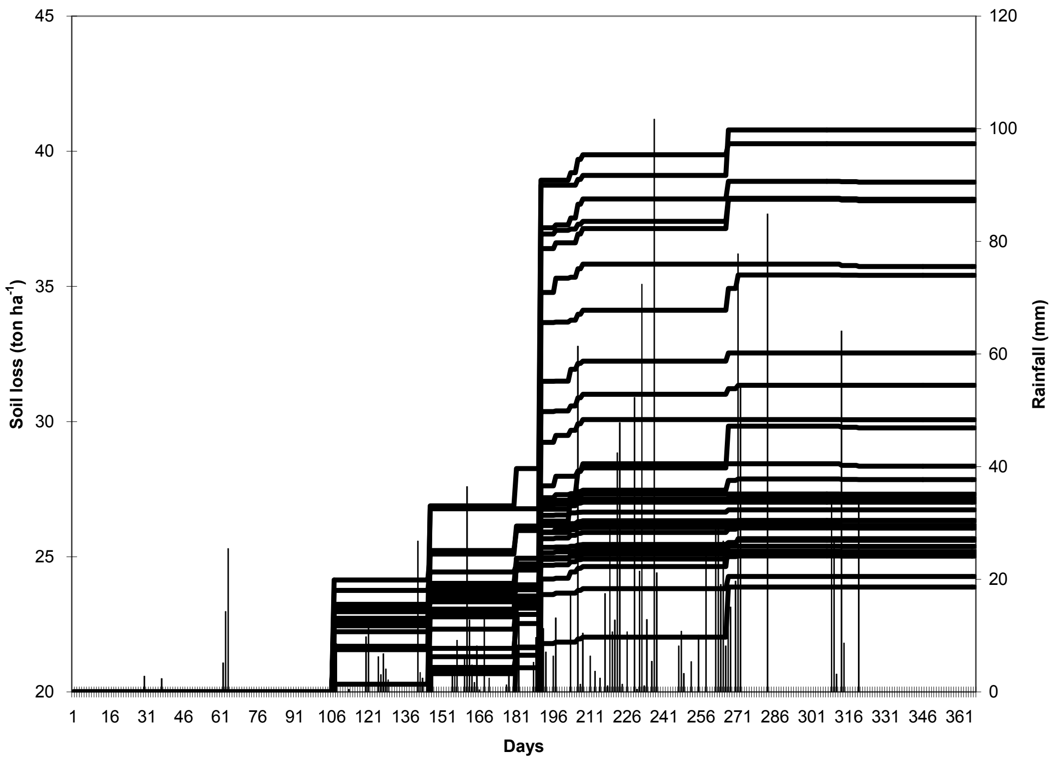
60
50
40
30
20
10
0
Soil loss (ton ha-1)
120
100
80
60
40
20
0
Rainfall (mm)
1 16 31 46 61 76 91 106 121 136 151 166 181 196 211 226 241 256 271 286 301 316 331 346 361
Days
rain
Soil loss

Fig. 6.



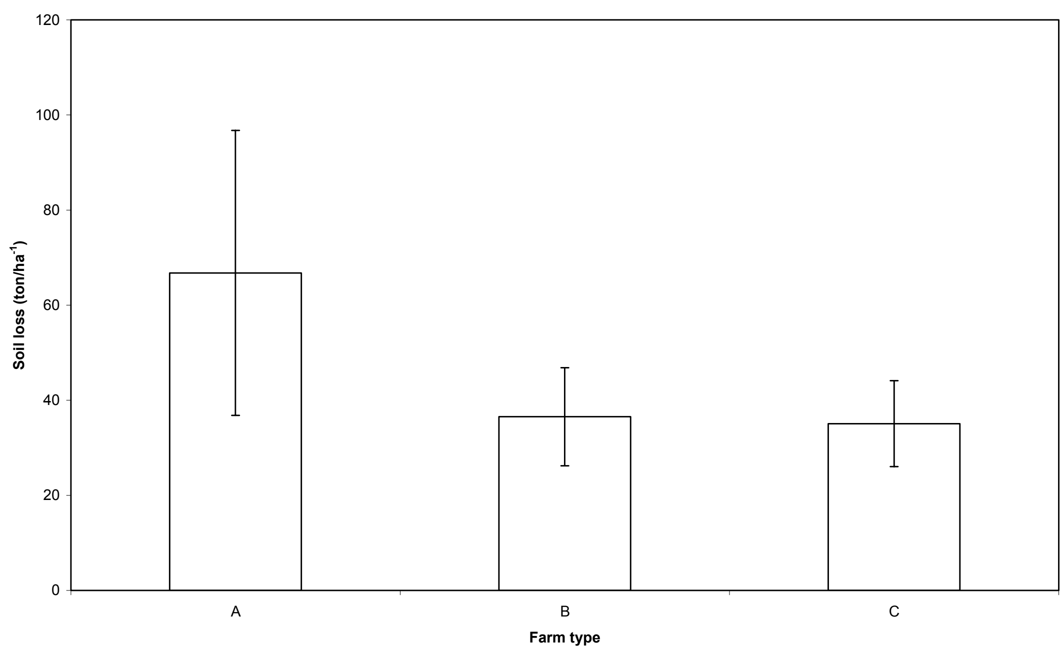
60
50
40
30
20
10
0
Soil loss (ton/ha-1)
1 11 21 31 41 51 61 71 81 91 101 111 121 131 141 151 161 171 181 191 201 211 221 231 241 251 261 271 281 291 301 311 321 331 341 351 361
Days

Fig. 7.



45
40
35
30
25
20
120
100
80
60
40
20
0
Soil loss (ton ha-1)
Rainfall (mm)
1 16 31 46 61 76 91 106 121 136 151 166 181 196 211 226 241 256 271 286 301 316 331 346 361
Days

Fig. 8.



120
100
80
60
40
20
0
Soil loss (ton/ha-1)
A
B
C
Farm type