Doctoral School in Environmental Engineering

Restoring forest landscapes for nature conservation and human well-being: Advanced spatial decision support tools

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Cover photo: landscape mosaic in Southern Mexico (courtesy of Elena Ianni).

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“The whole landscape showed design, like man’s noblest sculptures. How wonderful the power of its beauty! Gazing awestricken, I might have left everything for it. Glad, endless work would then be mine tracing the forces that have brought forth its features, its rocks and plants and animals and glorious weather. Beauty beyond thought everywhere, beneath, above, made and being made forever.”

(John Muir, My first summer in the Sierra, 1911)

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Summary

Forest management involves dealing with conflicts between the protection of nature and the use of natural resources. Bad management practices have led to significant forest degradation worldwide. It is estimated that globally about 13 million hectares of forest are lost every year, leading to a massive loss of biodiversity and other forest-related ecosystem services, such as soil stabilisation and watershed protection. This is particularly dangerous in poor regions, where livelihoods are strongly based on locally available natural resources. In 2000, IUCN and WWF have introduced a new restoration approach called Forest Landscape Restoration (FLR) that aims to regain ecological integrity and enhance human well-being in deforested or degraded forest landscapes. FLR goes well beyond planting trees: it is about re-designing the landscape mosaic in a way that both nature and people are benefited. To this purpose, different actions should be taken at different locations across the landscape. From a planning perspective, this calls for proper methods and tools that help identifying where to act and what to do. The present research aimed to contribute to this problem by developing and testing spatial decision tools to support the design of landscape mosaics. More specifically, the study had three main objectives.

The first objective was the identification of criteria and indicators (C&I) for the prioritisation of forest restoration interventions. Knowing which areas are ecologically more suitable to host a restoration intervention is a prerequisite of any FLR-based plan. There can be areas where restoration is more urgent, areas where it is more likely to succeed and areas where it is expected to bring the highest ecological benefits. Unfortunately, a widely accepted framework for the prioritisation of forest restoration areas is lacking. This problem was addressed by conducting an expert survey to define a set of readily applicable C&I. This was based on a two round Delphi involving 37 people, aimed at defining the key criteria and a broad set of indicators, and a final face-to-face meeting with a smaller group of experts, aimed at refining the list of indicators and making them operational. Finally, 8 criteria and 22 indicators were obtained, whose main advantage is their spatial character, which makes them suitable for spatial analysis and mapping.

The second objective was the development of a GIS-based multicriteria methodology to identify reforestation priorities, to design a number of landscape-scale reforestation options and to assess them according to their socio-ecological performance. The prioritisation was based on two main non-compensatory factors: the need for biodiversity conservation and the ecological feasibility of reforestation. Suitability maps were generated for both factors through spatial multicriteria analysis and threshold pairs used to extract priority areas. The minimum suitability levels and the total area to be reforested were used as input parameters

to generate a finite number of resulting reforestation options. These were assessed for their ability to conserve biodiversity and improve living conditions of local communities by introducing additional ecological and socioeconomic indicators. The methodology was tested in an area of Chiapas (Mexico), where forest degradation is significant and poverty widespread. The tool proved to be effective in shaping compact reforestation areas and easy to use. Nevertheless, it does not allow the user to a priori define targets on both conservation and livelihood standards. Also, the forest-poverty link was little explored and the issue of access to forest resources totally neglected.

This leads to the third objective of the thesis: the definition of a spatial optimization model to re-design the landscape mosaic through reforestation in a way that nature protection is enhanced, the provision of ecosystem services is ensured and livelihoods are sustained. Either one of two possible uses was assigned to forest: protection, if forest is primarily devoted to biodiversity conservation, and harvest, if forest is available for the collection of timber. The model, which is an Integer Programming-based one, identifies land to be reforested and assigns this to the two uses such that all environmental classes over the landscape are adequately covered by protected forest, each village has a sufficient amount of harvestable forest at short distance and a given amount of erosion-prone land is reforested. The model also accounts for opportunity costs, by limiting the amount of economically strategic lands (e.g. agriculture) to be converted to forest. The model is the first of its kind to account for local people's livelihoods by ensuring the accessibility to natural resources. The application to a case study in central Chiapas (Mexico) showed that increasing the demand for the provision of an ecosystem service does not significantly affect the ecological benefits up to a given threshold. Although some assumptions had to be made, the model provided a demonstration that the principles of the FLR can be put in practice and ad hoc planning tools can be designed to support decision-makers in their activity. Most of all, the model provided a solution to the problem of conserving biodiversity in poor regions where maintaining the access to local natural resources is vital to people.

Redesigning forest landscapes for nature conservation and livelihood improvement is a difficult task. But one of dramatic importance as well. This study provided tools that can be of practical help to decision-makers and planners willing to undertake the challenge. Nevertheless, the problem is complex and intrinsically affected by uncertainty: further research effort is needed to test indicators, include the time dimension into the model and involve stakeholders in the decision process.

Chapter 1

Scope and outline of the thesis

1.1 Introduction

The conflict between conservation and the use of natural resources is a challenging one. In the past, a separate vision has led to a dichotomy. On the one hand, economic growth has encouraged the overexploitation of resources that resulted in large environmental damages. On the other hand, increased ecological awareness has suggested a 'full protection' approach that banned any possible use on certain areas. Today a new approach is emerging: conservation and the use of resources must be reconciled and, to a certain extent, they can coexist. This is what sustainable development is all about: allowing the present generation to flourish without preventing future generations from fulfilling their own needs (Brundtland, 1987). In ecological terms, Rosenzweig (2003) has referred to this concept as 'reconciliation ecology': the idea that we should give wild species back their habitat without stealing humans'. Despite much emphasis is being given to these issues, there is not too much evidence that they are either attainable goals or priority issues in the agendas of politicians.

Land use planning is intrinsically aimed at reconciling different and sometimes conflicting objectives. Different land parcels have to be assigned different uses so that human well-being, nature protection and economic growth can be simultaneously achieved. Forest management is a planning problem that involves an evident conflict between the protection of nature (forest) and the use of the natural resource (e.g. timber). Today the total forest area is estimated to average 4 billion hectares, or nearly 30% of the total land area (FAO, 2006). The whole amount is not equally distributed among countries and continents, with about one fourth that is found in Europe, one fifth in South America, 17% on North and Central America, 15% on both Africa and Asia and 5% in Oceania. Forests are generally considered a reservoir of biodiversity for hosting a huge number of both animal and plant species. At the same time, they are suppliers of several services: from timber production to watershed protection, from soil stabilisation to cultural heritage. Forest products are generally categorised as timber forest products (TFP), and non-timber forest products (NTFP), that is commodities that do not require to harvest trees (e.g. forage, medicinal plants, seeds).

Unsustainable practices of forest management, besides threatening biodiversity, are likely to decrease and maybe stop the ability of the forest ecosystem to provide other services. According to FAO (2006) the annual world's deforestation rate is around 13 million hectares, whereas annual net forest decrease has averaged 8 million hectares in the period 1990-2005 when considering the contribution of reforestation to halting forest loss. Drivers of deforestation are many, but especially related to land use conversion (e.g. expansion of agricultural fields, construction of infrastructures) and bad land use practices (e.g. overgrazing, overharvesting).

Several measures have been considered to mitigate the effects of forest degradation and loss. Among these, emphasis has been given to restoration approaches and the sustainable management of forest resources. Most of these approaches however focus on one single aspect of the problem, namely the loss of biodiversity or the lack of timber for industry, but seem to miss the whole picture involving conservation, ecosystem services and people. The Forest Landscape Restoration (FLR) approach, officially introduced in 2000 by the International Union for the Conservation of Nature (IUCN) and the World Wildlife Fund (WWF), is "a process that aims to regain ecological integrity and enhance human well-being in deforested or degraded forest landscapes" (WWF and IUCN, 2000). The approach maintains that, by implementing different actions at different locations within the whole landscape, it is possible to achieve multiple objectives. Although some FLR experiences have been recorded and several guidelines produced, there is still a significant lack of scientific literature on the topic. Tools are needed to verify whether this 'landscape mosaic approach' is feasible in practice, and how it can be implemented. The relevance of the subject is particularly high in poor regions ('marginalised contexts'), where the quality of the environment and the possibility to use its services constitute a key element in people's livelihoods.

1.2 Objectives of the study

The main objective of this study is to develop and test advanced spatial tools to support the design of forest-based landscape mosaics that benefit both nature and people.

Towards the achievement of this objective, the identification of forest restoration priorities is a first fundamental point. There are areas over the landscape where the restoration is more urgent, areas where it can bring the highest ecological benefits and areas where it is more likely to succeed. Knowing the indicators that allow such priorities to be identified may constitute the input of any decision support tool. Multi-Criteria Decision Analysis (MCDA) offers powerful spatial tools for land allocation that can be adopted and further developed for putting the FLR principles into practice. Among these, traditional multicriteria techniques may help selecting the best restoration alternative out of a small set. Such techniques are often user-friendly, but present some major drawbacks that make them only partly effective for dealing with the FLR concepts. Spatial optimization models, based on more complex mathematical concepts, can tackle the problem of several possible alternatives to choose from. Nevertheless, designing proper models for FLR applications is not a straightforward task. These issues are described in the specific research objectives, and related questions, below.

Objective 1: Identifying criteria and indicators to be used for the prioritisation of forest restoration areas.

The definition of ecological criteria and indicators (C&I) is actually the first step towards designing the above mentioned landscape mosaic. C&I are expected to provide information about where the restoration is more urgent and where it is supposed to be more feasible. This should help identifying those areas where the restoration investment is more effective in terms of biological benefits. This has to be intended just as an initial step that subsequently must be integrated with further information on the socioeconomic side. Proper C&I can constitute a preferential input for various types of models attempting to re-design the landscape mosaic.

Research questions
Does the literature provide a widely accepted framework for the prioritisation of forest restoration areas?
Can expert judgement provide relevant information about which areas should be accorded priority for forest restoration?
Is it possible to define a compact set of ecological criteria and indicators to identify restoration priorities?
Can spatially-explicit indicators be identified?

Objective 2: Defining a multicriteria methodology for the design of restoration options and their comprehensive evaluation.

Multicriteria techniques offer a strategic tool to decision-making for their ability to integrate multiple information. They allow the identified C&I to be combined in a GIS environment such that restoration priorities can be identified. Ad hoc techniques are needed to actually shape possible restoration options. Multicriteria techniques can be used again to assess those options according to their socio-ecological performance.

Research questions
Are spatial multicriteria methods applicable to the implementation of FLR principles?
How to design restoration options by means of suitability thresholds?
How to evaluate options according to their socio-ecological performance?
How to handle the uncertainty related to thresholds?

Objective 3: Defining a spatial optimization model for the design of a landscape mosaic that enhances nature conservation, ensures the provision of ecosystem services and sustains livelihoods.

Spatial optimization models are broadly used in conservation biology for reserve selection. Compared to basic multicriteria techniques, such models offer considerable advantages as they allow the best alternative to be univocally identified according to the targets that the user has fixed a priori. Their potential contribution to the implementation of FLR is great. In particular, models have to be designed that, besides the conservation of nature, account for the provision of ecosystem services and the access of human communities to natural resources.

Research questions
Is it possible to account for local people's livelihoods in a spatial optimization model?
How can we ensure that forest resources are accessible to people?
Can restored areas enhance both nature conservation and the provision of ecosystem services?
Does uncertainty heavily affect the output of the model?

1.3 Outline of the thesis

The outline of the thesis is shown in Figure 1.1. **Chapter 2** describes the conceptual framework by introducing approaches and tools. The description of the FLR is made with a strong emphasis on its potential contribution to environmental and livelihood improvements in marginalised contexts. Multi-Criteria Decision Analysis (MCDA) methods are presented in the light of their usefulness for turning the FLR principles into practice. The core part of the thesis is based upon three chapters (within the dashed frame in Figure 1.1), which address the three specific objectives described in § 1.2. **Chapter 3** proposes an expert panel-based method to elicit criteria and indicators for the identification of forest restoration priorities. The final result of this chapter feeds the two following chapters. The methodology introduced in **Chapter 4** applies some of these indicators to generate prioritisation maps from which to extract reforestation options. The spatial optimization model introduced in **Chapter 5** also takes advantage of some of the proposed indicators to force the reforestation actions towards the areas that are expected to bring the highest ecological benefits. Chapters 4 and 5 are related to each other in that the methodology introduced in the latter shows a way to address the drawbacks of the approach proposed by the former. Methodologies introduced in Chapters 4 and 5 were applied to two case studies in Chiapas, Mexico. Finally, **Chapter 6** summarizes the results of the research, discusses the main findings, their strengths and weaknesses, and contains some recommendations for future research.

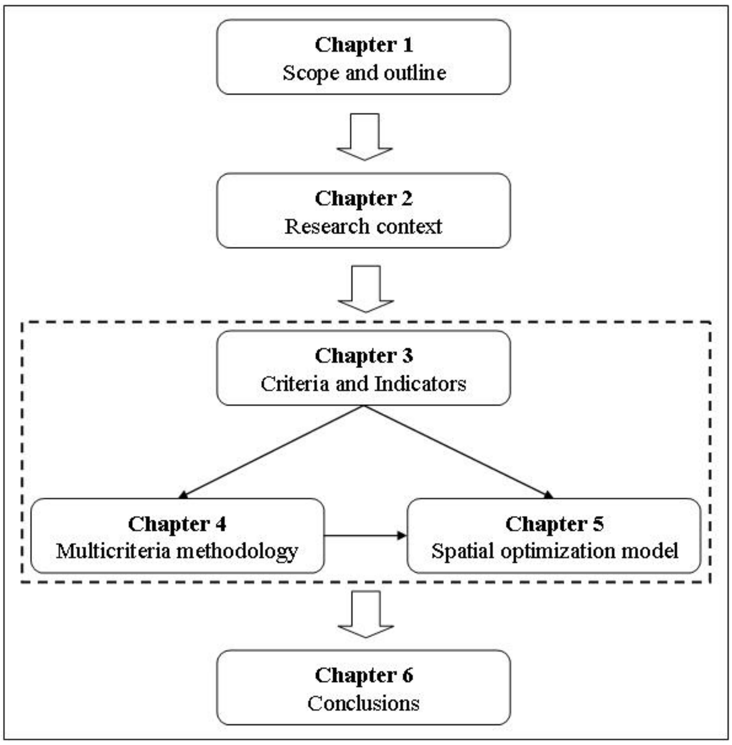

Figure 1.1. The outline of the thesis

Chapter 2

Research context

2.1 Forest Landscape Restoration

In 2000 the International Union for the Conservation of Nature (IUCN) and the World Wildlife Fund (WWF) introduced a novel forest restoration approach called the Forest Landscape Restoration (FLR). By definition the FLR aims to regain the ecological integrity of a forest landscape while enhancing human well-being. With respect to traditional restoration methods, the FLR does not specifically attempt to bring the ecosystem back to a pristine or pre-disturbance state, but rather to build up a forest-based landscape that benefits both nature and people (Maginnis and Jackson, 2002). The FLR founds its roots in a number of concepts that have developed over the last decade of the 20th century. The idea that land management must be undertaken in the framework of ecosystem functioning, the identification of the landscape as the natural region at which ecosystem processes take place and the involvement of several actors as a fundamental requirement for conservation planning had already been stated in the ecosystem approach proposed by the Convention on Biological Diversity (United Nations, 1992). Moving restoration from a site-centred perspective to a landscape-oriented one was also emphasised by Naveh (1994) and the ecoregion approach (Olson and Dinerstein, 1998), adopted by the WWF among others. The FLR is characterised by the following key features: landscape-level view, ecological and socio-economic orientation, stakeholder involvement, optimization of forest functionality (ITTO, 2005a). Restoring at the landscape scale means that forest restoration occurs in a complex context of various elements (social, economic, biological) and that the focus is not simply on enhancing wood cover, but rather on ensuring that a set of functions (habitat, material, etc.) is guaranteed (Mansourian, 2005).

The FLR promotes best practices at the site level that can obtain socio-ecological benefits at the landscape level (Lamb and Gilmour, 2003), because the trade-off between conservation and improvements in human well-being is likely to be better handled at the landscape level (Lamb et al., 2005). How to intervene on a specific site is defined by biophysical and social factors. The degradation level of a forest ecosystem is one of these. Degraded sites can vary from those where most of the original biodiversity, structure and productivity are lost to sites where structure and biomass are largely altered but where some trees are remaining as well as some of the primary forest tree species. Restoration approaches can then range from those merely intended to recover the productivity of the site to those involving a full ecological restoration through which structure, productivity and species diversity of the original forest are reproduced. These forms of restoration can bring different effects on human communities living in the landscape. There can be forms of ecological restoration that dramatically enhance the biodiversity status of an area while bringing no advantages to human well-being, and other forms that ensure an immediate economic output but no significant improvements in the ecological conditions. Both extreme positions are likely to generate negative effects in the long run when the first approach will not be sustaining livelihoods anymore, and the second will start threatening the ecological functioning.

Decisions about what to do must be coupled with decisions about where to do it. The location of restoration interventions is a strategic step of FLR. The choice of where to act first depends on the purpose of the action itself. Conservation biologists have been dealing with the prioritisation issue for years (Margules and Pressey, 2000). Financial and time constraints have encouraged them to protect those areas that are likely to bring the maximum biological benefits at the least cost (Myers, 2000). The case of FLR is a complex one in that restoration sites comprehensively should achieve a number of quite different goals. In this context, a new configuration of the landscape mosaic should be identified in which the location, restoration method and function of each restored site are specified. It is not straightforward to say what is a priority and what is not. For example, from an ecological point of view, riparian areas can be good for protecting stream banks from erosion or giving riparian species a better protection; degraded or unforested areas around protected areas can be suitable for reducing the edge effect; potential corridors between forest fragments can be strategic for supporting species movement. From a socioeconomic point of view, restoring unproductive lands of low expected biodiversity can be a good choice to provide timber and eventually generate income on areas where environmental degradation has brought particularly bad effects on livelihoods.

Restoration literature does not provide some definitive guidelines about where to restore first. In 2000 the World Conservation Monitoring Centre of the United Nations Environment Programme (WCMC-UNEP) reviewed a list of potential criteria out of which the five most suitable ones were selected (WCMC, 2000). According to this document, priority should be accorded to original forest areas which are currently unforested, areas containing woodland which are currently unforested, areas of low population density, areas in close proximity to forests, areas rich in biodiversity. Newton and Kapos (2003) raised a number of relevant issues applicable to a wide range of landscapes, while other studies, which have focused on specific restoration case studies, have provided several case-specific criteria (Cipollini et al., 2005; Marjokorpi and Otsamo, 2006). The issue of where to restore includes a further problem: whether or not the restoration intervention can succeed. This issue is somehow accounted for by the WCMC's list, where the low population density criterion refers to the pressure on natural resources and the subsequent threat to the restoration effort. Feasibility, intended as the 'restorability' of a site (Hobbs and Harris, 2001; Suding et al., 2004), can be epitomized by the following question: should we restore the most degraded areas, which are more in need for restoration or the least degraded areas, where the restoration is more likely to succeed (Newton and Kapos, 2003)? It is actually true that investing considerable amounts of money and human resources into the restoration of extremely degraded sites might be useless. Miller and Hobbs (2007) suggested that the factors affecting the restoration success are of three types: ecological, constraining what is possible to restore, financial, constraining what is realistic to restore and social, constraining what is acceptable restoring. The FLR should tackle the whole spectrum of restoration constraints. Working at the landscape level means that financial resources can be directed to the sites that are expected to bring the most significant ecological and livelihood benefits at the least cost. At the same time, the people-oriented approach would allow communities to have part in the restoration process and prevent the conservation goals from outweighing people's needs.

The FLR is much more than just planting trees; it is a practical way to reconcile nature and human needs by planning restoration areas that return as wide a range of forest functions as possible (Dudley et al., 2005). Across the globe several initiatives have already been conducted to implement FLR in practice that resulted in a series of lessons learned (Dudley and Aldrich, 2007). Moreover, experiences from the past, not labelled as FLR-based initiatives, show that it is possible to restore landscapes for nature and human well-being (Gilmour and Fisher, 1991; Michon and de Foresta, 1997). Despite several reports (Lamb and Gilmour, 2003; ITTO, 2005a) and some books (Barrow et al., 2002; Mansourian et al., 2005) have been written on the FLR, few scientific papers exist in the literature proving that and showing how it is practically possible to build-up the landscape mosaic that benefits both nature and people (Zhou et al., 2008). Demonstrations of how to use advanced spatial decision support tools for FLR implementation are also lacking.

2.2 FLR in marginalised contexts

In 2003 the Millennium Ecosystem Assessment panel conducted a thorough analysis of the connections between the quality of ecosystems and human well-being (Millennium Ecosystem Assessment, 2003). They ended up by emphasising how the degradation of ecosystem services poses a considerable barrier against the achievement of the Millennium Development Goals. Among the main issues is vulnerability: poor people are far more dependent on locally available resources than rich ones and thus much more vulnerable to changes in ecosystem quality (Millennium Ecosystem Assessment, 2003). Several authors have debated whether poverty leads to environmental degradation or environmental degradation fosters poverty, suggesting that market and institutional failures, the level and the ‘type’ of poverty have a role in that (Reardon and Vosti, 1995; Duraiappah, 1998; Scherr, 2000). Reardon and Vosti (1995) classified the types of poverty according to the lack of various assets: natural resource assets, human resource assets, on-farm physical and financial assets and off-farm physical and financial assets. The potential for substitutability among assets affects the relationship between poverty in an asset and household behaviour. Understanding which type of poverty is driving the households’ behaviour is maybe the best way for reducing poverty and protecting the environment (Reardon and Vosti, 1995). While the link between environmental degradation and poverty is widely accepted, there is growing scepticism on the possibility to identify conservation strategies that both protect biodiversity and reduce poverty (Sanderson and Redford, 2003; Sanderson, 2005). Common conservation approaches, strongly based on protected areas, may preclude future land use options, and likely result in most of the conservation costs being paid by local people (Roe and Elliott, 2004). Forest conditions and poverty are tightly connected in marginalised contexts: poverty is often seen as a cause of forest loss and forest loss contributes to maintain or increase poverty (Angelsen and Wunder, 2003). It is actually difficult to develop restoration methods at a particular site that can both protect biodiversity and reduce poverty. Figure 2.1, adapted from Lamb et al. (2005), shows how different restoration approaches can bring different effects in terms of biodiversity improvements and financial and livelihood benefits. Arrow 1 refers to the case of a commercial plantation: it is expected to bring immediate effects on economy and livelihoods but only few positive effects on biodiversity. Arrow 2 on the contrary reflects an intervention specifically aimed at improving biodiversity protection with minimal benefits on the socioeconomic side. Arrows 3 and 4 instead refer to a mix of actions taken over the landscape mosaic that, giving initial priority to one of the two objectives, comprehensively achieve optimal benefits. The FLR, by working at a large scale and diversifying the roles of each portion of the landscape, is expected to put the principle of arrows 3 and 4 in practice. To this extent, its potential towards reducing poverty and protecting biodiversity is significant.

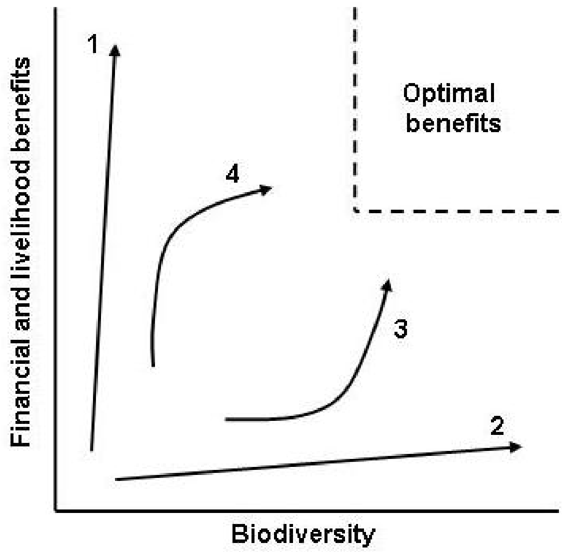

Figure 2.1. Benefits of different restoration approaches. While plantations are expected to bring primarily financial and livelihood benefits (arrow 1) and restoration for biodiversity will bring few positive socioeconomic effects (arrow 2), a restoration approach that uses several options within the landscape mosaic has more possibilities to achieve multiple objectives (arrows 3 and 4) (adapted from: Lamb et al., 2005).

From a planning perspective, the question is, as already suggested in § 2.1, whether it is possible in practice to build-up a landscape configuration whose overall benefits are likely to follow path 3 or 4. To this purpose, there are a number of critical issues that must be taken into account, especially with reference to forest landscapes in marginalised regions:

- Ecosystem services: a thorough analysis of the services provided by the landscape should be carried out to assess the potential for improvements. Through the restoration of strategic areas it is possible to enhance biodiversity protection, service provision and people’s access to natural resources.
- Plantation forestry: plantations can have a strong role in conserving biodiversity (Hartley, 2002). From a spatial point of view they can buffer remnants, thus reducing edge effects, and bridge gaps between forest patches, thus improving connectivity (Norton, 1998).
- NTFPs: today there is a bit of criticism on the fact that the collection of NTFPs is ecologically sound enough to contribute to both conservation and development objectives (Arnold and Ruiz Pérez, 2001). There can be specific areas where the management of NTFPs actually makes the two objectives coincide, but it is not

always so. The problem is that the collection of NTFPs does not occur without impact on the forest. Nevertheless, in many parts of the world their use and commerce is fundamental to sustaining livelihoods.

- Restoration costs: this may vary widely due to ecological conditions and the socioeconomic context. They must be carefully taken into account to see what is realistic to achieve in a reasonable time lag.
- Land use conversion: converting economically strategic land uses (e.g. agriculture) to forest may result in substantial loss of income. Conversions should be undertaken at the extent that a community's economic balance is not impaired.
- Restoration techniques: these are again dependent on the ecological and socioeconomic conditions and may vary substantially. Active restoration, natural regeneration, livestock removal are all techniques that can be applied on the ground according to the local conditions and the specific purpose of intervention.
- Accessibility: natural resources necessary to sustain the livelihood of human communities must be accessible. In rural areas, where people move predominantly by foot, this means paying great attention to the distance of resources from villages: even few kilometres would result in hours of walk. In regions of high conservation value, accessible forest stands for the collection of timber (e.g. plantations) are likely to prevent people from harvesting high-valued primary forest.
- Willingness of locals: this may affect the feasibility of the restoration project and the restoration technique to be applied at a given site. Knowing in advance that a community is willing to actively participate in the restoration project is likely to modify the ranking of restoration priorities.

The above list, though not a complete one, emphasises how many issues may apply to the case of re-shaping landscape mosaics in poor regions. The underlying concept is that the direct linkages between humans and nature are so tight that any decision is likely to bring immediate consequences on nature and society. Some regions of the planet are particularly critical for the occurrence of extremely high biodiversity and widespread poverty.

2.2.1 A specific context: the tropical dry forests of Latin America

Arid and semi-arid areas, which cover nearly 30% of the Earth's surface, present significant problems of environmental degradation due to increasing human pressure (UNDP, 2004). Dryland areas are of global importance for their biodiversity and considerable agricultural biodiversity as the result of historical human activities. Tropical dry forests, defined as forests located in tropical regions undergoing long drought periods (Mooney et al., 1995), are among the most threatened forest types (Janzen, 1988; Trejo and Dirzo, 2000). Being close to large population centres, dry forests have been exposed to disturbances for thousands of years (Murphy and Lugo, 1986). These forests have been harvested primarily for fuel purposes, but not only for that. Plantations have been used for the production of hardwood, which is anyway limited by water availability. Murphy and Lugo (1986) drew a model of dry forest response to human disturbance which is described by the diagram in Figure 2.2. This is mostly an overview of the dynamics involved in the use and degradation of dry forest, and details are likely to change depending on the characteristics (e.g. climate, forest composition) of a specific site.

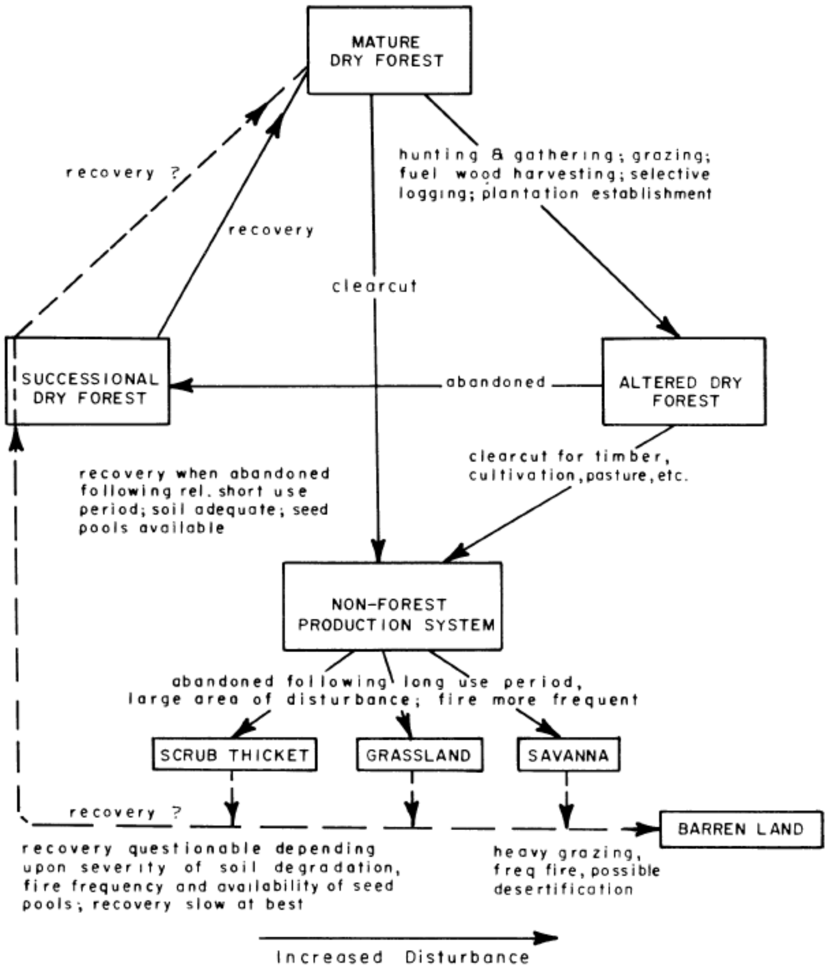

Figure 2.2. The hypothetical response of dry forest to human disturbance (from: Murphy and Lugo, 1986)

Today the major threats to tropical dry forest include: climate change, fire, forest fragmentation and conversion to agriculture. Decrease in precipitation is a threat to existing forest, while it can create suitable conditions for the establishment of dry forest on other areas. Fragmentation may expose existing patches to heavier pressure from the outside. Although fire is a typical element of dry forests, it can become a serious problem when its frequency does not allow forest to regenerate. The conversion to agriculture threatens those areas that are particularly suitable for cultivation. Latin America presents some of the world's largest contiguous areas of tropical dry forest, among which the most extensive ones are located in northeastern Brazil, northern Argentina, southeastern Bolivia and Paraguay (Figure 2.3). Some major areas also occur in Mexico, especially in the Yucatan peninsula, while the distribution is quite fragmented elsewhere (Miles et al., 2006). The dry forests of the region have experienced the greatest percentage decrease between 1980 and 2000, with an estimated 12% loss (Miles et al., 2006). This study focuses on two areas in central and western Chiapas (Mexico). These are characterized by high human population density, the presence of scattered villages and significant poverty patterns. Here tropical dry forest is subject to multiple pressures, particularly related to the expansion of agriculture fields, harvest and overgrazing. These characteristics make the location a very interesting case study for the implementation of FLR.

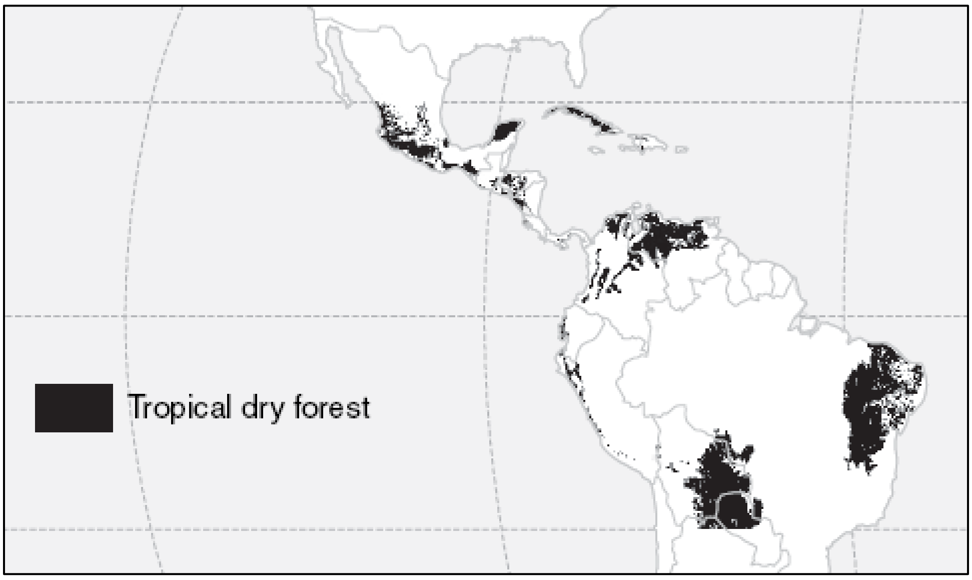

Figure 2.3. Tropical dry forests in Latin America (from: Miles et al., 2006)

2.3 Tools

2.3.1 Multi-Criteria Decision Analysis

The identification of suitable sites for forest restoration is essentially a decision problem. The most widely accepted conceptualisation of a decision process dates back to the early 60's when Simon (1960) divided it into three main stages: *intelligence*, *design* and *choice*. The *intelligence* is about defining the problem, the *design* involves the identification of the available alternatives and the *choice* is aimed at selecting the best alternative. Alternatives are usually evaluated on the basis of criteria. These are standards to test the desirability of alternatives (Hwang and Yoon, 1981) and represent the fundamental values on which a decision is taken (Keeney, 1992). This kind of analysis is often referred to as Multi-Criteria Decision Analysis (MCDA) or simply Multi-Criteria Analysis (MCA).The identification of suitable areas for forest restoration is a spatial problem, in that it is defined over the bi-dimensional space, involving a large set of alternatives that can be evaluated by means of several criteria. This kind of problems are dealt with by coupling MCDA techniques and Geographical Information Systems (GIS) (Carver, 1991; Malczewski, 1999). MCDA techniques can be divided into multiattribute decision analysis (MADA) and multiobjective decision analysis (MODA). While the former involves a predetermined finite set of alternatives, the latter finds the best solution anywhere in the region of feasible solutions (Malczewski, 2006).

Some interesting examples of MADA applications to natural resource management can be found in the literature. Pereira and Duckstein (1993) proposed a method for assessing ecological suitability through the combination of categorical and continuous variables. Kangas et al. (2000) utilised ecological knowledge to evaluate alternative forest plans. Schlaepfer et al. (2002) showed the importance of multicriteria approaches for including ecological, economic and social considerations into sustainable forest management. MADA procedures are typically applied to define management priorities. Geneletti (2004) ranked forest remnants according to their priority for conservation. Cipollini et al. (2005) modelled expert knowledge to prioritise the management of limestone prairies. Marjokorpi and Otsamo (2006) proposed a methodology to find rehabilitation priorities at the landscape scale when considering areas surrounding culturally important forests as the most suitable ones. MADA techniques are often based on simple combination rules such as the weighted summation (Malczewski, 1999) or the Analytic Hierarchy Process (Saaty, 1980), which make the implementation in a GIS environment sufficiently easy. Nevertheless, putting the FLR into practice raises some issues that can be hardly tackled with basic MADA procedures. In particular, alternatives are not known in advance, but the best possible landscape mosaic has to be designed such that a set of conditions are simultaneously satisfied. This means a huge number of alternative solutions to choose from (continuous problem). MODA techniques are based on evolved mathematical techniques (e.g. linear programming, heuristics) that allow continuous problems to be handled. These approaches are commonly referred to as optimization models and encompass three things: decision variables, the objective function and constraints. Solving an optimization problem means finding the alternative that either maximises or minimises the objective function, subject to a set of constraints. Heuristic algorithms are robust techniques that can solve optimization models, but give no warranty that the obtained solution is optimal. Nevertheless, they are widely applied because of their ability to handle non-linear problems and large datasets. When all equations in the model are linear instead, Linear Programming (LP) solvers can be successfully applied and are able to find the optimal solution (Underhill, 1994). Moreover, today the evolution of hardware and software tools has made their application to large datasets fully reliable. Land use allocation problems are generally dealt with by applying a subset of LP known as Integer Programming (IP). Land use allocation is indeed about either assigning a use to a unit (‘yes’) or not (‘no’). IP considers binary integer variables that can assume values of 1, when a unit is assigned that particular use, or 0, when the unit is not assigned that particular use (Wright et al., 1983). This technique calls for one variable to be assigned to each unit of analysis per land use to be allocated. That means thousands of variables when the area is particularly large and the unit of analysis particularly small (e.g. raster cells). That is why most of the early applications of linear programming to allocation problems could only be defined partly spatial (Campbell et al., 1992; Chuvieco et al., 1993). These were actually normal LP-based models that computed the best allocation strategy just in terms of area (e.g. how many hectares of agriculture/pasture/forest to maximize/minimize the objective function and meet all constraints?), and land parcels were assigned a use on the basis of suitability criteria up to the fulfilment of the areas resulting from the optimization model. Today IP-based models are widely applied to allocation problems and conservation planning issues in particular (Rodrigues and Gaston, 2002; Önal and Briers, 2006). The definition of the basic unit of analysis depends on the physical and administrative features of a territory, as well as on the purpose of the analysis. They might be natural divisions (e.g. watersheds) when a territory with clearly defined zones has to be redesigned to improve its overall ecological and/or economic performance (e.g. protected areas). They might be artificial divisions (e.g. raster cells) when new areas have to be shaped or enough freedom is left to planners for redesigning a territory. Even though a cell-based optimization model might theoretically lead to the undesired situation of land uses being scattered across the territory, approaches have been developed to deal with the problem of compactness. Both additional terms added to the objective function (Wright et al., 1983) and the use of ‘impedance’ surfaces (i.e. suitability maps) (Crossman and Bryan, 2006) have proved to be effective in generating compact outputs that fit with the needs and aims of the decision-maker.

In the following chapters MCDA-MADA methods will be referred to as multicriteria analysis (MCA), while MCDA-MODA methods will be referred to as (spatial) optimization models.

2.3.2 Spatial optimization models for socio-ecological problems

Implementing an FLR-based action requires proper models to integrate ecological (e.g. enhancement of biological corridors) and socioeconomic issues (e.g. supplying of timber to human communities). The inclusion of human activities into planning and the optimization of landscape patterns are also a research priority of landscape ecology (Wu and Hobbs, 2002). The inclusion of socioeconomic factors into conservation biology models is not a new concept. Originally it was essentially looked at as an issue of economic feasibility: land should be allocated in a way that minimizes opportunity costs and maximizes the economic benefits. Teeguarden (1981) for example proposed an LP-based method for selecting least-cost sets of wilderness areas to meet a specific allocation goal. In the 90's the maximal covering location problem (Church et al., 1996) was introduced to maximize the number of species included in protected areas subject to limits in the available budget for protection. In the specific field of forestry, much has been done to explore the trade-offs between wilderness protection and timber harvesting (Bettinger et al., 1997; Calkin et al., 2002; Nalle et al., 2004). Recently Polasky et al. (2005, 2008) have thoroughly investigated the design of land management options that sustain both biodiversity and economic returns. The acknowledged concept is that conservation is possible also in 'working lands', that is areas where human communities live. Unfortunately, these applications only account for large-scale economic revenues (e.g. industry or country-level) and largely dismiss the problems related to small-scale local economies. The issue of accessibility to resources, which is crucial in subsistence economies, for example is totally neglected. Therefore these studies are not replicable on marginalised contexts where decisions on the use of local resources are not just expected to cause variations in the economic output, but most probably serious threats to livelihoods. An early modelling attempt to account for the local provision of natural resources is that of Allen (1985). The model, which was applied to a Tanzanian case study, focused on three broad objectives: the efficiency of wood production, the efficiency of labour allocation and the protection of local woodlands. These are some crucial concepts to be incorporated in a model for implementing the FLR. In particular, accessibility, intended as the ease of reaching harvestable forest stands, should play a greater role in re-designing the forest landscape.

Chapter 3

Selection of ecological criteria and indicators for the identification of forest restoration priorities[1]

3.1 Introduction

An urgent question in nature conservation is: where to act first? This is primarily related to concerns of an economic kind: financial resources are limited, hence conservation efforts should focus on areas where interventions will produce the greatest benefits. Conservationists have addressed the prioritisation issue in a variety of ways (Mittermeier et al., 1998; Roberts et al., 2002). For example a biodiversity hotspot is defined as an area with exceptional concentration of endemic species and with high rates of habitat loss, and can be seen as a priority for conserving the most species at the least cost (Myers et al., 2000). Alternatively, species richness, endemism, unusual ecological or evolutionary phenomena and habitat rarity have been used at a global scale to identify ecoregions that should be accorded priority for conservation (Olson and Dinerstein, 1998). Previous research into conservation priority-setting has primarily focused on the design of protected area networks, which may be informed by analysis of the relative vulnerability of different areas to environmental pressures or threats (Wilson et al., 2005). However, relatively little attention has been given to priority-setting in the context of ecological restoration activities.

Ecological restoration refers to the concept of re-establishing the main characteristics of an ecosystem that has been degraded, damaged or destroyed (Jordan et al., 1987), and is usually carried out to enhance the conservation value or productivity of a given area (Hobbs and Norton, 1996). Restoration actions are increasingly being implemented throughout the world (van Andel and Aronson, 2005; Rey Benayas et al., 2009), supported by global policy commitments such as the Convention on Biological Diversity (Article 8f), in response to growing concerns about widespread ecological degradation and habitat loss. Forest ecosystems have received particular attention in this respect (Lamb et al., 2005), reflecting both the widespread extent of the deforestation and the high importance of forests with

[1]This chapter is based on: Orsi, F., Geneletti, D., Newton, A.C. Towards a common set of criteria and indicators to identify forest restoration priorities: an expert panel-based approach *(submitted to Ecological Indicators).*

respect to the maintenance of biodiversity and the provision of ecosystem services to human populations (FAO, 2006). The problem of prioritising forest areas to be restored is a critical one. The identification of priorities depends upon the objectives of the restoration process, which are often multiple and different in nature: enhancing biodiversity, providing local communities with financial and livelihoods benefits, etc. (Lamb and Gilmour, 2003; Mansourian et al., 2005). Different objectives may result in identification of different priority sites, establishment of different tree species and selection of different restoration methods. Approaches are therefore required that are able to account for multiple objectives and enable their potential implications to be explored (Lamb et al., 2005).

Operationally, the objectives driving restoration prioritisation can be linked to a number of criteria that express the degree of achievement of restoration objectives (Kangas and Kangas 2002). With respect to forests, criteria relating to management objectives might usefully be viewed in the context of sustainable forest management (SFM), which has been the focus of an intensive international policy dialogue during the past two decades (Nussbaum and Simula, 2005). Specifically, this has led to the development of a wide variety of different criteria and indicators (C&I) designed to assess progress towards SFM. Criteria may be defined as the essential elements or major components that define SFM (e.g. 'structure and diversity of forest ecosystem resembles original forest'), whereas indicators are qualitative or quantitative parameters of a criterion, which provide a basis for assessing the status of, and trends in, forests and forest management (e.g. 'canopy opening is minimised') (Prabhu et al., 1996). The C&I have been developed under a series of international processes, including ITTO, the Pan-European (or 'Helsinki') Process, the Montreal Process, and the Tarapoto, Lepaterique, Near East, Dry Zone Asia and Dry Zone Africa processes, each of which have generated sets of C&I (Newton, 2007). C&I have found widespread application in the forest sector and they are considered as a useful tool for assessing progress towards SFM (Wijewardana, 2008), as indicated by a substantial literature (Stork et al., 1997; Mendoza and Prabhu, 2003; ITTO, 2005b). Although the C&I processes share similar objectives and overall approach, and provide a valuable source of information on the indicators that are considered important for forests in different regions, most have focused on developing C&I for application at the regional or national level. Only four of the nine processes (ATO, ITTO, Lepaterique and Tarapoto) have produced sets of C&I for application at the local level, which is the level most likely to be of value in supporting practical forest management.

Although forest restoration can be viewed as one of the management options that might contribute to the broader goals of SFM, indicator sets specifically designed for the identification of forest restoration priorities are few. There have been some attempts at defining prioritisation criteria at global and regional levels (WCMC, 2000; Newton and Kapos, 2003). At a more local level, some studies coupling decision analysis and GIS have used small sets of case-specific criteria to identify priorities (Cipollini et al., 2005;

Marjokorpi and Otsamo, 2006). Nevertheless, a ready-to-use list of criteria that restoration practitioners can directly apply in practice is lacking. On the one hand, regional-level criteria are too generic (e.g. potential of a given area to support forest cover) or vague (e.g. areas in close proximity to forests), and few specifications are made regarding how they might be assessed in practice (WCMC, 2000; Newton and Kapos, 2003). On the other hand, local-level criteria are context-specific; their applicability to other contexts has rarely been examined (Cipollini et al., 2005).

Consequently, there is a need for C&I appropriate for prioritising forest restoration actions at local levels, that are readily applicable to different contexts. In order to be useful for the identification of priority sites, C&I should be able to capture spatial variability, given that forest management plans are spatially explicit and are typically developed and implemented using a Geographical Information System (GIS) (Kangas et al., 2000). The development of C&I sets is commonly based on past experience; existing sets are considered and a pool of experts is involved to review and/or develop them (Prabhu et al., 1999). The value of expert knowledge for natural resource management is widely recognised, because it allows decision makers to take decisions when knowledge based on objective observations is not available (Hannah et al., 1998; Burgman et al., 2001; Kangas and Leskinen, 2005; Geneletti, 2007).

Based on these considerations, this chapter aims to provide a contribution towards defining a generally applicable set of criteria and indicators to identify forest restoration priorities for biodiversity conservation. The method is based on surveys and interviews conducted with a panel of experts. The term criterion is used to indicate the general concept (e.g. fragmentation of native forest), while the term indicator is used to refer to an operational way to express or measure a criterion (e.g. edge density, patch density). Both definitions are consistent with SFM C&I processes, such as the Montreal Process (1995). The study was designed to develop criteria and indicators that are applicable to a wide range of ecological contexts and appropriate for use at the landscape scale (i.e. tens to hundreds of square kilometres), at which forest restoration decisions are typically made in practice.

3.2 Methods

Previous studies on the selection of restoration priorities (WCMC, 2000; Newton and Kapos, 2003) simultaneously considered areas where restoration is needed (e.g. owing to the presence of endemic species or threats), and areas where restoration is likely to succeed (e.g. owing to soil conditions). This suggested that C&I should belong to two main groups: those that refer to the need for biodiversity restoration (B), and those that refer to the feasibility of the restoration interventions (F). The first group of C&I is then expected to define where restoration is more urgent for the conservation of biodiversity. The second group is intended to provide an information about the ‘restorability’ of land (Hobbs and Harris, 2001; Suding et al., 2004; Miller and Hobbs, 2007), which is the ecological cost of successfully achieving the restoration goals. Starting from this rationale, a combination of distance surveys and face-to-face meetings with a panel of experts were used to develop a list of C&I linked to B and F.

The Delphi survey technique was used for the distance elicitation. This technique, developed in the early 1950's by the RAND Corporation, is a method for structuring a group communication process in a way that allows individuals to deal with a complex problem (Linstone and Turoff, 1975). Delphi surveys aim to solicit the advice of a panel of experts, and whenever possible to forge a consensus (Richey et al., 1985; Oliver 2002). The approach is based on structured and written questionnaires to which panellists are asked to answer anonymously. All responses are summarised and reported back to panellists who have the opportunity to revise their judgments. Turoff and Hiltz (1996) highlighted the opportunities offered by computer-based Delphi processes and today most Delphi surveys are carried out via the internet. The Delphi technique has been extensively applied to conservation and natural resource management (Crance, 1987; Hess and King, 2002; Oliver, 2002; MacMillan and Marshall, 2006; Geneletti, 2008), but rarely to ecological restoration.

The knowledge elicitation method was structured into two phases: a two-round Delphi survey and a final face-to-face meeting. The Delphi survey, which was entirely managed via email, was based on questionnaires with both open and closed questions. In the first round participants were asked to specify their expertise and draw preliminary lists of C&I. Responses were rearranged by clustering similar criteria, and the reviewed lists were re-distributed to experts. In the second round experts were asked to choose from the lists a limited number of criteria for B and for F and to attach indicators to each of them. The information provided in round two was used to define the final lists of criteria for B and F and to reduce the number of indicators. Anonymity was preserved throughout the Delphi survey. Finally, a face-to-face meeting was held with some of the participants in order to further revise the list of criteria, and solve ambiguities related to the definition of indicators.

3.2.1 Identification of the panel of experts

The experts involved in the Delphi process were identified in three ways: personal knowledge, literature review and project databases. This study was carried out in the framework of an EC-funded research project (ReForLan) involving ten research institutions from Europe and Latin America (Newton, 2008). A group of forest restoration experts involved in ReForLan constituted the primary scientific panel that participated in the survey, which was extended to include their individual networks of contacts of other specialists in the field. A literature review on forest restoration, mostly carried out on international peer-reviewed journals, provided a further list of names. Finally, restoration projects databases, such as the Forest Restoration Information Service (FRIS) of UNEP-WCMC (2008) and that of the Society for Ecological Restoration International (2008), were browsed to obtain names of people who actively conducted forest restoration projects around the world. The definition of the sample was aimed at obtaining varied expertise both in terms of geographical area and habitat type. I contacted via email more than 120 people affiliated with universities, governmental agencies, corporations and private consultants in the five continents.

3.2.2 Delphi survey: round one

The first round included four tasks (see Appendix 1): (i) define the geographical expertise; (ii) define the ecological expertise; (iii) identify C&I that lead to the identification of areas that should be accorded priority for biodiversity restoration; and (iv) identify C&I that influence whether or not restoration is feasible on a particular site. Participants were asked to rank on a four-point Likert scale (with categories 'none', 'moderate', 'good', 'very good') their level of expertise in different geographical regions. Participants were then asked to specify their ecological experience by ranking on the same four-point scale their level of expertise in different habitat types. The classification of forest habitats proposed by the FRIS was employed for this purpose. Tasks 3 and 4 referred to factors B and F respectively and were similarly structured. Experts were asked to identify criteria, to specify why these were considered important, and to attach one or more indicators to each criterion. Experts were given the possibility to comment on each of the four tasks of the questionnaire.

The questionnaire was accompanied by a one-page description of the project and its purposes. Particular attention was given to the definition of C&I and to the rationale of the method with reference to B and F. Regarding indicators, it was specified that an indicator must: (i) show a clear relationship between their levels and related consequences; (ii) be measurable over the bi-dimensional space; and (iii) show a direct relationship with the broad factor (B or F) they refer to.

The set of indicators related to a given criterion was expected to fully describe it, by providing a comprehensive description of its contribution to the broad factor (B or F) it refers to.

3.2.3 Delphi survey: round two

In the second round, participants were presented with the lists for B and F that resulted from round one (see Appendix 2). The lists were generated after processing the results of the first round. In particular, semantic clusters of criteria were obtained following a two-step process. Firstly, criteria defined by similar wording or synonyms were aggregated. Secondly, a further aggregation was carried out by bringing together criteria that, although defined by non-synonymic words, had the same meaning according to the comments provided by experts. Criteria or indicators not complying with the definitions provided were disregarded.

Participants were asked to select up to eight criteria each from the B and F lists. For each criterion, they were also asked to select up to three indicators. As in the first round, experts were given the opportunity to provide comments and remarks.

3.2.4 Face-to-face meeting

The people involved in the final face-to-face meeting were the experts of the ReForLan project, during a project workshop in Salta (Argentina) in May 2008. The meeting, which started from the definitive lists of criteria resulting from the Delphi process, was primarily aimed at refining the list of indicators, by making sure that they are all actually measurable and none are redundant. A meeting was preferred to a further Delphi round as it was considered to be a more effective and immediate process. Experts were provided with the definitive lists of criteria that emerged from the second round of the Delphi. The selection of criteria was based on a quantitative analysis of consensus: only criteria selected by a minimum rate of participants in round two of the Delphi were considered. For each criterion, all of the indicators selected at least once during round two were presented to experts. The preference rate accorded to each indicator during round two was also provided. Experts were now asked to define for each criterion the set of indicators necessary and sufficient to completely define that criterion. For this purpose, the indicator requirements provided in the questionnaires were considered as the fundamental guidelines. Experts were free to revise indicators if they did not entirely satisfy the above requirements.

3.3 Results

3.3.1 Delphi survey: round one

Round one was completed by 37 people (response rate: 30.8%). Table 3.1 reports the assessment of geographical and ecological expertise as structured in the questionnaire. Europe, North America and Latin America were the best known regions among experts. With respect to habitats, there were three types (Temperate continental, Temperate mountain, Tropical mountain) on which more than 50% of experts possessed some knowledge and twelve with a knowledge ranging from around 27 to 50%.

Table 3.1. Geographical and ecological expertise of the participants. Numbers represent the percentage of respondents who have a certain level of expertise in a particular geographical area or habitat. Total number of respondents was 37.

	Level of expertise [% of the total respondents]			
	None	Moderate	Good	Very good
Geographical region				
Europe	51.35	24.32	10.81	13.51
North America	43.24	27.03	10.81	18.92
Caribbean	86.49	8.11	5.41	0.00
Latin America	45.95	10.81	8.11	35.14
Africa	72.97	13.51	10.81	2.70
Asia	64.86	10.81	8.11	16.22
Middle East	91.89	8.11	0.00	0.00
Oceania	81.08	8.11	2.70	8.11
Forest habitat				
Boreal coniferous forest	67.57	8.11	5.41	18.92
Boreal mountain	72.97	5.41	13.51	8.11
Boreal tundra woodland	75.68	8.11	13.51	2.70
Temperate continental forest	16.22	32.43	24.32	27.03
Temperate mountain	37.84	21.62	10.81	29.73
Temperate oceanic forest	62.16	10.81	2.70	24.32
Temperate steppe/prairie	51.35	29.73	8.11	10.81
Subtropical desert	72.97	21.62	2.70	2.70
Subtropical dry forest	67.57	16.22	5.41	10.81
Subtropical humid forest	64.86	10.81	16.22	8.11
Subtropical mountain	67.57	10.81	18.92	2.70
Subtropical steppe	89.19	8.11	2.70	0.00
Tropical desert	83.78	13.51	2.70	0.00
Tropical dry forest	51.35	16.22	21.62	10.81
Tropical moist deciduous forest	59.46	10.81	16.22	13.51
Tropical mountain	48.65	13.51	16.22	21.62
Tropical rain forest	51.35	16.22	13.51	18.92
Tropical shrubland	70.27	18.92	8.11	2.70
Mangrove	78.38	13.51	5.41	2.70

Experts listed 205 indicators for the B factor and 184 for the F factor. These were grouped into 20 and 18 clusters respectively, according to different criteria as shown in Tables 3.2 and 3.3, which summarise the responses to tasks 3 and 4. The list for the F factor is divided into ecological criteria (10) and socioeconomic criteria (8). 345 indicators were proposed for the B factor, and 324 for the F factor. Slightly fewer than 50% of them were discarded for not meeting the requirements that had been specified in the instructions attached to the questionnaire. The number of indicators per criterion varied from only one (e.g. historically forested area) to 18 (e.g. diversity at the species level).

Table 3.2. Criteria and indicators for the B factor, which refers to the need for biodiversity conservation. Criterion names represent the clusters of synonymic criteria as provided by experts, while indicators include all those related to a given criterion that were consistent with the instructions provided.

Criteria	Indicators
Climatic conditions	Humidity; precipitation; temperature
Connectivity-corridors	Amount of interior habitat within a unit; corridor length; corridor width; distance from protected sites; linkages between habitat units; presence or absence of wild areas connected to the restoration area; types of linkages
Degree of threat	Area with threatened species; number of red list species; presence or absence of red list species; % of endangered forest; % of remained forest
Disturbance	Amount of area logged (ha); area of vegetation type after disturbance/area of vegetation type before disturbance; area/perimeter; density of steam crossings; distance from roads; disturbance classification; number of people depending upon the ecosystem; number of people living within the ecosystem; Natural Disturbance Type (NDT) classification; road density; % of agricultural area; % of area logged by slope class; % of invasive species; % of populated area
Diversity (ecosystem and landscape level)	Altitudinal variation; amount of dead wood; amount of deciduous trees; azimuthal variation; canopy cover; diversity of soil; landscape functional diversity; landscape structural diversity; presence or absence of diverse ecosystems at the landscape scale; presence or absence of water; quality of dead water
Diversity (species level)	Abundance; age; Beta diversity; evenness; Fisher's Alpha; forest density; number of birds; number of endemic species; number of interactions among species; number of keystone species; number of keystone species lost; number of major vegetation types; number of native species / number of exotic species; number of TER species; presence or absence of non-game species; Shannon diversity; species richness; % live/dead (mortality)
Diversity (genetic level)	Adaptive traits; canopy cover; genetic diversity among population; isozymes; number of stems per hectare by size class; neutral markers; nuclear inheritance; species-specific microsatellites
Ecosystem services	Carbon sequestration/productivity; distance from water; elevation; slope; soil retention (mass/ha); water provision (yield)
Fragmentation	Area of the fragments; core area; forest patch density; isolation; number of fragments; proximity; representativeness of the ecosystem in the world
Habitat availability	% ecosystem type by habitat type by watershed (500-5000 ha) (fine filter); % ecosystem type by habitat type by region (medium filter); % habitat type by region (coarse filter)
Historically forested area	Areas that were historically forested
Landscape degradation	Deforestation rate; fire frequency; frequency of landslides; land use change (%); pollution indices; road density; soil erosion; volume of sediment-debris
Protected areas	Distance from protected areas; presence or absence of protected areas
Rarity	Presence or absence of rare species; representation of biotype in the broader landscape; uniqueness index
Recreation	Amenity value; number of people visiting the area; visual impact assessment
Remnants	Amount of primary and secondary forest at varying distances; distance form edge of forest; distance from forest of certain size; distance from remnant vegetation; distance from seed sources; presence or absence of adjacent areas with land use types suitable for restoration; presence or absence of remnant vegetation; presence or absence of seed dispersers; tree and shrub density
Size	Area; area needed for restoring a vegetation type
Soil conditions	Nitrogen soil content; Organic matter content of upper soil horizon; Phosphorous soil content; soil macrofauna abundance; soil respiration; soil texture
Vegetation structure	Height distribution; horizontal structure: coarse woody debris-amount, size, level of decay; plant – strata diversity; structural stage; tree diameters; vertical structure: plant species composition, snags/wildlife trees-level of decay, cavity trees
Water ecosystem	Alkalinity; bank height; channel depth; channel width; dissolved O_2; distance from large rivers; hardness; length of water courses in the restoration areas; peak flow; pH; water clarity; wetness index; width of active floodplain

Table 3.3. Criteria and indicators for the F factor, which refers to the feasibility of restoration interventions. Criterion names represent the clusters of synonymic criteria as provided by experts, while indicators include all those related to a given criterion that were consistent with the instructions provided.

Criteria	Indicators
Ecological	
Accessibility	Distance from centres of appropriate capacities; distance from transport infrastructures; distance from cities; geomorphology; number of available vehicles; type of roads; type of vegetation
Climate	Climate change parameters; rainfall; relative humidity; wind
Degradation levels	Amount of old-growth trees; amount of remnant vegetation; amount of seed dispersers; compaction; erosion of topsoil; number of pioneer species; number of remnant tree species; nutrient depletion; soil fertility; species richness
Disturbance	Amount of herbivores; fire frequency; land use; livestock data; number of invasive species; people per Km^2; presence or absence of invasive species; presence or absence of noxious weeds; presence or absence of pests and diseases in the region; regeneration ability of invasive species; road density; type of livestock
Forest characteristics	Calliper – diameter; diversity; historical forest composition and structure; Landscape Biological Survey of Vegetetion (LaBiSV); number of exotic species; number of forest patches; number of stems per hectare by size class; patch distribution; presence or absence of desired plant species; presence or absence of mycorrhizae; presence or absence of old growth forest; presence or absence of secondary forest; species richness; tree height; uneven-aged / even aged forest; % live / dead; % threatened plants; % tree - plant species composition as a deviation from a baseline such as site series or late-seral plant community
Land use conflicts	Differential land cover use transformation rates; land use; landscape development plans; presence or absence of abandoned lands; presence or absence of private properties; presence or absence of utilities (power lines, etc.); suitability of land for alternative land uses; transformation matrix for each land cover type
Natural regeneration potential	Distance from natural forest; distance from protected areas; distance to seed sources; growth potential; number of birds; number of seed trees and shrubs; pests and diseases adaptability; presence or absence of minimal biotic structures; presence or absence of biological corridors; presence or absence of unique genetic variants at populations using neutral markers, such as isozymes, microsatellites or DNA sequences; rhizomes and root material; seedling density; survival capacity; syndromes classification of the landscape unit; wind direction; % of species with different dispersal modes
Size of habitat	Area; number of fragments
Soil	Acidification of the substrate; altitude; aspect; bedrock type; bulk density; cation exchange capacity; compaction; concentrations of heavy metals; concentrations of pesticides; daily and annual temperature fluctuation; depth; erosion; fertility; microbial communities; organic matter (%); pH; plant-available Phosphorous; precipitation; presence or absence of toxic chemicals; presence or absence of toxins; slope; slope below 35 %; soil type; structure; total Nitrogen
Water availability	Annual precipitation; aridity and humidity index; distance from rivers; elevation above the average groundwater level; field capacity of the soil; infiltration rate; precipitation distribution; soil depth
Socioeconomic	
Economic sustainability	Amount of food provided; amount of wood provided; number of economically important species; price of products
Forest governance	Inspections; laws and regulations
Land ownership	Area of ownership; pattern of land ownership and tenure; public or private owner
Monitoring	Amount of funds; partnerships
Political will	Amount of incentives; amount of resources invested; number of institutions involved; presence or absence of incentives; subsidies or fines to stimulate or discourage restoration activities
Restoration costs	Area to be restored; cost of fences; economic value of land; labour cost; monetary cost; perimeter; seedling production cost
Technical knowledge	Presence or absence of technical information
Willingness of locals	Amount of community investment; degree of interest; number of NGOs working in the area; number of people interested; number of programs of environmental education

3.3.2 Delphi survey: round two

Round two was completed by 30 people out of the initial 37 (response rate: 81.1%). Histograms for B and F were drawn to show the rate of consensus of experts on each criterion (Figure 3.1). The histogram for F was divided into two by distinguishing between ecological (Fe) and socioeconomic criteria (Fs). The histogram for B shows two criteria (disturbance and degree of threat) with very high accorded preference (more than 70%) and another four criteria (diversity at ecosystem/landscape level, diversity at species level, ecosystem services, landscape degradation) with preference equal or above 60%. The histogram for Fe shows four criteria (land-use conflicts, degradation, disturbance, natural regeneration potential) with a preference of 50% or more, with all others being largely below that percentage. Similar results were obtained with the histogram for Fs, where land ownership, political will, restoration costs and willingness of locals had a preference rate significantly higher than 50%. The results were used to construct curves that show, in a cumulative fashion, the relationship between the number of criteria and the rate of experts that agreed on those criteria (Figure 3.2). This allows identification of suitable cut-off thresholds to select the criteria most agreed upon. The curve for B has a steep trend with few steps. Using a 50% cut-off threshold, eight criteria are selected, which is equivalent to the number of criteria that were originally presented to experts. The inclusion of further criteria would require the threshold to be significantly lower (around 40%), while a slightly higher threshold would result in one or two criteria to be disregarded. Curves for F have a step-wise trend, making the analysis more straightforward. Regarding Fe, a 55% threshold is the best choice: it allows for the inclusion of four criteria. Regarding Fs, a 60% threshold is the best choice, with four criteria included. In both cases, inclusion of some additional criteria would require the threshold to be considerably lowered (i.e. up to 30%), while a higher consensus (e.g. + 15%) would dramatically reduce the number of criteria selected. In any case, the selection of criteria for Fe and Fs was far easier in that a clear divide was visible; four criteria were accorded a significant higher preference than all the others.

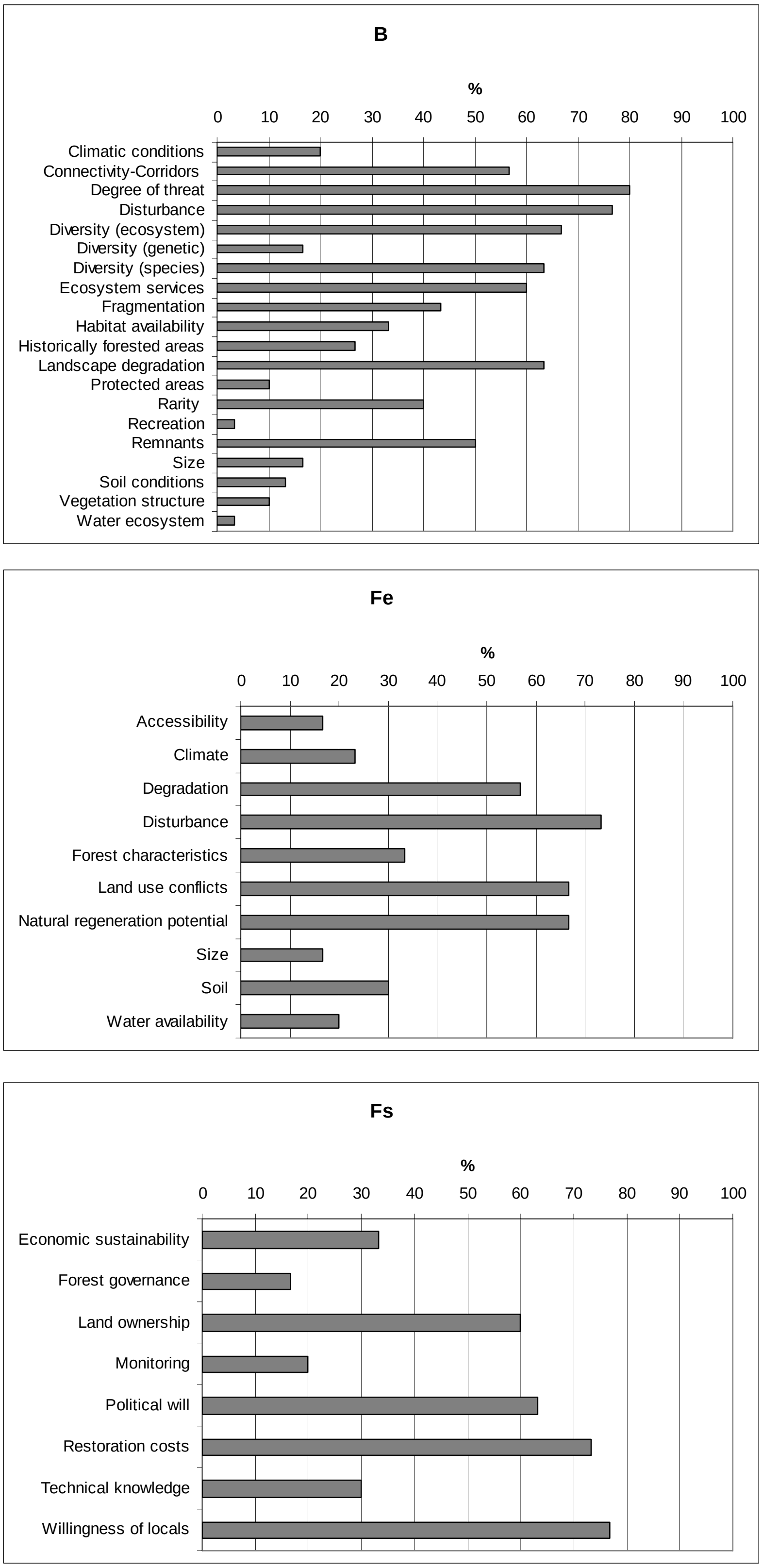

Figure 3.1. Histograms for B and F showing the citation rate for all criteria. The histogram for F is divided in two: ecological criteria (Fe) and socioeconomic criteria (Fs).

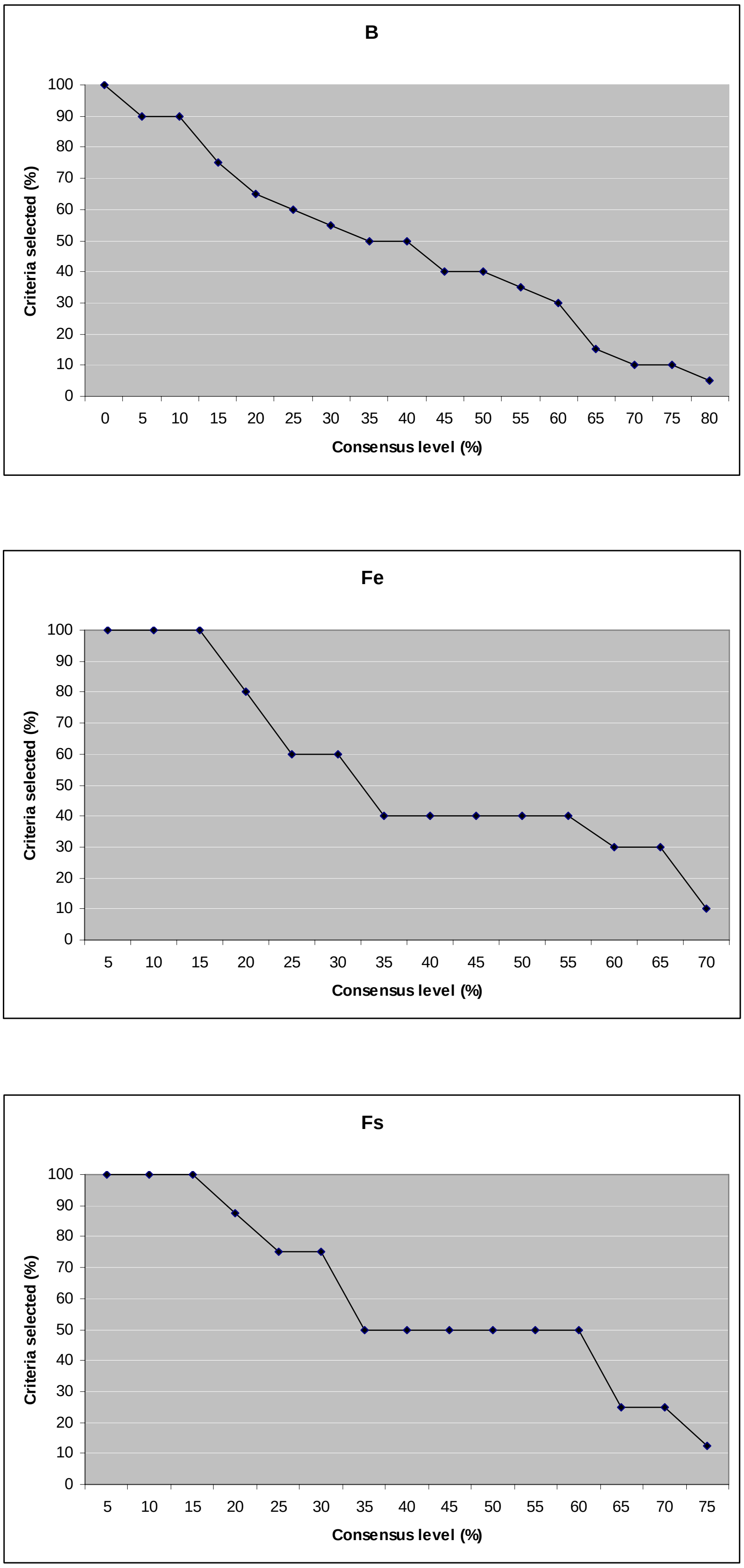

Figure 3.2. Percentage of criteria selected as a function of the consensus level

Comments provided by experts encouraged the decision of moving some criteria from a list to another. In particular, ‘ecosystem services’, ‘land use conflict’ and ‘recreation’ were moved to Fs, ‘remnants’ was joined to ‘natural regeneration potential’ in Fe, ‘degree of threat’ to ‘disturbance’. As the analysis is focused on ecological issues, socioeconomic criteria were not considered in the subsequent parts of the chapter. Therefore, socioeconomic criteria are not included in Table 3.4, which presents the definitive list of ecological criteria.

Table 3.4. The final sets of criteria: the list for F only reports ecological criteria. Consensus thresholds of 50 and 55 % were used for selecting criteria related to the B and F factor respectively

B	F
Connectivity-corridors	Degradation
Degradation	Disturbance
Disturbance	Natural regeneration potential
Diversity (landscape/ecosystem level)	
Diversity (species level)	

Table 3.5 and 3.6 show the selected indicators with indication of the intra-criterion citation rate, namely the percentage of respondents who selected that specific indicator among the respondents selecting the related criterion. As an average, each criterion was linked to 11 indicators. ‘Connectivity-corridors’ and ‘degradation (B)’ presented the lowest number of criteria (6), while ‘diversity (species level)’ presented the highest (17). The citation rate was highly variable within each criterion. Only four indicators were selected by at least 70% of experts: land use change, linkages between habitat unit, landscape structural diversity, and amount of remnant vegetation. Most indicators had citation rates between 10 and 40 %.

Table 3.5. Indicators for the B factor as selected by experts. The citation rate is the percentage of respondents who selected a given indicator out of those who selected the related criterion.

Criteria	Indicators	Citation (%)
Connectivity-corridors	Linkages between habitat units	70.59
	Presence or absence of wild areas connected to the restoration area	52.94
	Amount of interior habitat within a unit	47.06
	Distance from protected sites	29.41
	Corridor length	23.53
	Corridor width	23.53
Degradation	Land use change	89.47
	Deforestation rate	47.37
	Fire frequency	36.84
	Soil erosion	36.84
	Road density	21.05
	Pollution indices	5.26
Disturbance	Disturbance classification	65.22
	N. of people depending upon the ecosystem	47.83
	Area of vegetation type after disturbance/area of vegetation type before disturbance	43.48
	Amount of area logged	21.74
	% of invasive species	21.74
	N. of people living within the ecosystem	13.04
	Natural Disturbance Type (NDT) classification	13.04
	% of agricultural area	13.04
	% of populated area	13.04
	Area/perimeter	8.70
	Distance from roads	8.70
	Road density	8.70
	% of area logged by slope class	4.35
Diversity (ecosystem/landscape level)	Landscape structural diversity	70.00
	Landscape functional diversity	60.00
	Canopy cover	40.00
	Presence or absence of diverse ecosystem at the landscape scale	30.00
	Diversity of soils	20.00
	Presence or absence of water	20.00
	Altitudinal variation	15.00
	Amount of deciduous trees	10.00
	Amount of dead wood	5.00
	Azimuthal variation	5.00
	Quality of dead wood	5.00
Diversity (species level)	N. of endemic species	57.89
	Beta diversity	52.63
	N. of keystone species lost	47.37
	Species richness	47.37
	N. of keystone species	42.11
	N. of major vegetation types	26.32
	Abundance	10.53
	Age	10.53
	Forest density	10.53
	N. of native species / N. of exotic species	10.53
	Evenness	5.26
	Fisher's Alpha	5.26
	N. of birds	5.26
	N. of interactions among species	5.26
	N. of TER species	5.26
	Shannon diversity	5.26
	% live / dead	5.26

Table 3.6. Indicators for the F factor as selected by experts. The citation rate is the percentage of respondents who selected a given indicator out of those who selected the related criterion.

Criteria	Indicators	Citation (%)
Degradation	Amount of remnant vegetation	76.47
	Erosion of topsoil	47.06
	Amount of old-growth trees	41.18
	Compaction	35.29
	N. of remnant tree species	35.29
	Species richness	29.41
	Amount of seed dispersers	17.65
	N. of pioneer species	17.65
	Soil fertility	17.65
	Nutrient depletion	11.76
Disturbance	Land use	59.09
	Fire frequency	45.45
	Amount of herbivory	40.91
	People/km^2	36.36
	Livestock data	22.73
	Presence or absence of invasive species	22.73
	Regeneration ability of invasive species	22.73
	Road density	22.73
	N. of invasive species	9.09
	Presence or absence of pests and diseases in the region	9.09
	Presence or absence of noxious weeds	4.55
	Type of livestock	4.55
Natural regeneration potential	Survival capacity	45.00
	Distance from natural forest	40.00
	Growth potential	30.00
	Presence or absence of biological corridors	25.00
	Distance to seed sources	20.00
	Presence or absence of minimal biotic structures	20.00
	Seedling density	20.00
	N. of seed trees and shrubs	15.00
	Presence or absence of unique genetic variants	15.00
	Rhizomes and root material	15.00
	Distance from protected areas	10.00
	N. of birds	10.00
	Syndromes classification of the landscape unit	5.00

3.3.3 Face-to-face meeting

The face-to-face meeting gave participants the possibility to actively discuss the indicators resulting from the Delphi process and to improve them. The meeting lasted approximately four hours and involved six individuals, whose expertise is shown in Table 3.7. Experts considered one criterion at a time and remodelled or simply selected the indicators of Table 3.5 and 3.6 in order to provide the sets that are likely to fully assess the contribution of each criterion to B or F. The final list (Table 3.8) encompasses 22 indicators: 14 for B and 8 for F. Each criterion is associated with not more than three and not less than 2 indicators. Some indicators are exactly the same as in Table 3.5 and 3.6 (e.g. 'road density'), some are slightly different (e.g. 'distance from nearest forest patch' instead of 'distance from protected sites') and some are completely different (e.g. 'predicted deforestation risk'). With respect to the B factor, the criterion 'connectivity-corridors' is described by three indicators, which reflect those resulting from the Delphi process: the concepts of corridor length and interior habitat (B.1.1), distance from forest (B.1.2) and fragmentation (B.1.3) are emphasised. Indicators for the criterion ‘degradation’ strongly differ from those of the Delphi process, except in that they consider the concepts of deforestation and land use change (B.2.2). The indicators proposed for the criterion ‘disturbance’ and ‘diversity at ecosystem/landscape level’ entirely reflect those resulting from the Delphi process. Two indicators, ‘species richness’ and ‘presence of threatened species’, were considered to be sufficient to assess diversity at the species level. Participants also specified that ‘presence of threatened species’ should be evaluated as a probability of having threatened species on a site (e.g. produced through modelling species distribution) or as a distance from the location of a threatened species. With respect to factor F, two indicators were specified for the criterion ‘degradation’ that deal with the issues of erosion (F.1.1) and density (F.1.2). The latter can be assessed through satellite remote sensing data such as MODIS. Indicators for ‘disturbance’ deal with the already stressed issues of invasive species and livestock pressure and added a new one: predicted risk of deforestation. Finally, for ‘natural regeneration potential’, the concept of a forest ‘remnant’ is able to summarise a range of information (i.e. distance from forest, seed sources, etc.), while emphasis is given to the problem of climate and vegetation type, the latter referring to early successional stages.

Table 3.7. Geographical and ecological expertise of the participants in the face-to-face meeting. Numbers represent the percentage of participants who have a certain level of expertise in a particular geographical area or habitat. Total number of participants was 6

	Level of expertise [% of the total participants]			
	None	Moderate	Good	Very good
Geographical region				
Europe	50.0	16.7	0.0	33.3
North America	50.0	50.0	0.0	0.0
Caribbean	83.3	16.7	0.0	0.0
Latin America	0.0	0.0	16.7	83.3
Africa	66.7	16.7	16.7	0.0
Asia	66.7	16.7	16.7	0.0
Middle East	83.3	16.7	0.0	0.0
Oceania	66.7	33.3	0.0	0.0
Forest habitat				
Boreal coniferous forest	66.7	0.0	33.3	0.0
Boreal mountain	66.7	16.7	16.7	0.0
Boreal tundra woodland	66.7	33.3	0.0	0.0
Temperate continental forest	16.7	50.0	16.7	16.7
Temperate mountain	50.0	33.3	0.0	16.7
Temperate oceanic forest	50.0	16.7	0.0	33.3
Temperate steppe/prairie	66.7	16.7	16.7	0.0
Subtropical desert	50.0	33.3	0.0	16.7
Subtropical dry forest	50.0	16.7	0.0	33.3
Subtropical humid forest	50.0	16.7	16.7	16.7
Subtropical mountain	50.0	16.7	16.7	16.7
Subtropical steppe	66.7	33.3	0.0	0.0
Tropical desert	66.7	33.3	0.0	0.0
Tropical dry forest	33.3	33.3	33.3	0.0
Tropical moist deciduous forest	50.0	16.7	16.7	16.7
Tropical mountain	33.3	16.7	0.0	50.0
Tropical rain forest	33.3	33.3	33.3	0.0
Tropical shrubland	50.0	50.0	0.0	0.0
Mangrove	83.3	16.7	0.0	0.0

Table 3.8. The final sets of criteria with related indicators. Criteria are the same as reported in tables 5 and 6, while indicators are those refined by experts during the face-to-face meeting

Criteria	Indicators
B.1 Connectivity-corridors	B.1.1 Corridor length connected with the interior habitat
	B.1.2 Distance from nearest forest patch
	B.1.3 Edge density
B.2 Degradation	B.2.1 Patch area
	B.2.2 Previously forested area
	B.2.3 Successional stages
B.3 Disturbance	B.3.1 Distance to towns
	B.3.2 Population density
	B.3.3 Road density (distance to roads)
B.4 Diversity (ecosystem/landscape level)	B.4.1 Aspect heterogeneity
	B.4.2 Elevation heterogeneity
	B.4.3 Land cover heterogeneity
B.5 Diversity (species level)	B.5.1 Presence of threatened tree species
	B.5.2 Tree species richness
F.1 Degradation	F.1.1 Erosion risk
	F.1.2 Tree density
F.2 Disturbance	F.2.1 Invasive species
	F.2.2 Livestock grazing pressure
	F.2.3 Predicted deforestation risk
F.3 Natural regeneration potential	F.3.1 Climate
	F.3.2 Distance from remnants
	F.3.3 Vegetation types

3.4 Discussion

This chapter has provided a set of generally applicable C&I that could potentially be used to prioritise areas for forest restoration. These have been designed for implementation at the level of individual landscapes, which is the level at which forest management decisions are typically made. The C&I could be of direct value in supporting the implementation of policy initiatives focusing on the restoration of forest landscapes (Mansourian et al., 2005), by enabling resources to be targeted on those areas where positive outcomes are most likely to be achieved. This development of C&I also directly addresses one of the policy-relevant ecological issues recently identified as a priority by a consortium of scientists and decision-makers in the UK (Sutherland et al., 2006), namely how to decide which areas should be prioritised for restoration.

One of the problems that has characterised the development of ecological C&I relating to forests is the difficulty of ensuring that they can be operationalised (Newton and Kapos, 2002; Newton, 2007). Many indicators that have been proposed previously are difficult or even impossible to measure meaningfully, limiting their practical value. An example is provided by the concept of 'authenticity', which has featured in the discourse relating to forest landscape restoration as a way of describing the 'quality' of forest habitat (IUCN/WWF, 1999; Mansourian et al., 2005). As noted by Newton (2007), the concept of authenticity is very difficult to operationalise because it incorporates vaguely defined terms such as 'a balanced ecology' and 'a full range of species' within its definition, which themselves are difficult to measure. In this study, a particular effort was made to ensure that the sets of indicators developed could be readily operationalised, which was achieved through the expert consultation process (particularly the face-to-face meeting). The final shortlist presented here (Table 3.8) therefore provides the basis for developing ready-to-use tools to support restoration planning. Further research might usefully be undertaken to apply these C&I to real-world situations, to evaluate their practicality and usefulness.

Most of the proposed indicators meet the criterion of easy measurability suggested by Dale and Beyeler (2001), though some of them (e.g. 'land cover heterogeneity') leave room for different interpretations about practical measurement techniques. Some indicators also predict changes that can be averted by management actions (e.g. 'distance to towns', 'road density'), some have a known response to disturbances, anthropogenic stresses and changes over time (e.g. 'edge density'), while the indicators referring to 'diversity' are integrative, in that the full suite provides an assessment of the system at different scales of concern (Dale and Beyeler, 2001). Moreover, the double-level (ecosystem and species) description of the diversity criterion accounts for coarse and fine-filter conservation strategies, thus allowing a mesofilter approach to be potentially implemented (Hunter, 2005). One of the main advantages of the proposed indicators is their spatial character: all are expected to show variability over space, enabling them to be used in support of landscape planning activities. With access to appropriate data, the indicators could be mapped using basic GIS operations (e.g. distance calculation), facilitating their calculation and enhancing their practical value (Aspinall and Pearson, 2000; Newton and Kapos 2002). However, some extra work is needed on some indicators (e.g. 'climate') that do not fully meet the expected requirements and, at present, are just relevant parameters rather than proper indicators ready to be applied.

Although a shortlist of relatively tractable C&I was successfully developed using the approach adopted here, it is important to recognise the variation in responses received from the experts who were consulted. The experts initially provided a large number of criteria, which needed to be grouped into cognate areas in order to make them manageable for the purpose of the study. This diversity in responses partly arises from the ambiguity associated with many of the terms and concepts used in restoration ecology, which has been recognised as a general problem in ecological science (Peters, 1991; Starzomski et al., 2004). The use of a consensus threshold to decide whether a criterion should or should not be included can be criticised because it considers one criterion at a time, rather than the set of criteria as a whole. However, when considering the results of this study, it can be noted that the concepts underlying the disregarded criteria are partly embedded in the selected ones,.For example, 'fragmentation' is partly described by 'connectivity-corridors', 'historically forested area' is included in 'degradation', 'forest characteristics' are stressed by both 'degradation' and 'natural regeneration potential' and 'soil' refers to issues partly taken into account by 'degradation'. Another source of variation in the responses received reflects the different values held by the experts consulted. This is illustrated by the fact that only ten of the 88 indicators analysed (i.e. 11%) were cited by more than 50% of respondents. To a degree, this illustrates the complexity of the problem; a relatively large number of indicators could reasonably be taken into account when prioritising areas for restoration. However, as noted by Tacconi (2000), any conservation research or management action is influenced by the values held by those involved, and the values held by a researcher will influence an individual conception of a problem and its interpretation. Restoration actions can therefore be considered similar to other forms of natural resource management, where no single perspective is necessarily complete, and no single solution is likely to be optimal (Lal et al., 2001).

In such circumstances, an integrated approach to resource management is required, in which the views of different stakeholders are explored and taken into account. Clearly, the ecological C&I identified here would constitute only an element of such an approach; prioritisation of areas for restoration should also include socio-economic as well as ecological criteria and incorporate the range of perspectives held by different stakeholders (Mansourian et al., 2005). However, the current results highlight the diversity of views and values held even within a single group of stakeholders, namely the ecological research community. The integrated management perspective (Lal et al., 2001) arguably also militates against the development of a generally applicable set of C&I for forest restoration. Proposals for developing generally applicable (or 'core') sets of indicators have been made for SFM (Castañeda, 2000) and for biodiversity indicators more generally (Newton and Kapos, 2002). A recent review of progress in C&I for SFM (Wijewardana, 2008) highlighted the value of rationalising indicator sets, to improve their applicability and usefulness. At the very least, therefore, the final set of C&I produced here could provide a useful tool for eliciting stakeholder views on the relative importance of the different criteria, during development of a forest restoration initiative. The results presented here also provide an indication of the degree of consensus that exists (or does not exist) within the scientific community active in forest restoration research. However, the proposed C&I could potentially be rationalised further, by exploring their practical application in real-world case studies, using approaches such as those described by Lundquist and Beatty (1999), Stoddard et al. (2008) and Kumar et al. (2009).

One of the key contributions of the current study relates to the methods used. Although other studies have proposed criteria that might be used to prioritise areas for forest restoration (Newton and Kapos, 2003; Marjokorpi and Otsamo, 2006), this is the first to employ the Delphi technique. The value of the Delphi in supporting natural resource management is widely recognised (Gokhale, 2001; Eakin et al., 2007) and its integration with face-to-face discussions can be of particular value in clarifying complex issues (Katzenbach and Smith, 1993; Gokhale, 2001). The main concern was to obtain reliable results over an acceptable timescale. An approach entirely based on the Delphi technique would have needed at least one further online round, resulting in loss of participants and eventually credibility of the results. Thus, the proposed approach was a two-stage one. The Delphi process was used to define the definitive sets of criteria and a sample of indicators from which participants could start to elaborate definitive sets of indicators. The approach was satisfactory in that the Delphi and the face-to-face meeting are complementary. On the one hand, using this integrated approach, the Delphi process requires fewer rounds because the final consensus can be achieved via the meeting. On the other hand, the face-to-face meeting starts from a solid basis, which helps reduce the discussion time required. The size of the sample (37 experts) and the wide spectrum of expertise in terms of geographical region, habitat type and restoration approaches should help ensure that the final results are sufficiently robust. However, it should be noted that different outcomes could have been detected had a different group of experts participated in the survey.

It is important to note that the survey was driven by the need to design (instead of simply selecting from a list) C&I, and therefore open-ended questions were proposed as the starting point. This is quite common in classical Delphi approaches, which leave participants free to identify issues through unstructured questionnaires (Martino, 1983). However, it calls for complex qualitative analyses and sometimes arbitrary choices in order to summarise the sample of responses. While unstructured questionnaires give experts a considerable freedom in listing issues, such freedom becomes a significant drawback if not correctly managed. There is a substantial literature on qualitative analysis methods (Malterud, 2001; Patton, 2002), but little guidance is available on how such methods might be applied to Delphi studies. Some authors (Miller, 2001) have addressed this issue by introducing pre-determined indicators on which experts were invited to comment. This simplified approach, which is supposed not to reduce the value of comments received (Miller, 2001), has the fundamental drawback of preventing experts from designing ad hoc C&I.

The proposed approach to grouping criteria was essentially based on synonyms and comments provided by experts. The task was not straightforward and it necessarily led to loss of information. It was found that the group names selected could not always fully describe all possible nuances that constituting criteria had provided. This may have reduced criterion diversity for the subsequent rounds. Furthermore, a significant problem was encountered because of a lack of understanding regarding the information requested. This highlights the difficulty of communicating the research objectives and scope, and may account for some of the variation in responses received. Indeed, it was necessary to exclude from further stages a number of responses that did not meet the requirements stated in the questionnaires. In particular criteria were omitted that were too generic (e.g. ‘mosaic of surrounding land uses’), too specific (e.g. ‘flagship species’) or that failed to provide supporting information regarding their relevance. Similarly, indicators were omitted that were not operational (e.g. 'assessment of forest global status'), that just proposed specific tools (e.g. 'GIS mapping') or procedures (e.g. 'measure disturbance from historical records'). When a criterion was excluded, its indicators were excluded as well.

Chapter 4

A multicriteria method to integrate ecological and socioeconomic variables[1]

4.1 Introduction

One of the fundamental issue and a key stage in the FLR process is the identification of areas that should be accorded priority for intervention (Vallauri et al., 2005). The prioritisation issue is a rather common topic of conservation science when the shortage of economic resources calls for the identification of those sites whose protection is likely to provide the maximum benefits (Myers et al., 2000). The selection of an area as a restoration priority heavily depends on the objectives of the restoration action. The identification of restoration priorities at the landscape scale can be seen as a multi-objective planning problem in which nature conservation and other issues (social, economic) are involved (Kangas and Leskinen, 2005).

The task is a complex one that involves, prior to the comparison of possible restoration sites, their actual identification and design. Further, tools are needed that allow planners to assess spatial configurations of sites, instead of single sites, in order to select the one that maximizes the landscape-scale benefits. Finally, the multi-objective nature of the problem calls for the integration of different types of variables, with different levels of (spatial) accuracy.

Multicriteria Analysis (MCA) proved to be effective in handling decision problems that involve a high number of different and conflicting objectives (Malczewski, 1999). In the case of forest restoration, the spatial nature of the problem makes the use of Geographical Information Systems (GIS) necessary to easily manage georeferenced data. MCA and GIS can be coupled to provide spatial decision support, as shown in a number of applications related to nature conservation, environmental planning and forest management (Pereira and Duckstein, 1993; Store and Kangas, 2001; Ceballos-Silva and Lopez-Blanco, 2003).

This chapter presents a raster-based operational method for the identification of reforestation

[1] This chapter is based on: Orsi, F., Geneletti, D., 2010. Identifying priority areas for Forest Landscape Restoration in Chiapas (Mexico): An operational approach combining ecological and socioeconomic criteria. Landscape and Urban Planning 94, 20-30.

priority sites, the design of landscape-scale reforestation options, and the comparison of such options by considering ecological and socioeconomic criteria. Restoration was intended here just as reforestation, which makes the analysis easier: the restoration action can only be directed towards unforested areas. This assumption is particularly relevant when no information on the degradation of existing forest is available. A reforestation site is defined as a single group of contiguous cells, whereas a reforestation option includes all the proposed reforestation sites within the study area. The prioritisation is based upon a suitability assessment of land with respect to its need for reforestation, and its likelihood to make the reforestation intervention succeed. The design of priority sites is carried out by means of thresholds. Thus, decision-makers are provided with a tool that, given the overall area to be reforested and the minimum required suitability levels, allows them to generate a number of reforestation options, and to evaluate them according to their ability to protect biodiversity, improve ecosystem functioning and human living conditions.

4.2 Study area

The area investigated by this research is located in the central part of the State of Chiapas (Mexico) and includes the Frailesca region and surrounding areas. It covers about 18,500 km^2 and falls between 15° 29' and 16° 38' N and between 92° 15' and 93° 48' W (Figure 4.1). Elevation varies greatly, ranging from 0 to around 2,500 m above the sea level. The study region is characterized, in its central part, by a high mountain range (Sierra Madre de Chiapas) with steep slopes of igneous rocks (mostly granite), which follows a northwest-southeast direction. Soils, according to the FAO classification (FAO, 1998), belong to four main groups: acrisols, cambisols, litosols and regosols. The area occupies three hydrological regions: Medio Grijalva, Alto Grijalva and Coastal. Major rivers follow a northeast-southwest direction.

Forests are constituted by three main types of vegetation: tropical dry forest (*Selva Baja Caducifolia*), pine-oak, which is found in the eastern slopes of Sierra Madre at elevations between 1,300 and 2,500 m and cloud forest, which is typical of Sierra Madre at elevations of 1,300-2,550 m and high relative humidity (Breedlove, 1981; Luna Vega et al., 1999). Two Biosphere Reserves are located along the Sierra Madre and partly included in the study area: La Sepultura (160,000 ha) in the western side and El Triunfo (120,000 ha) in the eastern one. Both reserves are part of the Grijalva watershed that supplies water to a number of towns and villages of western Chiapas. The reserves are aimed at protecting some the most ecologically diverse areas of Chiapas and are linked by a biological corridor, recognised for its importance towards species conservation as part of the Corredor Biologico Mesoamericano.

The biggest urban areas are Jaltenango de la Paz, El Parral, Villa Corzo and Villa Flores, while hundreds of small and very small scattered villages are found across the entire area. According to CONAPO (2005), which integrated different socioeconomic information (education, sanitation, etc.) to provide a ‘marginalisation’ index, marginalisation in most of these villages ranges from high to very high. Poverty levels are closely linked to the remoteness of human settlements and a strong correlation was found between poverty and the presence of indigenous communities. Three are the main land uses of the region: agriculture, forest and pasture. The actual portion of land dedicated to pasture is varying, as often, especially in the dry season, animals are allowed to trespass on forested or agricultural areas. Current land use change dynamics are threatening forest conservation due to the expansion of agricultural fields and pastures (Vásquez Sánchez, 2005).

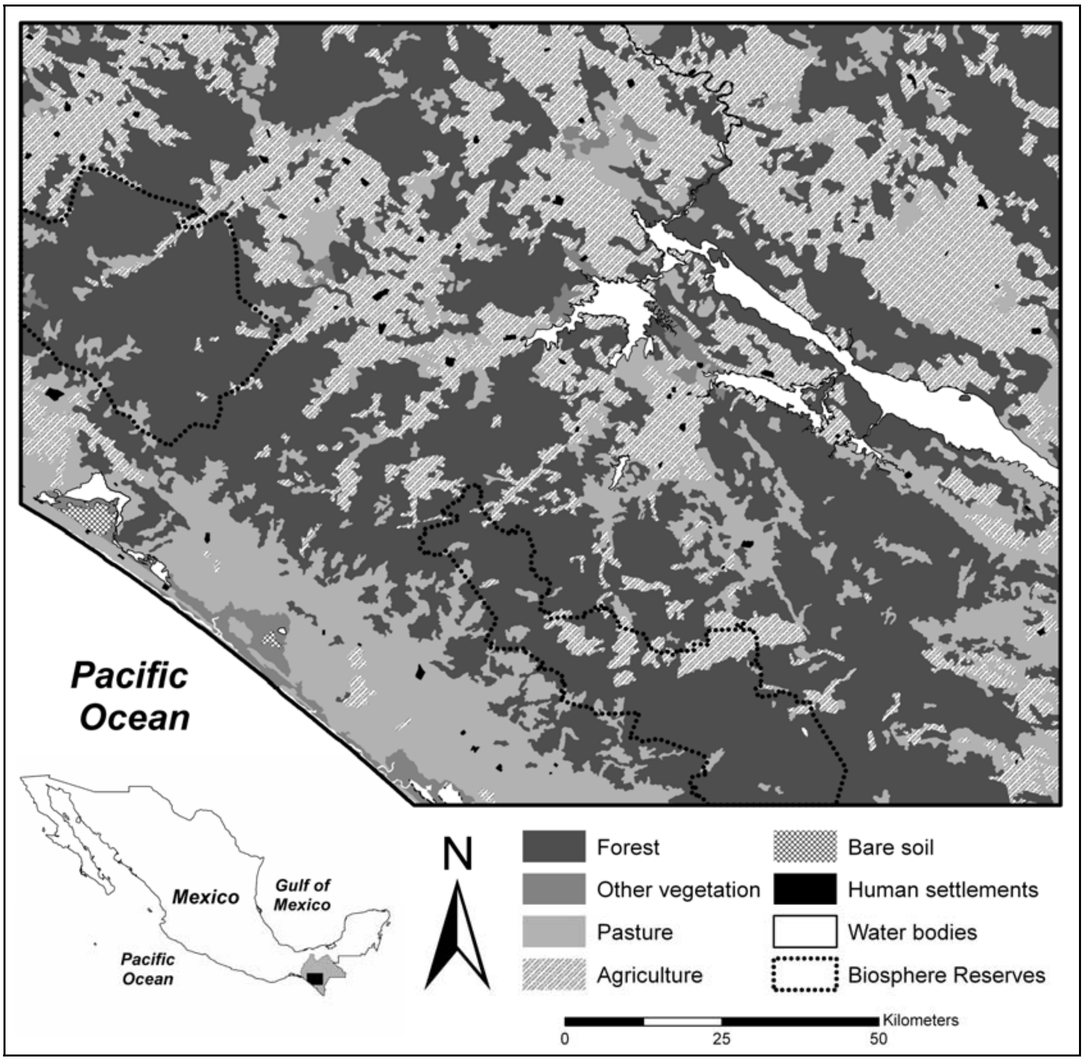

Figure 4.1. The study area in the State of Chiapas, Mexico

4.3 Methods and materials

Initially ecological objectives were considered for the identification of potential priority sites to be reforested, and subsequently the socioeconomic objectives were added for comparing sets of reforestation sites (reforestation options). The concept of 'biodiversity hotspot', a site where large concentrations of endemic species are threatened by the loss of habitat (Myers et al., 2000), and existing studies on forest restoration priorities (WCMC, 2000; Newton and Kapos, 2003) suggested the basic assumption of the method, summarised through the following equation:

$$\textit{Reforestation priority} = f(B, F) \quad (4.1)$$

where:
B represents the need for reforestation: where should biodiversity be protected?
F represents the feasibility of the reforestation process: where is reforestation likely to succeed?

Factor B refers to the identification of those areas that play a major role for the conservation of biodiversity, intended here as species richness and core habitats. The reforestation of such areas is expected to preserve habitats (e.g. sites of high biodiversity) and the ecological structures that help maintaining connectivity within the landscape (e.g. biological corridors). The adoption of factor F is consistent with the idea that restoration plans should account for the 'restorability' of land (Hobbs and Harris, 2001; Suding et al., 2004; Miller and Hobbs, 2007).
The method was structured into three main steps:

1. Generation of suitability maps
2. Design of reforestation options
3. Assessment of reforestation options

4.3.1 Generating suitability maps

The factors B and F of equation 4.1 were assessed by introducing a number of criteria that can be spatially represented. Raster cells, instead of habitat patches, were chosen as the minimum units of analysis because reforestation sites had to be properly shaped for ensuring the achievement of biological and socioeconomic goals. The criteria selection process was based on the results of the survey described in Chapter 3 and influenced by the availability of georeferenced data for the study area.

The following criteria were selected to assess the B factor:

- Distance from ecological corridors: ecological corridors, allowing species to move over the landscape, are one of the key-components of nature conservation plans (Jongman, 1995) and their reforestation may help reducing species isolation.
- Distance from existing forest: areas around existing forests are a priority for their proximity to reservoirs of native species (WCMC, 2000).
- Distance from protected areas: protected areas are a sample of a region's biodiversity to which they provide protection from external threats (Margules and Pressey, 2000). Reforesting in and around a protected site means both enhancing the forested ecosystem and create a buffer zone that prevent the site from being disturbed.
- Tree species richness: sites characterised by high numbers of species are the main target of a reforestation process aimed at conserving biodiversity.

The following criteria were selected to assess the F factor:

- Distance from agricultural fields: areas around existing agricultural fields are more likely to undergo land use change.
- Distance from roads: roads are a source of disturbance as they allow people to have access to nearby areas.
- Distance from urban areas: towns and villages represent a high concentration of human activities, which demands resources from the surroundings.
- Risk of soil erosion: soil degradation can undermine the success of a restoration intervention (Newton and Kapos, 2003).

According to these criteria, the most suitable areas to host reforestation interventions are biologically diverse areas within or around ecological corridors, forests, and nature reserves; not in close proximity to agriculture, roads and settlements; and in areas not exposed to severe soil erosion. Additionally, a spatial constraint was introduced to restrict the analysis to deforested areas not currently covered by settlements.

Most of the data used in this study were obtained from the Programa Estatal de Ordenamiento Territorial (PEOT) for the State of Chiapas (Vásquez Sánchez, 2005). Maps were available that represented the Biosphere Reserves and the ecological corridor linking them. Information on forests, agricultural fields and urban areas were obtained from maps of vegetation and land use that were based on LANDSAT ETM (Enhanced Thematic Mapper) satellite imagery (30-m resolution) from 1999 and 2000, analyzed by the Instituto de Geografía at Universidad Nacional Autónoma de México (UNAM) and personnel of Instituto Nacional de Estadística y Geografía (Palacio-Prieto et al., 2000). A total of 14 land cover categories had been considered: irrigated and seasonal agriculture, cultivated and induced grasslands, secondary vegetation, woodland (mesophile, deciduous, conifer), forest (rain, dry), other vegetation, shrubs, urban centres, water. The risk of soil erosion was an information also available that had been computed from the land cover map as a combination of slope, rainfall and soil type. No specific information on tree species richness was available, hence two sub-criteria were used as proxy variables (Keeney, 1992): aspect heterogeneity and elevation heterogeneity. This is consistent with the idea that geomorphology is highly correlated to species richness (Nichols et al., 1998).

For each criterion, a map was generated with a 30-m resolution through standard GIS operations, such as distance calculation. Disturbance caused by urban areas was assumed proportional to their size. Four maps, each showing the distance from urban areas of different population ranges, were computed. These were then merged into a single map through value functions (see below). Aspect heterogeneity and elevation heterogeneity were computed by using 9X9-cell filters (Burrough and McDonnell, 1998) and associating to the cell at the centre of the filter the number of different aspect classes (aspect was reclassified in 16 classes, according to slope direction), and the standard deviation of elevations respectively.

All criterion maps were combined in a multicriteria fashion. In order to make them comparable, a value function was assessed for each criterion (Beinat, 1997; Geneletti, 2005a). Value functions transform the score of a given criterion into values between 0 and 1, where 0 corresponds to minimum desirability and 1 to maximum desirability (Geneletti, 2005a). They also show whether a criterion is a benefit (the higher the score the higher the desirability) or a cost (the higher the score the lower the desirability). The assessed value functions, as shown in Figure 4.2, belong to four main categories. Those for distance from ecological corridors, distance from existing forest and distance from protected areas followed the prototype (a); that for tree species richness followed a concave shape (b); those for distance from agricultural fields, distance from roads and distance from urban areas followed prototype (c); that for the risk of soil erosion followed a convex shape (d). Prototypes (a) and (d) are costs, prototypes (b) and (c) are benefits.

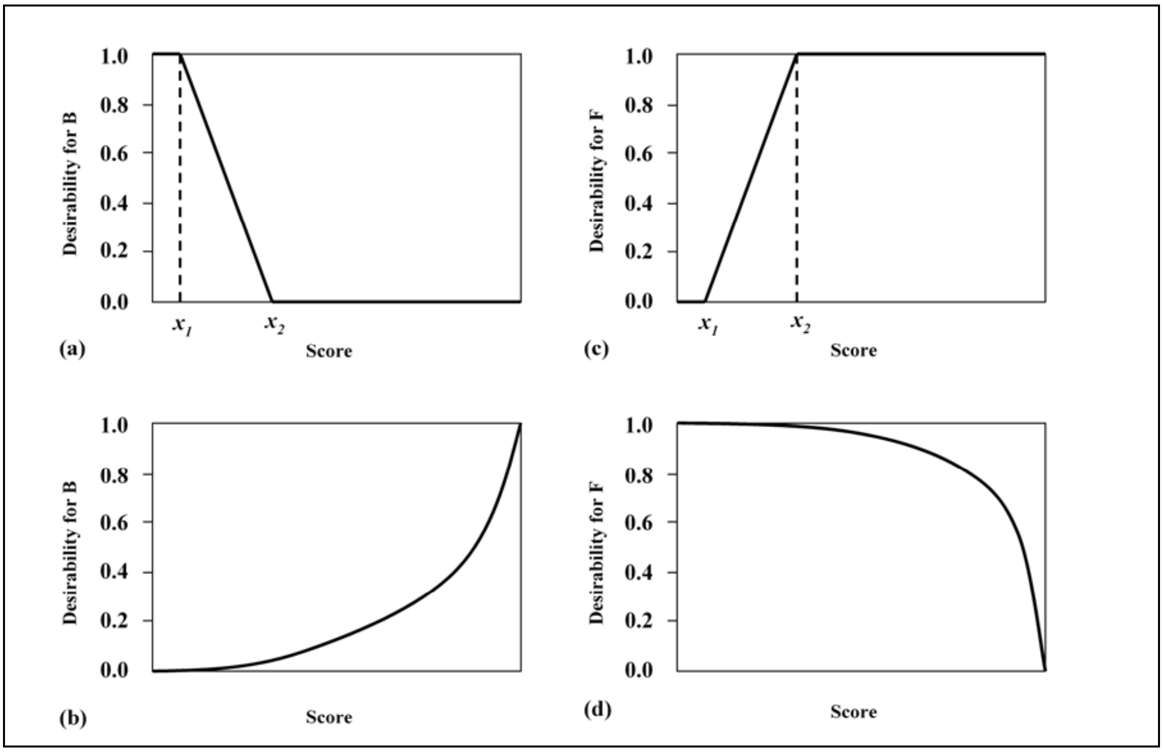

Figure 4.2. Prototypes of the value functions assessed for the eight criteria for factors B and F: (a) for the distance from ecological corridors, the distance from existing forest, the distance from protected areas; (b) for tree species richness; (c) for the distance from agricultural fields, the distance from roads, the distance from urban areas; (d) for the risk of soil erosion

The map of 'distance from urban areas' was obtained by integrating the four previously computed maps: different value functions, obtained by varying x_1 and x_2, were applied that could account for larger settlements having a stronger influence than smaller towns. The integration was a simple statistics of the four standardized maps: for each cell the lowest (most precautionary) value was chosen.

Once maps had been standardised through value functions, two suitability maps, one representing the B factor and one representing the F factor, were generated by simply adding up maps of the two groups. Criteria were considered to be equally important within each group (B and F): a 0.25 weight was assigned to all maps in order to make suitability maps range from 0 to 1. This was aimed at testing a base-case, though the user can vary weights upon his judgement. The constraints, applied to both summations, worked as masks: areas considered unsuitable (e.g. urban areas), no matter the values of other criteria, were not accounted for in the final suitability maps. The spatial multicriteria analysis was carried out using ILWIS 3.3 (ITC, 2001).

4.3.2 Designing reforestation options

The design was based on the extraction from the suitability maps of the best areas up to the fulfilment of the desired reforestation demand. The latter was considered to average 15,000 hectares, which is proportional to the deforestation that occurred between 1990 and 2007 in the Frailesca region. The overall surface was not intended as a sharp measure, but rather as a range ($A_{min} \div A_{max}$), which is acceptable by decision-makers. The present analysis considered a range between 15,000 and 16,500 hectares.

The basic assumption that guided the process of extracting the best areas was that a site can be restored only if it is sufficiently suitable for both the B and the F factors. Implementing this assumption requires to set thresholds that extract most suitable areas from B and F maps. The selection of the threshold is the most critical part of this process. The proposed approach is based on the study of the histogram to assess the number of cells above a given threshold. This allows to understand what threshold meets the surface demand. As two different maps (B and F) are simultaneously considered, the two histograms cannot be studied separately: for example, cells extracted by map B with given threshold b are not necessarily the same as those extracted by map F with threshold f. Therefore, the two maps were crossed on a cell-by-cell basis in order to obtain a combined histogram. Unfortunately, the latter can only provide a frequency information: the number of cells for each pair of values in the suitability maps. The cumulative information was then extracted from the frequency one by considering any pair of values as a threshold pair and computing, for each pair, the number of cells with higher values. A script was written to this purpose with the statistical software R (R Development Core Team, 2005). Now, among all possible threshold combinations, those subtending viable reforestation options were selected on the basis of the following inputs:

- the overall surface to be reforested (reforestation demand);
- the minimum acceptable suitability for B (b_{min});
- the minimum acceptable suitability for F (f_{min}).

For each selected combination of thresholds b and f above the minimum suitability (b_{min} and f_{min}) a map was generated, by selecting only cells above both thresholds in the original maps. Contiguous groups of such cells represented the reforestation sites, whereas each threshold combination shaped a reforestation option, that is a group of sites. Sites smaller than 5 hectares were filtered out because they were considered negligible at the landscape scale. Finally, only options with a total reforestation area still above A_{min} were considered for further analyses.

4.3.3 Comparing reforestation options

In order to compare the reforestation options that had been previously generated, additional criteria were introduced. These account for the spatial configuration of the options (e.g., patch size and shape), and therefore they can be assessed only after the possible reforestation options have been designed. The additional criteria were specifically designed to assess the performance of each reforestation option towards improving the ecological functioning of the landscape and the provision of services to people. They were grouped into ecological and socioeconomic criteria, and are described below, along with the indicator that was adopted to measure them (in brackets).

Ecological criteria:

I. Fragmentation of the landscape (Edge Density).
II. Average compactness of forest patches (Mean Shape Index).
III. Enhancement of ecological corridors (reforestation area occurring within ecological corridors).

Socioeconomic criteria:

IV. Land use conversion cost (reforestation area occurring within agricultural fields).
V. Reduction of soil erosion (reforestation area occurring in soil with intermediate erosion risk).
VI. Improvement of livelihoods (reforestation area occurring in poorest regions).

The rationale for these criterion sets is that the most suitable reforestation option is that minimising landscape fragmentation (criterion I and II), improving ecological networks (criterion III), minimising conflicts with agricultural land uses (criterion IV), contributing to reduce soil erosion (criterion V), and improving local livelihoods (criterion VI). The assumption for the use of the criterion VI was that reforesting poorer regions is likely to improve ecosystem conditions and provision of ecosystem services exactly where people are more vulnerable to ecosystem degradation, which is the case of many remote villages along the Sierra Madre mountain range.

The first two criteria were computed with FRAGSTATS (McGarigal et al., 2002) according to the formulas below by considering both existing forest and reforestation areas as current forest cover: this allowed to assess to which extent each reforestation option could reduce landscape fragmentation and improve compactness.

$$EdgeDensity = 10{,}000\ \frac{E}{A} \tag{4.2}$$

where:

E = total length (m) of edge in landscape;

A = total landscape area (m^2).

$$Mean\,Shape\,Index = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} \frac{p_{ij}}{\min p_{ij}}}{N} \tag{4.3}$$

where:
p_{ij} = *perimeter of patch ij in terms of number of cell surfaces;*
min p_{ij} = *minimum perimeter of patch ij in terms of number of cell surfaces;*
N = *total number of patches.*

Criterion VI was assessed by generating a poverty map for the region. The latter was built through the interpolation of an aggregated poverty index measured at more than 1,000 villages and towns over the study area. This index, called 'Indice de Marginacion' (CONAPO, 2005), results from the aggregation of eight socioeconomic indicators encompassing education, quality of water and sanitation systems, land ownership and availability of electricity. The interpolation was carried out by applying ordinary Kriging and considering a semivariogram model obtained from the combination of a nugget effect and an exponential model (Goovaerts, 1997). The poverty map was subsequently sliced by using the threshold that, according to CONAPO (2005), represents the lower bound to the condition of very high marginalisation (0.61268).

Scores showing the performance of different reforestation options against each criterion were computed and subsequently combined in a multicriteria way. Again, value functions were applied to convert criterion scores to a common value range (0-1). Interval standardisation and maximum standardisation methods (Sharifi et al., 2007) were applied to criteria I, II and III, IV, V, VI respectively. Criteria III, V, VI were considered benefits, while criteria I, II, IV were considered costs. The following are the formulas of the interval functions for benefits (4.4) and costs (4.5).

$$\frac{score - lowest\ score}{highest\ score - lowest\ score} \tag{4.4}$$

$$1 - \frac{score - lowest\ score}{highest\ score - lowest\ score} \tag{4.5}$$

The following are the formulas of the maximum functions for benefits (4.6) and costs (4.7).

$$\frac{score}{highest\ score} \tag{4.6}$$

$$1 - \frac{score - lowest\ score}{highest\ score} \tag{4.7}$$

The interval standardisation is particularly suitable when a relative scale is used (Sharifi et al., 2007), as it is the case of criteria I and II, whereas the maximum standardisation is good for keeping the differences between alternatives: the standardised values are proportional to the original values (Geneletti, 2005b). Weights were assigned both to the groups (ecological and socioeconomic) and the single criteria (I, II, III, IV, V, VI). While all criteria were considered equally important within the groups, three weight sets were introduced for the groups, according to different perspectives (balanced, environment oriented, socioeconomic oriented), as shown in Table 4.1.

Finally, a sensitivity analysis was performed to test the robustness of the ranking obtained during the choice phase. The analysis considered that both the criterion scores and the weights might be affected by a 10% error, due to uncertainty in the assessment of value functions and the evaluation of each criterion's relative importance. An iterative simulator performed some 10,000 iterations to provide an information about how rankings are modified because of variations in criterion scores or weights. A comparison of option rankings under different restoration perspectives (balanced, environment oriented, socioeconomic oriented) was also performed. The non-spatial multicriteria analysis and the subsequent sensitivity test were both implemented in DEFINITE (Janssen et al., 2003).

Table 4.1. Weight sets used to compare the reforestation options

Group	Criteria	Perspectives		
		Balanced	Environment oriented	Socioeconomic oriented
Ecological		0.5	0.7	0.3
	I	*0.333*	*0.333*	*0.333*
	II	*0.333*	*0.333*	*0.333*
	III	*0.333*	*0.333*	*0.333*
Socioeconomic		0.5	0.3	0.7
	IV	*0.333*	*0.333*	*0.333*
	V	*0.333*	*0.333*	*0.333*
	VI	*0.333*	*0.333*	*0.333*

4.4 Results

The suitability map for the B factor ranged between 0 and 0.95, whereas the suitability map for the factor F ranged between 0 and 1. A vast portion of both maps showed a zero suitability. The 3D-graph in Figure 4.3 represents the combined histogram: the z coordinate provides the number of cells associated to any pair of values in map B and map F. The pair (0, 0) is not represented as the area associated is far bigger than all others and the representation would have caused other z values to disappear. The graph shows that a huge number of cells have a value around 0.3-0.4 in map B and 0.5 in map F. In general, one could say that major ridges can be found for B around 0.05-0.15, 0.3-0.4 and 0.6 and F around 0.2, 0.5 and 0.65-0.75. A minor peak is found for B around 0.7-0.9 and F around 0.85-0.9: this means that a significant percentage of the whole study area can be suitable for reforestation. The cumulative information is reported in Table 4.2, which is only a part of the complete dataset. Each row shows a specific threshold combination (columns 1 and 2) and the area in hectares of cells with value above both thresholds (column 3).

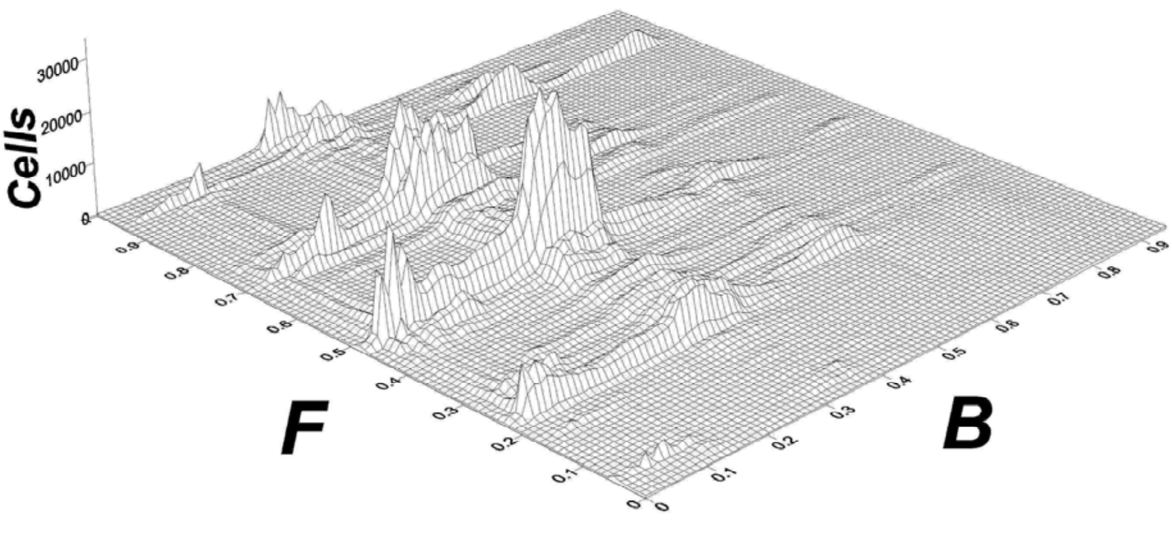

Figure 4.3. Combined histogram of the B and F suitability maps

Table 4.2. Sample of the cumulative information dataset showing the size of the suitable area for a set of threshold pairs for the B and F suitability maps

b	f	Area [ha]
0.62	0.71	20438
0.63	0.81	12857
0.64	0.89	2848
0.65	0.84	8803
0.68	0.64	12916
0.72	0.76	7353
0.75	0.71	7657
0.77	0.67	7858
0.78	0.74	6050
0.81	0.68	5685
0.83	0.83	3106
0.85	0.71	2931
0.87	0.93	25

One can observe that equivalent surfaces occur with very different threshold combinations: this lets suppose that, given a narrow surface range, considerably different spatial configurations might be obtained. The selection of 0.6 as the minimum suitability threshold for both B and F seemed relevant to how value functions were assessed and it resulted in 24 reforestation options. Nevertheless, only 14 options out of 24 were considered once reforestation sites smaller than 5 ha had been removed (Figure 4.4). Thresholds for B ranged from 0.6 to 0.66, while thresholds for F showed a greater fluctuation, ranging from 0.61 to 0.88 (Table 4.3). The variation of the overall reforestation area, ranging from 15,059 ha (option 7) to 16,141 ha (option 1), seems negligible. The maps show that, as expected, bigger differences in the spatial configuration occurred between options originated by more heterogeneous threshold pairs: option 1 is much more different from option 14 than option 1 from option 2. Figure 4.5 shows the frequency with which cells occur in the reforestation options: black zones represent the ‘reforestation core’, that is the area shared by all options. Most core areas are located in the southern part of the study area, though several smaller patches are found in the northwestern sector. The total potential reforestation area, that is the area of the cells selected by at least one option, is around 28,000 ha of which around one fourth is constituted of cells selected by all options (core areas). About 2,500 ha were selected by only one option and a total area of around 11,000 ha was selected by no more than five options. Also, Figure 4.5 highlights that while some patches are just extensions of the core areas, many others only appear in some specific options.

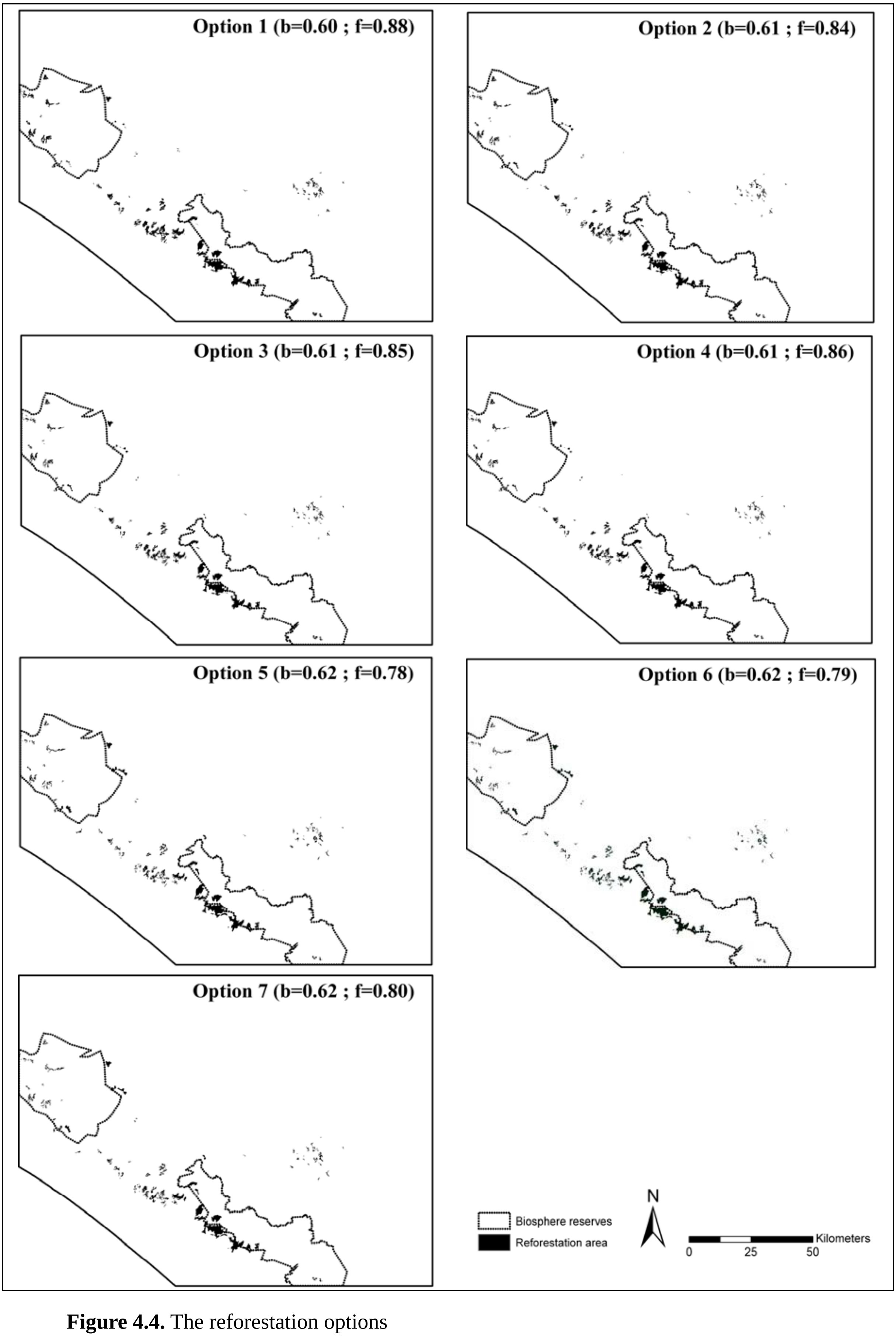

Figure 4.4. The reforestation options

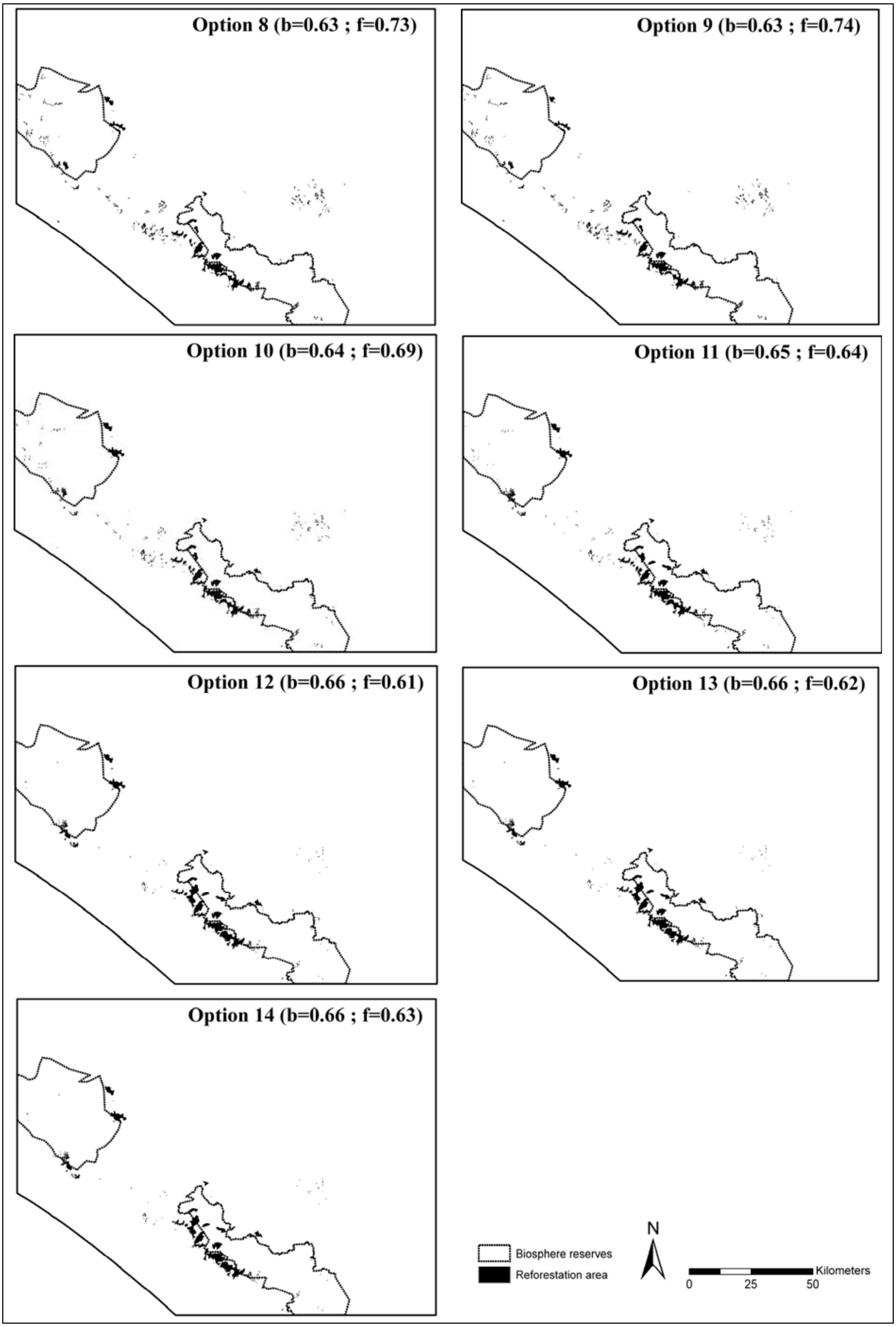

Figure 4.4. (continued) The reforestation options

Criterion scores for all options are presented in Table 4.3. The rankings (Figure 4.6) showed that two options performed significantly better than the other ones under any perspective: option 9 (0.63 for B and 0.74 for F) and option 10 (0.64 for B and 0.69 for F). Option 9 is the best option under both the balanced and the socioeconomic oriented perspectives: in the former case it shows the same performance as option 10, while in the latter it performs far better than any other reforestation alternative. Under the environment oriented perspective it ranks second. Option 10 has the best performance under both the balanced (equal to option 9) and the environment oriented perspectives, while under the socioeconomic oriented one it ranks third.

Table 4.3. Overview of the 14 reforestation options

Reforestation option	b	f	Area [ha]	Criterion I [dimensionless]	Criterion II [dimensionless]	Criterion III [ha]	Criterion IV [ha]	Criterion V [ha]	Criterion VI [ha]
1	0.60	0.88	16141	5.00	2.03	7745	0	303	9720
2	0.61	0.84	15849	5.04	2.00	7541	0	319	9571
3	0.61	0.85	15434	5.04	2.00	7421	0	303	9380
4	0.61	0.86	15076	5.04	1.99	7304	0	289	9206
5	0.62	0.78	15861	5.07	1.98	7409	0	268	9761
6	0.62	0.79	15506	5.06	1.97	7288	0	262	9548
7	0.62	0.80	15059	5.06	1.97	7175	0	259	9233
8	0.63	0.73	15940	5.08	1.98	7509	280	758	9728
9	0.63	0.74	15205	5.07	1.97	7072	7	629	9479
10	0.64	0.69	15338	5.01	1.94	7263	288	499	9265
11	0.65	0.64	15675	4.95	1.99	6983	542	439	9347
12	0.66	0.61	15844	4.90	2.02	7341	630	398	9599
13	0.66	0.62	15798	4.90	2.02	7334	623	398	9560
14	0.66	0.63	15671	4.89	2.02	7330	531	398	9504

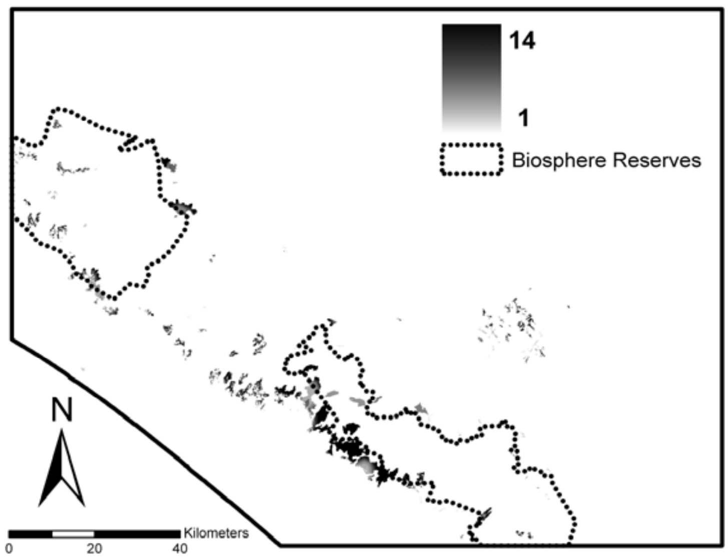

Figure 4.5. Frequency map of the 14 reforestation options (1: area selected by one option; 14: area selected by all options)

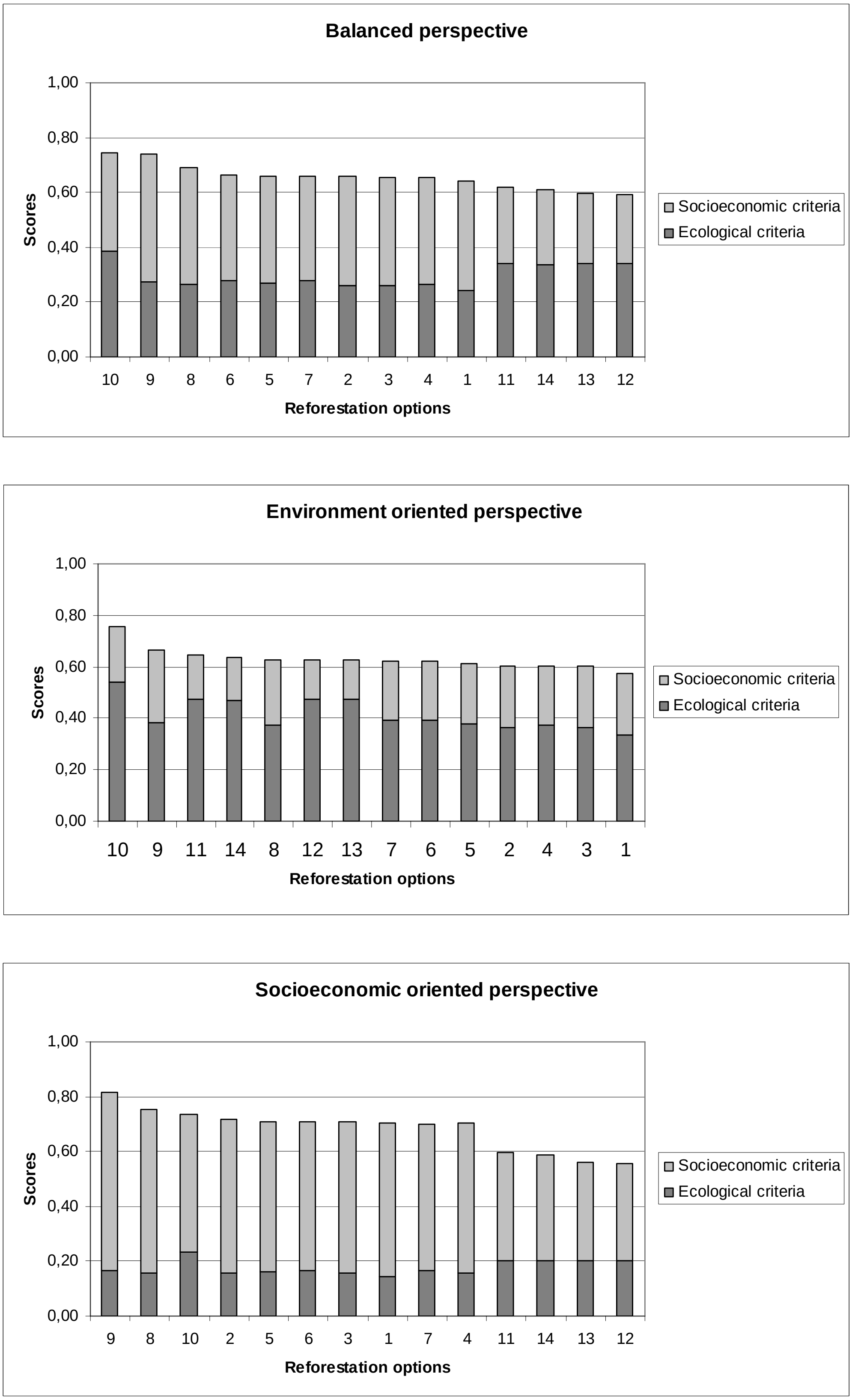

Figure 4.6. Rankings for each evaluation perspective. (the contribution of the ecological and the socioeconomic components is shown)

What actually makes the performance of options 9 and 10 more preferable is their stability: they rank at the top under all considered evaluation perspectives. When disaggregating the two main components (ecological and socioeconomic criteria), as shown in Figure 4.6, option 10 is the one that maximises both components, whereas option 9 performs very well from a socioeconomic point of view, but only sufficiently from an ecological one. The sensitivity analysis partially accounts for these dynamics when uncertainty in the weights is considered. Option 10, whose total area is 15,338 hectares, can be considered the best option (Figure 4.7).

The sensitivity analysis carried out for uncertainty in the criterion scores proved that top ranked options are stable under any evaluation perspectives (Figure 4.8). Instead, major fluctuations occur for the mid-ranked options under the balanced and socioeconomic oriented perspectives and for the bottom-ranked options under the environment oriented perspective. The uncertainty in the weights affects all options under all perspectives, but the fluctuations are small enough not to modify the rankings.

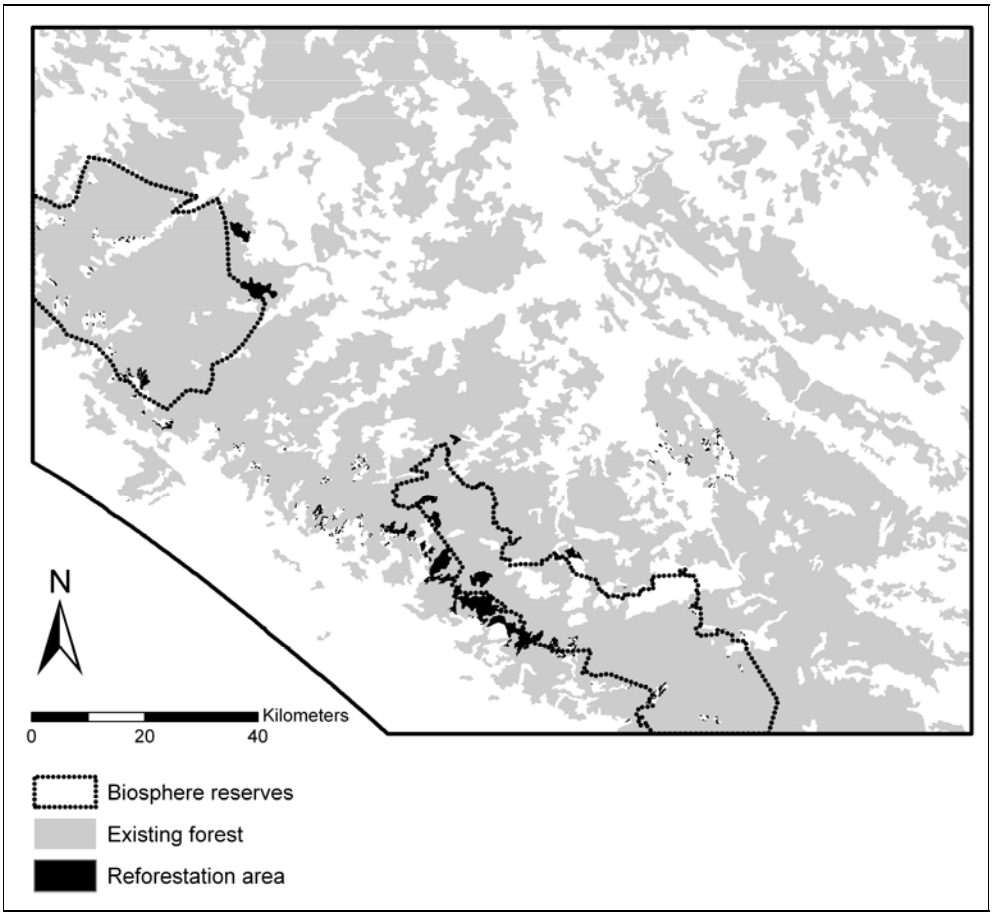

Figure 4.7. The best reforestation option (option 10), which was obtained with thresholds of 0.64 for B and 0.69 for F

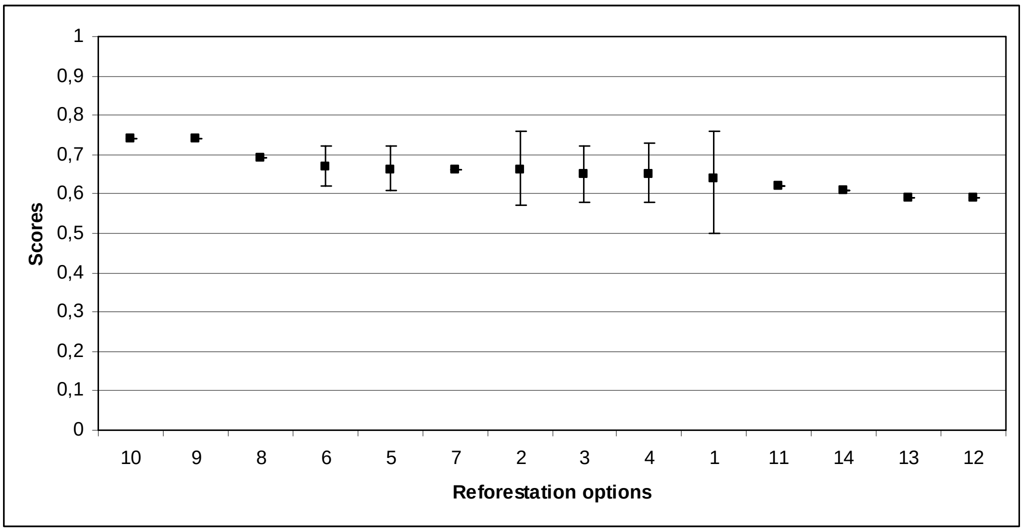

Figure 4.8. Fluctuations in the ranking of the reforestation options under the balanced perspective when uncertainty in the criterion scores is considered

4.5 Discussion

The key FLR concept that attention should be paid to the landscape mosaic instead of the single forest patch suggested this methodology, which provides configurations of reforestation sites through a three-step spatial multicriteria analysis. The need for integrating ecological and socioeconomic objectives was also addressed in subsequent steps: ecological objectives provided a basis for the analysis, while socioeconomic ones allowed for the refinement. This separation was necessary for both making the results ecologically consistent and preventing from a priori excluding valuable reforestation options. The fundamental assumption of the proposed approach is that a site should be accorded priority for reforestation if it offers a potential for biodiversity conservation (B) and if its conditions are likely to make the reforestation intervention succeed (F). This distinction is actually important for dealing with a tricky question: should reforestation be directed towards areas most threatened by human activities or should it keep far from those? To this extent, factor F was interpreted as a cost factor, providing important information about the ‘restorability’ of a site.

Criteria for representing such factors were selected on the basis of easy computability, direct relationship with the related factor and data availability. The use of many distance-based criteria allowed variations at the cell-scale to be captured, which is fundamental towards building suitability maps. Moreover, distance can represent a significant element for assessing both B, which is related to the vicinity to some kinds of biodiversity hotspots, and F, which deals with the distance from disturbance sources (e.g. roads, towns). The validity of using geomorphology as a proxy for tree species richness was proved by comparing the proxy map with a map of faunistic richness (birds, mammals, reptiles) (March, 1997). The availability of geographical data played a major role in the definition of the criteria sets: even though the adopted criteria were effective in providing the suitability information that was being looked for, the methodology could take great advantage of a better data set. This study was indeed primarily aimed at testing a methodology that, having proved to be effective, should be improved through the selection (or the production) of ad hoc data.

The adopted value functions maximized the suitability in close proximity of existing forest and protected areas, under the B factor, and they minimized the suitability in close proximity of disturbance sources, under the F factor. In this latter case, feasibility turned out to be very low in all those areas that are easily accessible, and therefore potentially exposed to exploitation. However, the approach does not prevent medium or good feasibility from being associated to areas in moderate vicinity of sources of disturbance. Although value functions are potentially affected by the uncertainty directly related to human judgement, the use of ‘swinging’ thresholds partly offsets this drawback, as discussed below.

The extraction of most suitable sites by means of thresholds is a common approach (Riitters et al., 1997; Hirzel et al., 2006), though a risky one, as the land is sliced merely on the basis of the cell value: no direct and preliminary control over important factors, say fragmentation, is possible (Geneletti and van Duren, 2008). The use of thresholds was twofold: on the one hand, it let suitable areas be separated from unsuitable ones; on the other hand, it allowed the non-compensatory (Hwang and Yoon, 1981) principle to be implemented. The process takes its origins from the concept of relating the threshold to a land demand (Eastman et al., 1995) and the concept of defining site any group of contiguous cells above a minimum area requirement (Brookes, 1997), and adapt both of them to the case of two suitability maps to be simultaneously analysed. The process is an innovative one and capable of dealing with uncertainty (e.g. related to human judgement), as reforestation options are the geographical representation of thresholds slightly moving up and down. The parameters (reforestation demand, b_{min}, f_{min}) needed to provide a finite set of solutions are linked to each other. Therefore the decision-maker can set a land demand (always intended as a narrow range) and search for the highest possible minimum suitability thresholds or set the minimum thresholds and check how much he can reforest depending on the specific context. The minimum thresholds (b_{min}, f_{min}) represent the minimum requirements for a cell to become a reforestation priority. Hence, their definition is consistent only if the scores of adopted criteria tell something about the achievement of the objectives those criteria refer to, and value functions are assessed accordingly.

The comparison phase shifted the analysis from the site to the landscape: reforestation options were compared as part of the existing landscape. From an ecological point of view, the attention was no longer paid to site suitability, which had already been guaranteed through the first two phases of the methodology, but to the ability of an option to improve landscape connectivity and conservation of key ecological lands (e.g. ecological corridor). This study used common fragmentation indices (edge density and mean shape index) to evaluate the level of fragmentation of the landscape under different reforestation schemes (criteria I and II). The shape index was chosen instead of the perimeter-area dimension, as the former is supposed to correct for the size problem of the latter (McGarigal et al., 2002). Whether such indices are able to adequately account for the spatial configuration is debated. Hargis et al. (1998) tested commonly used landscape metrics on nine series of fragmented landscapes finding usefulness and limitations of them. With regards to the edge density, they see it as an effective tool for measuring fragmentation, but warn about its dependence on patch dimension and shape. In this application, differences among options as provided by the indices are quite small, but this is supposed to depend on the small shape differences between options obtained by similar threshold combinations and the small reforestation area/total forest cover ratios. The criterion related to biological corridors (criterion III) was chosen because reforestation is one of the priority strategies for the sustainable use of biological resources within the Corredor Biologico Mesoamericano (Corredor Biologico Mesoamericano, 2006). From a socioeconomic point of view, attention was paid to the ability of an option to minimize costs of creation and to improve the provision of ecosystem services. Land use conversion costs (criterion IV) are computed by simply considering the agricultural surface to be reforested: this indeed seems to be the major cost due to the importance of agriculture in the study region. Soil erosion (criterion V) refers to intermediate risk, while under the F factor we were considering high risk. The assumption here is that highly erosion-prone areas may undermine the reforestation process, whereas reforestation can stabilize a mid erosion-prone land. Criterion VI was an attempt to integrate data from different sources and resolution formats. Goodchild et al. (1993) cited this problem as one of incompatible reporting zones, calling for reliable methods of spatial basis change and the identification of acceptable underlying continuous surfaces. To this purpose geostatistics seemed more indicated than other methods (e.g. Thiessen polygons) for its ability to generate continuous trend surfaces. Other applications of geostatistics to social data are found in the literature (Câmara et al., 2004; Liu et al., 2008). Although the result was satisfactory, it could be improved if mid-sized urban areas were removed from the sample, because they often show much lower poverty levels than those of surrounding settlements. Finally, no criterion was included to account for the overall suitability of options because the minimum thresholds for B and F had already ensured the fulfilment of a minimum ecological suitability requirement, above which any option could be potentially good for the restoration of the forested landscape.

The proposed approach refers to the general framework for spatial decision-making developed by Sharifi et al. (2007). A common approach is to firstly combine through MCA the maps of alternatives to get a suitability map for each alternative, and then to aggregate each map to a single non-spatial value (Sharifi and Zucca, 2009). This approach differs from conventional spatial multicriteria methods for what concerns the final evaluation of alternatives. We firstly performed an aggregation to get a single non-spatial value for each alternative and each criterion (see Table 4.3), and then combined all values through non-spatial MCA to get the final ranking. Herwijnen (1999) showed that it is possible to compare different spatial alternatives in a multicriteria fashion by first aggregating the spatial component and then combining the evaluation criteria. This path offers the advantage of allowing different aggregation techniques to be chosen for the different criteria, and to perform a complete sensitivity analysis.

Chapter 5

A spatial optimization model for Forest Landscape Restoration

5.1 Introduction

Conservation biology has been focusing on the dilemma of how to select natural reserves for years (Margules et al., 1988; Church et al., 1996; Pressey et al., 1997; Polasky et al., 2000; McDonnell et al., 2002; Snyder et al., 2004). The goal of supporting the most species at the least cost has been the driving force of such research effort (Pressey and Nicholls, 1989; Myers et al., 2000). In order to achieve this ambitious goal, the proposed models have incorporated important concepts, such as complementarity and representativeness (Margules and Pressey, 2000) and took advantage of advanced techniques from operations research and heuristics. While several studies have paid minimum attention to the actual economic feasibility of conservation, an increasing number of authors has been investigating the strict inter-connections between biological and economic benefits (Calkin et al., 2002; Nalle et al., 2004; Polasky et al., 2005; Polasky et al., 2008), aiming to show that conservation is actually possible on the so-called 'working lands' too (Polasky et al., 2005). Despite an excellent job has been conducted in exploring the trade-offs between conservation achievements and economic expenditures, these studies, usually based on large-scale economic revenues, disregard the issue of local people's livelihoods. This is maybe a negligible issue in modern economies where the flow of goods and services is particularly diversified, but it is not so in subsistence economies, where livelihoods are strongly dependent upon locally available natural resources. Here, establishing a conservation area often results in precluding the use of easily accessible resources with most of the conservation costs being paid by locals (Roe and Elliott, 2004). This is actually a missing theme in the modelling debate: models give pixels or habitat units a conservation status but do not account very much for the occurrence of human settlements in or around those pixels or habitat units. Unfortunately, this is going to undermine the success of the same conservation effort: areas in proximity of a village will hardly be protected if villagers are not given alternatives for obtaining the resources they need. The sustainability of conservation projects is likely to be achieved when biological benefits are maximised while allowing local human communities to receive the ecosystem services that they have historically received from the environment in an equally or more efficient way.

Today increasing human pressure on the environment is making ecological restoration a strategic action towards enhancing conservation values and protecting biodiversity from further degradation (Hobbs and Norton, 1996) and models have been developed accordingly (Crossman and Bryan, 2006; Westphal et al., 2007, Bryan and Crossman, 2008; Stralberg et al., 2009). A model for the implementation of the FLR should give several questions an answer: where to act first, which interventions to carry out, which proportion of the landscape to restore, how to satisfy the communities' need of forest products. In particular, restoration areas have to be found that are likely to protect conservation priorities, let people have access to forest stands from which to collect the resources they need, allow budget constraints to be met and provision of other kinds of ecosystem services to be enhanced. When it comes to models, giving a landscape unit a restoration status is a binary decision ('yes' or 'no'): a unit can either be assigned the restoration status or not. This kind of problems have been successfully dealt with for years by applying a class of mathematical optimisation models, known as Integer Programming (IP) (Underhill, 1994; Csuti et al., 1997). The main advantage of these tools, if compared to other methods such as heuristics, is that they actually guarantee that an optimal solution will always be found (Underhill, 1994). The implications of optimality in the algorithms for conservation planning have been questioned in the light of the main advantages of sub-optimal algorithms (e.g. heuristics), namely high processing speed with large datasets and the ability to deal with non-linear problems (Pressey et al., 1996; Vanderkam et al., 2007). Nevertheless, optimal solutions should always be preferred (Pressey et al., 1996) and today enhanced hardware and software tools allow users to process significantly large datasets. Applications of IP to conservation planning are many (Church et al., 1996; Williams and ReVelle, 1996; Haight et al., 2000; Rodrigues and Gaston, 2002; Önal and Briers, 2006), but only few of them deal with the problem of restoration. Crossman and Bryan (2006) identified priorities for Systematic Landscape Restoration in South Australia. Bryan and Crossman (2008) designed a model for setting revegetation priorities in a multi-objective fashion. However, none of these models accounts for the actual presence of human settlements on the landscape and any consideration about the delivery of ecosystem services to local people is missing.

This chapter proposes an IP-based model to set the forest restoration priorities that are likely to enhance the conservation value of a landscape, while also allowing communities to harvest accessible forest stands and a given amount of erosion-prone land to be stabilised. Opportunity costs related to the conversion of agriculture and pasture to forest are also taken into account. The model considers two forest uses: 'protection', assigned to a forest stand that primarily contributes to biodiversity conservation and 'harvest', assigned to a forest stand from which to collect fuelwood and timber. Suitability maps, generated through spatial multicriteria analysis, drive the prioritisation process and *ad hoc* constraints ensure that the harvestable forest is accessible from villages. The model is tested on a study area in the state of Chiapas (Mexico) where forest degradation patterns are significant and small and scattered human communities rely on forests for their livelihoods.

5.2 Methods

Forest restoration is usually implemented under two main circumstances: the occurrence of a degraded forest to be brought back to a pre-disturbance state or the presence of a cleared land to be reforested. For the purpose of this study, only the latter case is considered: this assumption limits the areas potentially selectable for restoration to non-forested areas only. In the proposed framework the above-mentioned uses (‘protection’ and ‘harvest’) apply to both the existing forest and the reforested land. This results in four forest categories: existing forest for protection (F), existing forest for harvest (E), reforested land for protection (Z) and reforested land for harvest (R). The model focuses on the latter three categories. The model is a raster-based one and cells constitute the basic unit of analysis. Each cell is assigned indices i and j, referring to its position in the raster file in terms of row and column respectively. Villages and conservation entities are assigned indices k and m, respectively.

5.2.1 Modelling the man-forest link

Livelihoods of rural communities within poor countries are essentially based on locally available natural resources. The concern is to allocate to each village enough forest-related resources to satisfy its need, and to ensure that these resources are easily accessible by the same village. Forest is supposed to provide villages with just timber: no other forest products are considered in the model.

The Classical Transportation Problem (CTP), introduced by Hitchcock (1941), aims to minimise the costs associated to shipping goods from a number of sources (supplies) to a number of destinations (demands). In this application it is assumed that the forested cells as sources of fuelwood and timber, and the villages as destinations of those goods. Consistent with the CTP, each supply has an upper limit (each forested cell can only provide a given amount of timber) and each demand has a lower limit (a minimum amount of timber should be guaranteed to each village). Timber demand at each village location is estimated by means of the following equation:

$$D_k = tn \times pop_k \times y \quad \forall k \tag{5.1}$$

where tn is timber need per person per year, pop_k is the population of the village k and y is the length in years of the considered time horizon.

The cost of delivering resources from forest to villages is represented by the effort that people have to make in order to reach the forest stand and go back to the village. This cost is supposed to be proportional to the expected travel time for reaching the forest stand from the closest village location. Accessibility is guaranteed by imposing that, for each village, the average travel time to reach surrounding forest stands is below a given threshold. In order to keep the modelling complexity low, each cell of harvestable forest is supposed to be harvested by one single village. This assumption is consistent with the problem of land ownership and the occurrence of administrative subdivisions.

5.2.2 Prioritisation and cost maps

The location and shape of reforestation sites are key determinants of the effectiveness of the restoration action, particularly concerning the biological benefits, the economic costs and the actual feasibility. Few papers exist in the literature that provide criteria for the practical identification of forest restoration priorities. Among those, WCMC (2000) drew some guidelines for the prioritisation at the regional level. They ended up with precise indications: forest restoration should be primarily directed towards original forest areas now unforested, areas containing woodland now unforested, areas of low population density, areas in close proximity to forests and areas rich in biodiversity. Similarly, other authors have stressed the importance of restoring in proximity of existing forest (Lindenmayer et al., 2002) and along corridors (Saunders and Hobbs, 1991), and emphasis has been given to the problem of restoration feasibility (Hobbs and Harris, 2001). Besides the location issue, the problem of shape is also relevant: few compact and contiguous restoration sites are far more manageable than many scattered and irregular patches. Dealing with shape may result in several additional constraints and maybe non-linearities (Aerts et al., 2003). The dependence of restoration priority on several different criteria and the complexities involved with accounting for shape make the use of suitability maps an attractive choice. This approach, already adopted by Crossman and Bryan (2006), uses what they called an 'impedance' surface (raster map) to force the selection of restoration sites on the most suitable parts of the landscape. The problem needs more than one of these surfaces as input: not only for specifying the reforestation priorities, but also for including additional spatially-explicit parameters (e.g. reforestation costs). Both reforestation priority and the other parameters depend on several criteria: therefore the generation of related maps is carried out through spatial multicriteria analysis. For each parameter all related criteria are turned into raster maps and then summed up on a cell-by-cell basis according to a weighted linear combination (Malczewski, 1999) as follows:

$$v_1 m_1 + v_2 m_2 + ... + v_n m_n \qquad (5.2) \qquad \text{with} \qquad v_1 + v_2 + ... + v_n = 1 \qquad (5.3)$$

where $v_1 ... v_n$ are the weights and $m_1 ... m_n$ the raster maps.

In order for maps $m_1 ... m_n$ to be summed up, their values are converted to a common range 0-1, representing a degree of desirability (0 = minimum desirability, 1 = maximum desirability). Value functions, which are the mathematical representation of human judgement on each criterion (Beinat, 1997; Geneletti, 2005a), are applied to this purpose.

5.2.3 The optimization model

The model attempts to maximise the restoration priority of land to be reforested and to minimise the ecological value of existing forest to be made available for harvest, while ensuring the supply of timber at each village location and the achievement of some conservation targets. Further constraints are included to reforest a given amount of erosion-prone land and account for the opportunity costs related to the agriculture-forest and pasture-forest conversions.

Three groups of variables are introduced that refer to Z (z_{ij}), R (r_{ij}) and E (e_{ij}). No variable is assigned to F as it is assumed that all existing forest not given up for exploitation is protected. As variables are defined on some land uses only (e.g. reforestation is only possible on non-forested land), sets are introduced to limit the overall number of variables involved in the computations.

Decision variables are defined as follows:

$$z_{ij} = \begin{cases} 1 & \textit{if cell i,j is reforested and protected,} \\ 0 & \textit{otherwise,} \end{cases}$$

$$r_{ij} = \begin{cases} 1 & \textit{if cell i,j is reforested and available for harvest,} \\ 0 & \textit{otherwise,} \end{cases}$$

$$e_{ij} = \begin{cases} 1 & \textit{if existing forest in cell i,j is available for harvest,} \\ 0 & \textit{otherwise.} \end{cases}$$

Sets are defined as follows:

$L = \{i,j \mid \text{cell } i,j \text{ is on erosion-prone land}\}$

$F = \{i,j \mid \text{cell } i,j \text{ is currently forested}\}$

$H = \{i,j \mid \text{cell } i,j \text{ is agriculture}\}$

$M = \{i,j \mid \text{cell } i,j \text{ is pasture or open land available to reforest}\}$

$P = \{i,j \mid \text{cell } i,j \text{ is pasture}\}$

$\Phi_k = \{i,j \mid \text{cell } i,j \text{ is on the territory of village } k\}$

$\Sigma_m = \{i,j \mid \text{cell } i,j \text{ hosts conservation entity } m\}$

$\Omega_k = \{i,j \mid \text{cell } i,j \text{ is easily accessible from village } k\}$

The following constants are introduced:

a = conversion factor from number of cells to number of hectares
$At(k)$ = limit (%) on the agriculture convertible to forest in the territory of village k
$area(H \cap \Phi_k)$ = area of agricultural fields within the territory of village k
$area(P \cap \Phi_k)$ = area of pastures within the territory of village k
$area(\Sigma_m)$ = area of conservation entity m
$area(F \cap \Sigma_m)$ = area of entity m currently forested
B = total budget available for reforestation
$C(m)$ = conservation target (%) for entity m
$D(k)$ = demand for timber at village k
Es_{ij} = harvest suitability of cell i,j
Lt = target on the stabilisation of erosion-prone land
$Pt(k)$ = limit (%) on the pasture convertible to forest in the territory of village k
Rc_{ij} = reforestation cost of cell i,j if assigned to R
Zc_{ij} = reforestation cost of cell i,j if assigned to Z
Rp_{ij} = priority of cell i,j towards reforestation and harvest
Zp_{ij} = priority of cell i,j towards reforestation and protection
t = trees/hectare
w_1, w_2 = weights of the objective function

The model attempts to:

maximise $$w_1\left(\sum_{i\in M}\sum_{j\in M} Zp_{ij} z_{ij} - \sum_{i\in M\cup H}\sum_{j\in M\cup H}(1-Rp_{ij})r_{ij}\right) - w_2\sum_{i\in F}\sum_{j\in F}(1-Es_{ij})e_{ij} \tag{5.4}$$

subject to

$$\sum_{i\in(M\cup H)\cap\Omega_k}\sum_{j\in(M\cup H)\cap\Omega_k} tr_{ij} + \sum_{i\in F\cap\Omega_k}\sum_{j\in F\cap\Omega_k} te_{ij} \geq D(k)\times a \quad \forall k \tag{5.5}$$

$$\sum_{i\in M\cup H}\sum_{j\in M\cup H} Rc_{ij} R_{ij} + \sum_{i\in M}\sum_{j\in M} Zc_{ij} Z_{ij} \leq B\times a \tag{5.6}$$

$$\sum_{i\in M\cap L}\sum_{j\in M\cap L} z_{ij} + \sum_{i\in(M\cup H)\cap L}\sum_{j\in(M\cup H)\cap L} r_{ij} \geq Lt\times a \tag{5.7}$$

$$\frac{\sum_{i\in H\cap\Phi_k}\sum_{j\in H\cap\Phi_k} r_{ij}}{area(H\cap\Phi_k)}\times 100 \leq At(k) \quad \forall k \tag{5.8}$$

$$\frac{\sum_{i\in P\cap\Phi_k}\sum_{j\in P\cap\Phi_k} z_{ij} + \sum_{i\in P\cap\Phi_k}\sum_{j\in P\cap\Phi_k} r_{ij}}{area(P\cap\Phi_k)}\times 100 \leq Pt(k) \quad \forall k \tag{5.9}$$

$$\frac{\sum_{i\in M\cap\Sigma_m}\sum_{j\in M\cap\Sigma_m} z_{ij} + area(F\cap\Sigma_m) - \sum_{i\in F\cap\Sigma_m}\sum_{j\in F\cap\Sigma_m} e_{ij}}{area(\Sigma_m)}\times 100 \geq C(m) \quad \forall m \tag{5.10}$$

$$\sum_{i\in(m\cup H)\cap\Omega_k}\sum_{j\in(m\cup H)\cap\Omega_k} r_{ij} + \sum_{i\in F\cap\Omega_k}\sum_{j\in F\cap\Omega_k} e_{ij} - \sum_{i\in M\cap\Omega_k}\sum_{j\in M\cap\Omega_k} z_{ij} \leq 0 \quad \forall k \tag{5.11}$$

$$\sum_{i\in F}\sum_{j\in F} e_{ij} - \sum_{i\in M}\sum_{j\in M} z_{ij} \leq 0 \tag{5.12}$$

$$\sum_{i\in F}\sum_{j\in F} e_{ij} - \sum_{i\in M\cup H}\sum_{j\in M\cup H} r_{ij} \leq 0 \tag{5.13}$$

$$z_{ij} + r_{ij} \leq 1 \quad \forall i,j\in M \tag{5.14}$$

$$r_{ij} \leq 1 \quad \forall i,j\in H \tag{5.15}$$

$$e_{ij} \leq 1 \quad \forall i,j\in F \tag{5.16}$$

Equation 5.4 includes two terms: the first one searches for the highest overall reforestation priority of land to be reforested and the second one maximises the harvest suitability of E. The first term in particular consists of two summations, of which the second one attempts to minimise the number of cells given to R (that is why the minus), while also maximising their reforestation priority (that is why $1 - rp$ is used instead of simply rp). The same thing applies to the second term: harvest suitability shoul be maximum, while the number of cells selected for being harvested should be minimised. It is quite clear indeed that the areas to be reforested should be those with the highest expected priority, but the number of those to be harvested should be minimised. Weights (w_1 and w_2) can be varied to define the relative importance of the two terms in the equation. Equation 5.5, computed at each village location, conveys a double information: it ensures that the demand for forest products is met and that the harvestable forest stands are easily accessible. Equation 5.6 introduces a budget constraint. The minimum area requirement on soil stabilisation is expressed by equation 5.7, which defines the area of erosion-prone land to be reforested. Equations 5.8 and 5.9 account for the opportunity costs associated to converting productive lands to forest by imposing an upper limit (%) to the conversion of agriculture and pasture within the territory of each village. Equation 5.10, defined for each conservation entity (e.g. environmental class), imposes the reforestation of non-forested land that, together with existing vegetation, covers a given percentage of that conservation entity. Equation 5.11 imposes that, within accessible distance from each village, harvestable areas outweigh areas given for Z. This is assumed to reduce the risk of having protected forest in between a village and harvestable forest. Equations 5.12 and 5.13 ensure that both Z and R are larger than E respectively. Such equations allow the total stock of existing forest to be preserved during the planning process. Equation 5.14 forces any eligible cell to be either assigned for reforestation and protection or reforestation and harvest. The trade-off between biological benefits and the provision of ecosystem services is explored by progressively increasing parameter Lt in equation 5.7 and assessing the performance of reforested areas in covering sites at higher reforestation priority.

5.3 Data

5.3.1 Study area

The site selected for testing the model is located in the central part of the state of Chiapas (Mexico), 20 km south of the city of Tuxtla Gutierrez, at latitude 16° 20'-16° 36' N and longitude 93° 02'-93° 18' W (Figure 5.1). The area stands between the Sierra Madre mountain range on the southwest side and the Altos de Chiapas region on the northeast one, and it is delimited on the southeast and northwest sides by two canyons. The topography is generally hilly with some larger flat lands on the east side and the southeastern corner.

Elevation ranges from 500 m on the bottom of the eastern canyon to around 1,400 m on the southern and western sides. The climate is highly seasonal (Aw) with an annual rainfall of 830-1000 mm (more than 85% occurring between May and October) and mean annual temperatures between 23 and 24°C. Forest cover is mainly concentrated in the southwestern and northwestern parts of the site where population density is significantly lower. Tropical dry forest (Selva Baja Caducifolia) is the most represented forest type, but pine, oak and pine-oak forests are also found. Human population is concentrated in a number of villages, of which only few have a population above 1,000 (Guadalupe Victoria, Ignacio Zaragoza, Roblada Grande). Agriculture and cattle-ranching are the main economic activities and they are one of the driving forces of the deforestation process. Forests are exploited for timber and fuelwood, which provide energy and construction materials. Deforestation has been considerable and only few forest patches are remaining in the central part of the study area. Bad land use practices and geomorphology contribute to soil erosion and currently almost one eighth of the whole study area is characterised by high erosion risk.

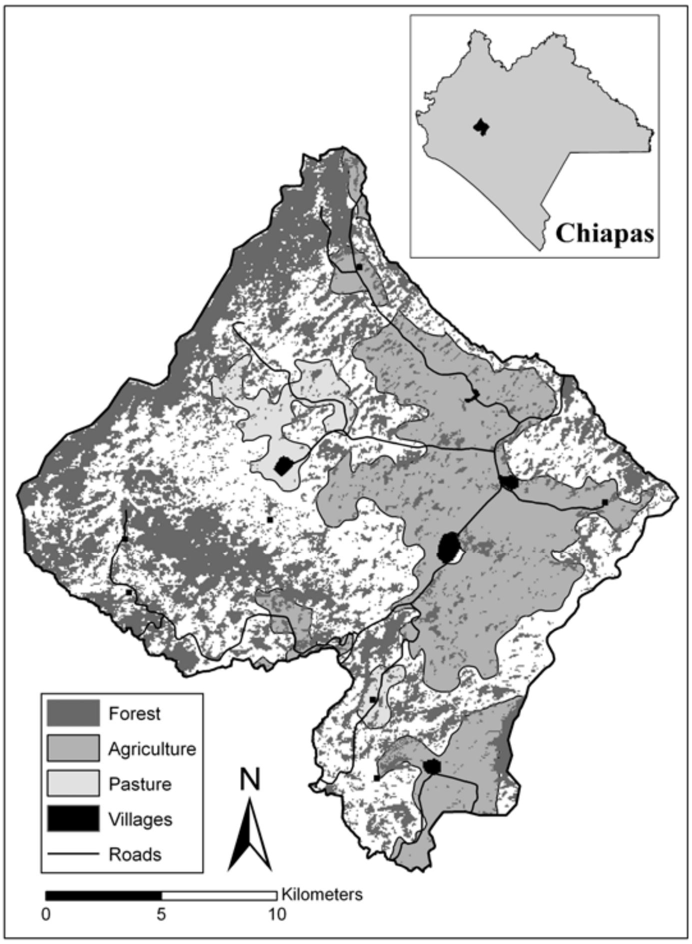

Figure 5.1. The study area

5.3.2 Biological variables

Directing conservation actions towards sites of higher biodiversity is a way to maximise the number of species protected at the least cost. When planning for reforestation of deforested lands, current tree species richness might be extremely low if not zero and thus constituting a useless information. Therefore, potential species richness was defined as the potential capacity of each land parcel to support different tree species due to its topographic, soil and climatic characteristics. At fine-grained scales these factors, along with disturbance patterns, are indeed relevant for explaining species diversity (Lawton et al., 1998; Ricklefs, 2004). Eleven factors were considered: elevation, slope, aspect, soil type, minimum temperatures in the months November-April, maximum temperatures in the months November-April, minimum temperatures in the months May-October, maximum temperatures in the months May-October, number of rainy days in the months November-April, number of rainy days in the months May-October, moisture. Temperature and rain data were collected from INEGI database. For moisture, an index was computed according to Iverson et al. (1997) as a combination of curvature, flow accumulation, hillshade and water holding capacity. The latter was approximated with the number of months with moisture in the soil. These factors were used to predict the potential distribution of a range of species by using Maxent (Phillips et al., 2004; Phillips et al., 2006). Relevant species were selected by analysing 35 plots in and around the study area. Plots were classified by means of a cluster analysis according to the relative presence of species of different successional stage (pioneer, early secondary, late secondary, climax). Four groups were identified representing different forest types. For each group two most representative species were identified as those occurring only (or almost only) in that group (Table 5.1). The occurrence of a given species in a minimum number of plots was also relevant in order to make the modelling reliable. For each species, 30 models were run with varying parameters and the best result was chosen on the basis of low prediction error and high achieved entropy. The 8 resulting distribution maps were summed up to obtain the potential species richness information. Anyway the latter, because of the variables considered, provide valuable insights on both forested and deforested land. Over the study area potential species richness ranges from 0 to 6. Among the selected species, *Calycophyllum candidissimum* and *Jacaratia mexicana* are particularly interesting for conservation, while *Cedrela salvadorensis* is specifically interesting for restoration as its population has significantly dropped over the last years.

The fact that reforestation action is headed towards supposedly most biologically diverse sites does not ensure, by itself, that all environmental classes within the study region will be given the adequate protection status. In order for this to occur eq. 5.10 was included in the model. Environmental classes were identified by considering the eleven factors listed above and carrying out an unsupervised classification over the study area that resulted in 8 classes.

Table 5.1. Species selected for computing the potential species richness map

Species	Successional stage	Group
Bursera bipinnata	Early secondary	3
Calycophyllum candidissimum	Climax	1
Cedrela salvadorensis	Late secondary	4
Ficus tuerckheimii	Early secondary	4
Guazuma ulmifolia	Pioneer	2
Jacaratia mexicana	Climax	1
Quercus peduncularis	Early secondary	3
Senna atomaria	Pioneer	2

5.3.3 Socioeconomic variables

Timber demand per person (*tn* in eq. 5.1) was computed according to a study conducted in the village of Ocuilapa de Juarez by researchers from El Colegio de la Frontera Sur (ECOSUR) based in San Cristobal de las Casas (Holz, personal communication). The village, with population around 3500, is situated 40 km northwest of the study area and shows physical and socioeconomic features somehow comparable to those of the study area. They considered 37 trees of *Acacia pennatula* of varying size, assessed their age and weighed the biomass of all their components (trunk, branches, leaves). In order to estimate per person wood consumption, they interviewed 100 households and weighed the wood that each of those consumed in two days. Both households using wood just for cooking purposes and households consuming wood just for domestic use were considered. Finally, they used data on biomass production and wood consumption to estimate the number of trees of *Acacia pennatula* needed to satisfy a person's demand for domestic use. They found that the median of trees of age 7-8 used by a person in one year is 28. For computing a village's demand the individual demand was assumed to average 30 trees per year (*tn* in eq. 5.1) and 8 years was selected as the time horizon (*y* in eq. 5.1). Therefore the stand that is harvested at year 1 has eight years to grow before the next harvest. Clearly, this assumption holds for fast growing species, while it is a bit overrated for species with a slower growth rate. The supply of trees from each land parcel was estimated by hypothesizing the number of trees per hectare that can be harvested from a each land parcel depending on its current and future use. It was assumed that, as a general rule, 1250 trees/hectare can be planted on a reforestation site aimed at providing people with timber. This number is halved (625 trees/hectare) when reforestation occurs on pasture areas: this is supposed to let animals move among trees. In order to minimise the depletion of current resources, it was assumed that only 200 trees/hectare can be harvested from existing forest. These numbers were discussed with researchers working in the area. Only villages with population above 30 were included in the analysis. Due to their small population and proximity to a larger village, Santa Isabel and Nuevo Leon were joined to Ignacio Zaragoza and El Portillo respectively, thus making the total number of villages equal to 12 (Table 5.2). All villages were mapped as 4-cell squares with the exception of Guadalupe Victoria, Ignacio Zaragoza, La Palma, Palenque de los

Pinos and Roblada Grande whose shape is detectable from satellite imagery. Travel time for reaching a forest stand from the village was assumed to be essentially dependent on the type of terrain and slope, with roads allowing the highest travel speed and steep slope reducing it (Table 5.3). A map reporting the inverse of travel speed expressed in min/m was generated and a weighted distance computed on it to obtain the final travel time information. Land was allocated to villages on the basis of the same travel time map by computing Thiessen polygons (Burrough and McDonnell, 1998). This is a theoretical assumption, as real allocation is based on administrative boundaries and private properties, but it makes the model far easier and seems widely acceptable for the purpose of this study. Erosion-prone areas were identified as those with a potential erosion above 50 tons/ha/year. Potential erosion, based on slope, precipitation and soil type, was derived from the Programa Estatal de Ordenamiento Territorial (Vásquez-Sánchez, 2005).

Table 5.2. Villages over the study area with populations and timber demand (* indicates villages to which nearby small settlements were attached)

Village	Municipality	Population	Timber demand
Carmen el Santuario	Villaflores	54	12960
El Portillo*	Villaflores	507 + 68	138000
El Porvenir	Villaflores	69	16560
Guadalupe Victoria	Villaflores	3124	749760
Guaymas	Villaflores	56	13440
Horacio Grajales	Villaflores	85	20400
Ignacio Zaragoza*	Villaflores	1063 + 37	264000
La Cienega	Suchiapa	57	13680
La Palma	Suchiapa	599	143760
Palenque de los Pinos	Villaflores	467	112080
Roblada Grande	Villaflores	1656	397440
Sierra Alta	Villaflores	34	8160

Table 5.3. Walking speed on different terrains

Terrain	Walking speed [km/h]
Road	4
Off-road (slope 0-5°)	3
Off-road (slope 6-15°)	2
Off-road (slope 16-25°)	1
Off-road (slope 26-40°) and forest	0.5
Off-road (slope > 40°)	0

5.3.4 Prioritisation and cost maps

Spatial Multicriteria Analysis was used to generate five inputs of the model: reforestation priority for protection (Zp), reforestation priority for harvest (Rp), harvest suitability (Es), reforestation cost for subsequent protection (Zc) and reforestation cost for subsequent harvest (Rc). Priority for reforestation was accorded to sites of high potential tree species richness, high fragmentation and recent deforestation. Accessibility was also included when assessing the priority for harvest: the higher the accessibility the higher the priority. Fragmentation was evaluated as the combination of two widely known metrics: number of patches and edge length. These were computed at each cell location by means of a 7-cell (420m diameter) moving filter in Fragstats 3.3 (McGarigal et al., 2002). Recent deforestation was mapped by comparison between 1990 and 2006 Landsat satellite imagery at 28.5 m of resolution. Accessibility of a cell was intended as the travel time for reaching the cell from the closest village on the shortest (least demanding) path (see § 5.3.1). Higher suitability for the use E was accorded to forested sites of low expected species richness, easy accessibility and adjacency to the forest edge. Estimating reforestation costs is a very difficult task as these are likely to change from site to site depending on several factors. For the purpose of this study, which is primarily aimed at describing a methodology, a simplified approach was adopted to coarsely predict the variations of reforestation costs over the space. Reforestation costs were assumed to be primarily dependent on: the density of plantations, the potential for natural regeneration, the accessibility of reforestation sites, the need for protecting reforestation sites from disturbance (e.g. grazing) and past land use. The cost of buying land was not accounted for. Initial plantation cost estimates were taken from Sathaye et al. (2001) and updated to current values by considering the average inflation rate in the period 2002-2010 in Mexico. This resulted in costs of \$620 ha^{-1} and \$930 ha^{-1} being considered for reforestation and harvest and reforestation and protection, respectively. These could be varied (increased or decreased) upon characteristics of a given site (cell) with respect to the factors listed above. In particular, only for reforestation and harvest, the cost was reduced by one third on areas at lower plantation density (625 trees/ha). Costs were halved within a 240m-buffer from existing forest where seed dispersal is likely to foster natural regeneration. Increasing distance from roads, due to extra time demanded for reaching the site, was assumed to increase the reforestation costs, according to a linear trend, up to one third beyond 5km. Costs were assumed to increase by one fifth on and around (within a 240m-buffer) pasture areas because of fence establishment to prevent cattle from entering newly reforested sites. Finally, costs were increased by one third and one fourth on agricultural fields and pasture respectively to account for increasing effort needed to reforest highly degraded grounds. These cost factors were combined through a weighted linear combination (Malczewski, 1999) to obtain two cost maps: one for reforestation and harvest and the other for reforestation and protection. Three sets of weights were considered for each of the five above-mentioned maps in order to deal with the problem of uncertainty. This resulted in 15 maps that, once entered into the model according to all possible combinations, allow 3^5=243 different problems to be obtained. Table 5.4 summarises the criteria involved in the definition of prioritisation and cost maps and the weights assigned for the basic analysis and the uncertainty one. The Spatial Multi Criteria Evaluation (SMCE) module of Ilwis (ITC, 2001) was used to perform all multicriteria analyses.

Table 5.4. Weight sets adopted in the spatial multicriteria evaluation to compute maps for: priority for R (a), priority for Z (b), priority for E (c), cost for R (d), cost for Z (e). The basic output was obtained with weight set 1. Sets 1, 2 and 3 were used for generating the 243 inputs of the uncertainty analysis

Map	Criteria	1	2	3
a	Fragmentation	0.2	0.3	0.25
	Pre-forested	0.3	0.2	0.25
	Species richness	0.3	0.2	0.25
	Travel time	0.2	0.3	0.25
b	Fragmentation	0.4	0.33	0.3
	Pre-forested	0.2	0.33	0.4
	Species richness	0.4	0.33	0.3
c	Distance from edge	0.3	0.33	0.4
	Species richness	0.4	0.33	0.2
	Travel time	0.3	0.33	0.2
d	Accessibility	0.2	0.15	0.1
	Current land use	0.2	0.4	0.15
	Fences	0.2	0.15	0.1
	Plantation density	0.2	0.15	0.25
	Regeneration potential	0.2	0.15	0.3
e	Accessibility	0.25	0.2	0.3
	Current land use	0.25	0.3	0.2
	Fences	0.25	0.2	0.3
	Regeneration potential	0.25	0.2	0.3

5.3.5 Model implementation

The model was stored in MPS (Mathematical Programming System) format, which is a common way for archiving LP problems such that they could be readable by a wide variety of optimisation softwares. Among those, CPLEX 11.0 (ILOG, 2007) was chosen for its high reliability when dealing with large problems. A program in Visual Basic (Microsoft Inc.) was written for reading input data and generating the MPS text. All data were prepared in a GIS as 60m-resolution raster files and then exported in Ascii format for input into the Visual Basic program. A further program was written in Visual Basic to read the results of the optimisation process and generate the Ascii files that could be imported in a GIS for visualisation. Despite the large number of variables (163,119) and constraints (116,764), the model took only few seconds to run on a normal desktop computer. The uncertainty analysis was carried out by performing 243 optimization runs with varying input maps as described in § 3.4.

A common set of values was adopted as the input of model parameters for all basic analyses in this study. An overall 2.5 million $ was assumed as the available reforestation budget, which corresponds to an investment of roughly $6,000 km^{-2} on average, considering the size of the study area. The proportion of protected forest on each environmental class was imposed to increase by 10% with respect to present conditions. The acceptable travel time for reaching a forest stand from the closest village was assumed to be 45 minutes one way. A 10% threshold was fixed as the maximum proportion of both agriculture and pasture areas available for conversion to forest on each village's territory. Finally, equal weights (0.5, 0.5) were introduced in the objective function.

5.4 Results

Considering 1,000 ha as the overall area of erosion-prone land to be reforested, the output shown in Figure 5.2 was obtained. Total reforestation area is 3,426 ha, of which 1,947 ha are for protection and 1,479 ha are available for harvest; while 199 ha of existing forest are given up for harvest. Sites assigned to Z are mostly located on the northern corner and south-eastern side of the study area. Nevertheless, smaller patches are found across the whole landscape to comply with conservation constraints. A summary of the model output is given in Table 5.5. Sites assigned to R are located, as expected, all around villages with larger sites near more populated settlements. The actual minimum distance of such sites from villages greatly varies: from zero in some cases to few hundreds of metres in others. This is strongly dependent upon current land uses: when a village is surrounded by vast areas of agricultural fields or pastures the model is forced to search for available areas a bit farther not to exceed the threshold on agriculture and pasture conversion. This is also consistent with the assumption that people go daily to the fields, while only once in a while to forest stands for harvesting. Such outcome is evident for the village of Roblada Grande (the big village in the central part of the study area), which is surrounded by vast areas of pasture, and the village of Guadalupe Victoria (shown in Extent 2 of Figure 5.2), which is surrounded by vast areas of agricultural fields. Extents 1 and 3 shows the areas surrounding the villages of Palenque de los Pinos and Ignacio Zaragoza, respectively. Regarding E, related sites are always found on the edge of existing forest patches, this ensuring that core areas will not be crossed by people. About one sixth of the cells assigned to E are located outside of the areas easily accessible by people (travel time above 45 minutes). These provide a surplus of timber and therefore have to be intended more as an indication of which areas are more suitable for exploitation rather than areas whose exploitation is necessary to meet the timber demand. Protected forest is never found in between a village and the harvestable forest, in the sense that, with few exceptions, no large stripes of protected forest are likely to restrict the access to the harvestable stands. This should help minimise the risk of forest degradation due to the passage of people. As a general rule, reforestation sites are integrated quite well within the existing forest framework, bridging its gaps and enlarging the size of its patches. The number of isolated cells selected for reforestation is extremely low if compared to the total number of cells selected, which makes the practical implementation of the reforestation plan more feasible.

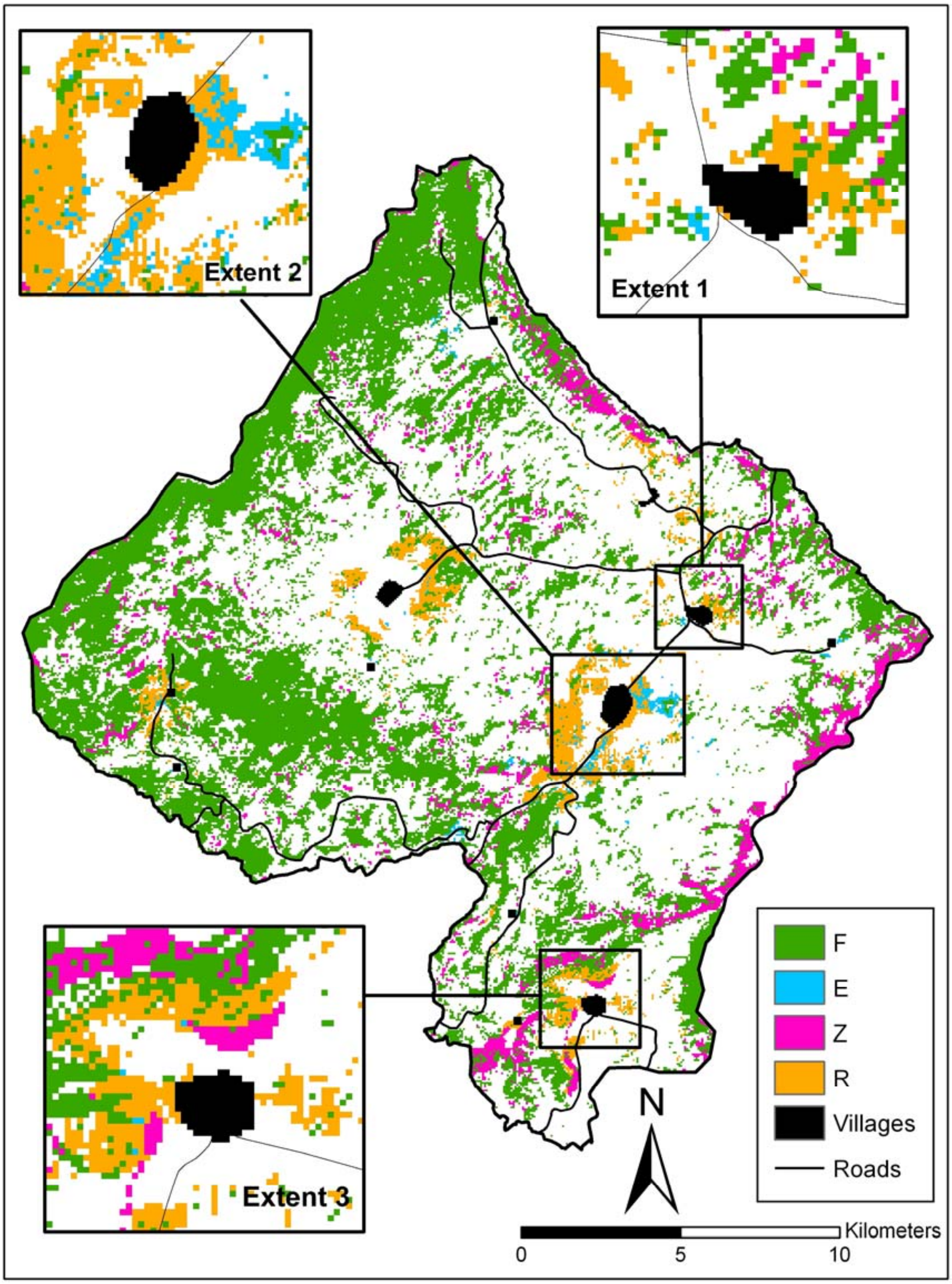

Figure 5.2. The output of the model obtained by imposing that 1,000 ha of erosion-prone land is reforested

Table 5.5. A comparison between the current land allocation and the new allocation as found by the model (villages have to be intended as the entire territories around the settlements, i.e. the Thiessen polygons introduced in § 5.3.3)

		Area [ha]	Current land allocation			Land allocation after reforestation					
			Forest	Agriculture	Pasture	F	E	Z	R	Agriculture	Pasture
Villages	Carmen el Santuario	2894.04	1352.88	172.8	0	1351.44	1.44	42.12	10.08	172.8	0
	El Portillo	3049.56	1927.8	0	0	1920.24	7.56	104.76	109.08	0	0
	El Porvenir	2050.2	741.6	184.68	257.4	740.16	1.44	91.08	12.96	184.68	255.24
	Guadalupe Victoria	6535.8	1136.88	3410.64	0	986.76	150.12	219.6	575.64	3069.72	0
	Guaymas	3082.32	1697.04	1.44	0	1694.88	2.16	68.76	10.08	1.44	0
	Horacio Grajales	796.68	211.32	25.2	0	211.32	0	125.64	16.2	22.68	0
	Ignacio Zaragoza	3339.72	722.52	1518.84	0	720.72	1.8	317.52	210.6	1396.08	0
	La Cienega	4946.04	2854.08	713.88	0	2834.28	19.8	223.92	7.56	708.12	0
	La Palma	3268.08	548.28	2069.64	0	548.28	0	200.16	114.84	1957.68	0
	Palenque de los Pinos	3012.48	365.04	2035.44	0	362.16	2.88	90.72	88.92	1971.36	0
	Roblada Grande	7321.68	2126.52	442.44	1326.24	2120.76	5.76	132.84	316.8	440.28	1314.72
	Sierra Alta	2038.68	583.56	461.52	0	577.08	6.48	327.6	5.4	456.12	0
	Total	42335.28	14267.52	11036.52	1583.64	14068.08	199.44	1944.72	1478.16	10380.96	1569.96
Environmental classes	Class 1	2054.16	171.72	1209.24	0	171.72	0	444.24	74.88	1134.72	0
	Class 2	5577.12	1644.48	2304.72	13.68	1539	105.48	173.88	357.12	2077.2	13.68
	Class 3	13528.8	3514.32	6275.52	159.12	3486.96	27.36	571.68	566.64	5949.36	155.52
	Class 4	10429.92	3859.56	835.92	929.16	3800.16	59.4	331.56	273.6	811.08	920.52
	Class 5	5712.84	2688.84	343.44	445.68	2686.32	2.52	226.08	124.2	343.44	444.6
	Class 6	4890.6	2303.28	67.68	36	2298.6	4.68	183.96	81.72	65.16	35.64
	Class 7	140.04	84.24	0	0	84.24	0	13.32	0	0	0
	Class 8	1.8	1.08	0	0	1.08	0	0	0	0	0
	Total	42335.28	14267.52	11036.52	1583.64	14068.08	199.44	1944.72	1478.16	10380.96	1569.96

The amount of erosion-prone land to be reforested was increased from 1000 ha to 2000 ha with steps of 200ha and traded-off against the reforestation of deforested land (Figure 5.3.a), the reforestation of fragmented lands (Figure 5.3.b), the reforestation of species-rich lands (Figure 5.3.c) and the amount of existing forest given up for harvest (Figure 5.3.d). Deforested lands are considered those having lost their forest cover between 1990 and 2006, fragmented lands are those constituting the 10% more fragmented part of the landscape as expressed by Fragstats indices and species-rich lands are those potentially supporting at least 3 out of the 8 species for which potential distribution had been mapped. The first three figures show a mostly decreasing trend for increasing amounts of erosion-prone land reforested. The reforestation of deforested lands drops from 386 ha to 143 ha, the reforestation of fragmented areas passes from 1617 ha to 1383 ha, the reforestation of species-rich areas from 859 ha to 581 ha. and forest available for harvest drops from more than 217 ha to around 164 ha. The use of the existing forest instead increases constantly from 199 ha to 250 ha until 1800 ha of erosion-prone land are reforested and then it jumps to a stunning 847 ha. This is related to an increasing amount of reforestation resources devoted to the stabilisation of erosion-prone lands with subsequent timber demand satisfied by the existing forest, whose expected harvesting rate per area is very low (200 trees/ha). The results of the first three cases are also interesting when considering the contributions of Z and R separately. What emerges from the graph related to species richness for example is that beyond 1800ha of erosion-prone land reforested the curve for R starts rising. This is due to the fact that very often supposedly species-rich areas are also prone to erosion. Figure 5.4 shows how the spatial configuration of reforested sites changes during the trade-off process over the study area. With increasing proportions of erosion-prone land to be reforested, the area reforested for harvest, though still satisfying the demand of the village, is more and more forced to cover the local erosion-prone feature.

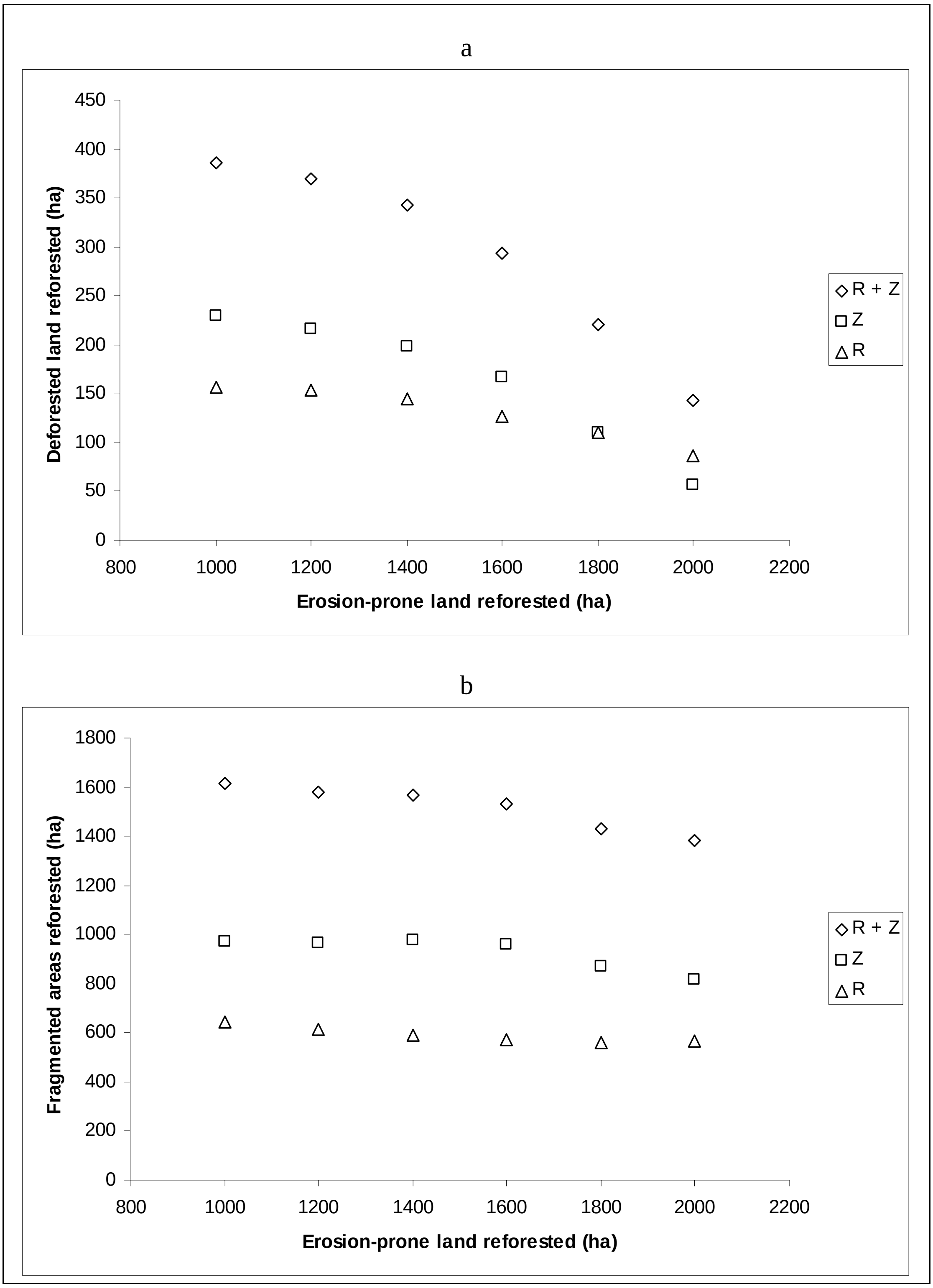

Figure 5.3. Trade-offs between the reforestation of erosion-prone land and: the reforestation of deforested areas (a), the reforestation of highly fragmented areas (b), the reforestation of species-rich areas (c), the harvest of existing forest (d)

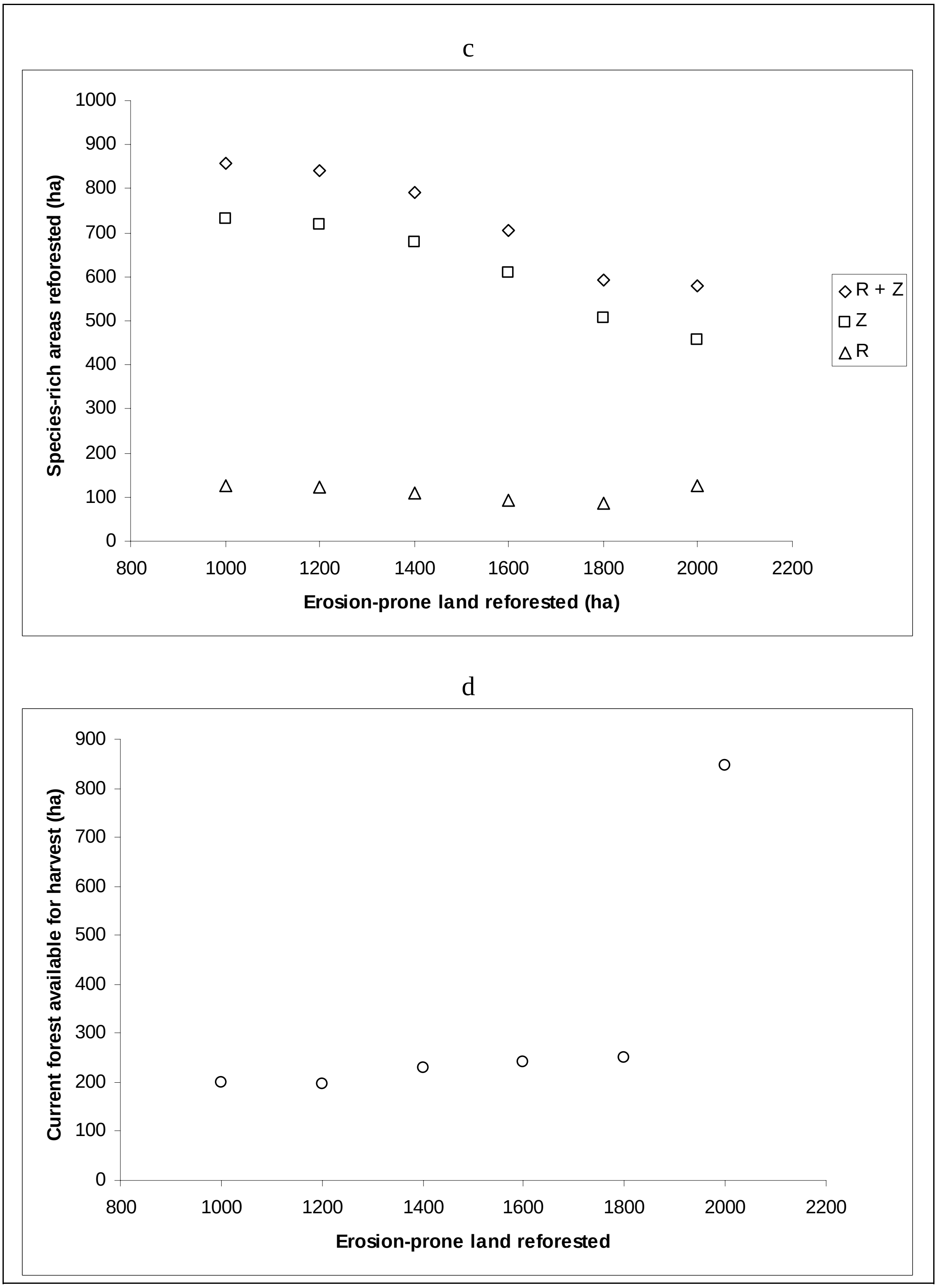

Figure 5.3. (continued) Trade-offs between the reforestation of erosion-prone land the reforestation of deforested areas (a), the reforestation of highly fragmented areas (b), the reforestation of species-rich areas (c), the harvest of existing forest (d)

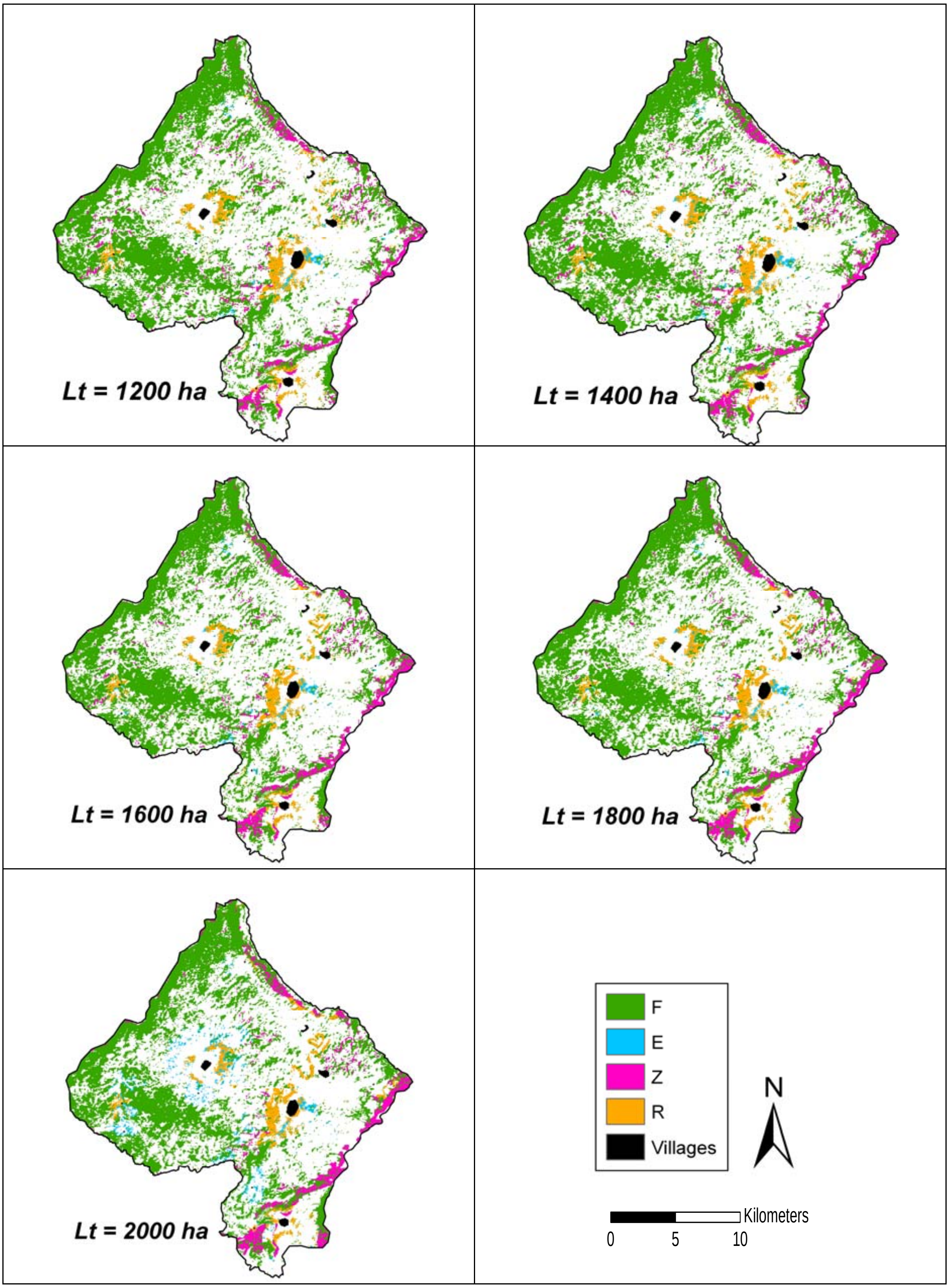

Figure 5.4. Different model outputs obtained by increasing the amount of erosion-prone land to be reforested (*Lt*)

The maps included in Figure 5.5 tells how often each cell is selected for a specific use (E, Z, R) during the 243 optimisation runs performed during the uncertainty analysis. It is surprising to see, as summarised in Table 5.6, that a vast proportion of selected cells (39%, 71%, 57% for E, Z and R, respectively) are selected in all runs and have therefore a 100% probability of being assigned that particular use, no matter the input. This tells much about the reliability of the model and its scarce sensitivity to uncertainty in the input. Table 5.6 should be read as follows: considering the use E, 103 ha of land have a 100% probability of being assigned the use E, 18 ha have a probability between 90 and 99% of being assigned the same use and so on. The information is also provided in terms of percentage. It is surprising to see that, among areas characterised by lower probabilities, the distribution is essentially flat (Table 5.6). Besides that, the total amount of areas being assigned to both reforestation and protection and reforestation and harvest is pretty low, averaging a mere 148 ha.

Table 5.6. Results of the uncertainty analysis

	E		Z		R	
Probability (%)	[ha]	[%]	[ha]	[%]	[ha]	[%]
100	103	39.46	1610	70.89	1086	56.53
90-99	18	6.90	91	4.01	64	3.33
80-89	6	2.30	62	2.73	60	3.12
70-79	10	3.83	58	2.55	65	3.38
60-69	13	4.98	97	4.27	154	8.02
50-59	16	6.13	38	1.67	51	2.65
40-49	10	3.83	47	2.07	56	2.92
30-39	15	5.75	45	1.98	154	8.02
20-29	13	4.98	59	2.60	67	3.49
10-19	19	7.28	73	3.21	98	5.10
0.01-9	38	14.56	91	4.01	66	3.44
Total	261	100.00	2271	100.00	1921	100.00

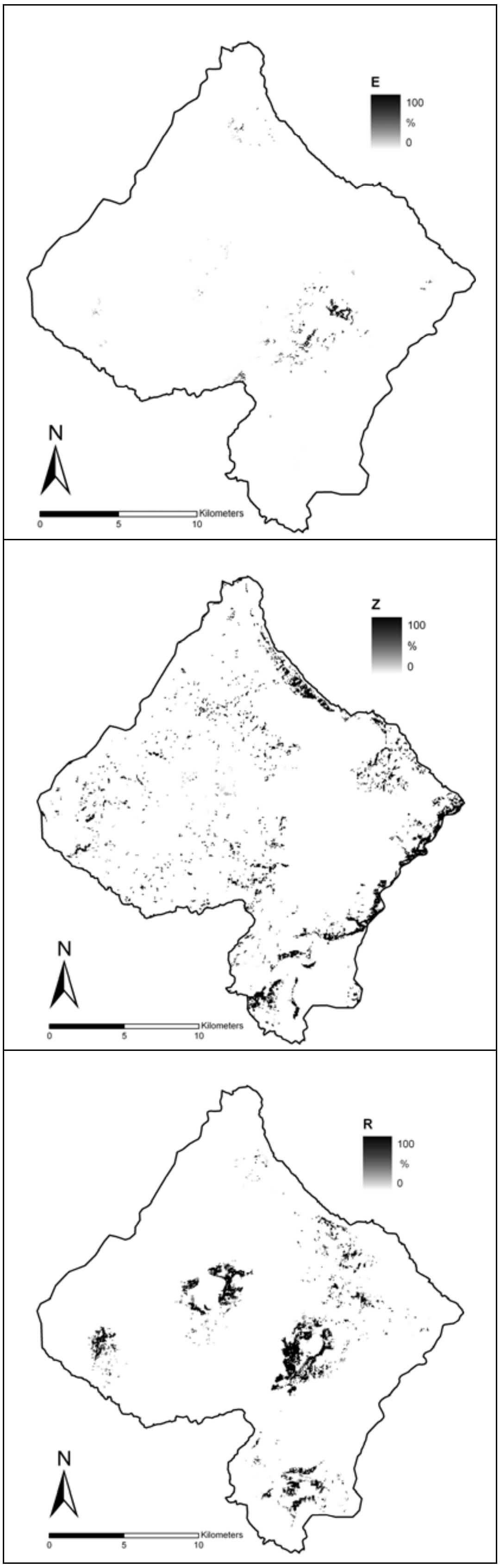

Figure 5.5. Results of the uncertainty analysis. Maps show on a gray scale (dark = high probability; bright = low probability) the probability of each cell of being assigned the use E (top), Z (middle) and R (bottom)

5.5 Discussion

When conservation actions have to be taken on areas characterised by high biodiversity and the presence of small human communities relying on locally available natural resources, most of the existing models would fall short of finding a credible solution. On such areas a traditional reserve selection approach would identify areas that in the real world would never be protected because people have to satisfy their need of resources somehow. This chapter introduces an innovative IP technique to shape a new forest landscape that is able to both enhance the protection of biodiversity and ensure that people have an easy access to the forest-related resources they need. In this respect it can be seen as the spatially-explicit evolution of Allen’s (1985) early attempt to model the compromise between preservation of nature and supply of wood to people in an African village. The test conducted in central Chiapas proves that it is actually possible to find reforestation options that better preserve local biodiversity, while also ensuring to people an accessible source of timber and minimising the conversion to forest of fundamental land uses (i.e. agriculture, pasture). The model is reliable because it identified compact and contiguous reforestation patches, it satisfied conservation and livelihoods goals, it showed scarce sensitivity to uncertainty in the input and was fast in finding the optimal solution. Trade-off analyses emphasised that high demands of a service (i.e. erosion control) still allow important biological targets (e.g. reforestation of pre-forested areas) to be achieved and do not prevent all other conditions (e.g. timber supply, conservation of environmental classes) from being met.

The use of IP was a good choice in that it allowed optimal (and repeatable) solutions to be obtained. In general terms, the formulation of the problem was easily and efficiently carried out through linear equations. The model integrates some of the traditional reserve selection-kind features with the transportation problem features and a bunch of other constraints to ensure the coherence of results. No tests were carried out to analyse the effects on the model of changes in objective function’s weights. They were introduced to give the user more freedom and possibly allowing him to explore trade-offs between reforestation and use of the existing forest. Conservation constraints (eq. 5.10) are based on the multi-level set covering location model (Church and Gerrard, 2003) and able to guarantee that protected forest represents the whole range of conservation entities (environmental classes) in the landscape (Margules and Pressey, 2000). The implementation of the supply-demand model was essentially based on one single constraint (eq. 5.5). After conducting some tests, this proved to perform way better than the double-equation approach: one equation for ensuring the satisfaction of demand and the other for the accessibility. In this case the accessibility equation should limit the average distance of harvestable forest, but that would not prevent cells too far to be reachable from being selected anyway. A prominent role within the model is held by the three ‘balance’ equations 5.11, 5.12 and 5.13. The last two are intended to preserve the current stock of forest: if one cell of existing forest is harvested, at least one cell of cleared land should be reforested for protection and one cell reforested for harvest. Equation 5.13, in particular, prevents the case of having the entire timber demand satisfied by existing forest. Although equation 5.11 was determinant towards reducing the amount of protected forest in between a village and an harvestable forest stand, it is not a secure solution. This would require a more complex non-linear set of constraints to really ensure that, on the shortest path towards an harvestable stand, a person does not enter a protected stand. Moreover, the equation does not account for the existing protected forest.

The processing speed of the model was indeed high and this has three main reasons. Firstly, as suggested by equations 5.14, 5.15 and 5.16, the relaxation problem was considered. This choice, which prevented the need for using the memory-consuming branch-and-bound algorithm, was supported by the results, where only 10-15 out of 163,119 variables were assigned values between 0 and 1. Secondly, the set-based formulation allowed the number of variables to be dramatically reduced, as these are only defined where they can actually take a non-zero value. Finally, the 60 m resolution offered a great balance between accuracy and reasonable overall amount of cells. Actually, choosing the right resolution is a critical part of this model. Too fine resolution would lead to an unmanageable number of variables, while too coarse resolution, besides making the representation of forest cover completely inaccurate, would miss the scale of human walking.

The decision of using suitability maps (priority and cost), already adopted by Crossman and Bryan (2006), was determinant towards the objective of having compact patches. This is very important when passing from plans to practice, where thousands of scattered patches are basically impossible to manage. The problem of suitability maps, that was not really addressed by Crossman and Bryan (2006), is related to uncertainty. Actually weights and value functions, as stated in § 5.2.2, are based on human judgement and therefore affected by uncertainty. The uncertainty analysis showed quite clearly that small variations in the input maps are not likely to result in big changes in the final output. Moreover, some extra tests whose results are not included in this chapter suggested that even larger variations should not lead to dramatic modifications. Nevertheless, only uncertainty in the weights was considered, and not the uncertainty of the value functions. The analysis of value functions was not included in § 5.3 as this would have opened an entire new chapter that is not too relevant to the model itself. Usually, the assessment of value functions is conducted by experts who can understand how desirable each level of a criterion is within the framework of the decision at stake. The problem, especially when applying continuous value functions, is that it is extremely difficult to shape them precisely for each level of a given criterion. During a workshop recently conducted with the participants in the ReForLan project on criteria for identifying restoration priorities, the difficulty related to achieving an acceptable consensus among experts on the assessment of value functions was evident. For the purpose of this research, as simple functions as possible (i.e. linear or slightly convex) were defined.

However this topic would deserve a more thorough study to investigate the implications of such uncertainty on the final outputs of the model.

The fact that data on species were not abundant, and in particular lack of information on rare or threatened species, prevented the methodology from being truly species-specific. While constituting a significant limiting factor, this is typical of many of the most biologically diverse areas on Earth and calls for conservation practitioners to search for alternative efficient solutions (Gaston and Rodrigues, 2003). The methodology was instead based on environmental classes, whose identification was possible through the analysis of some topographic and climatic data. These were also not particularly abundant and some redundancy might have limited the reliability of the final classification. Nevertheless, the results of the analysis are coherent with the characteristics of the study area and thus fully suitable to the purpose of testing the methodology. Besides the idea of directing reforestation actions towards the protection of all environmental classes found on the study area, the prioritisation approach reflects in the criteria selected for generating maps for Z, R and E. Common to all of those is the concept of "potential species richness". The basic idea is that reforestation efforts should be primarily directed towards those areas whose characteristics are likely to make them capable of supporting the highest number of species. This supporting capacity depends also on several factors that evolve through time and that were mostly disregarded (e.g. human disturbance, etc.). Nevertheless, these are very difficult to define and even more difficult to include into the model. In the case of E, it is assumed that the decision-maker is more willing to give up for harvest those forest stands that are expected to support the least biodiversity. Some may not like the idea of giving up part of the existing forest and maybe they see it as a way of voluntarily sacrificing the current natural capital. On the other hand, it should be considered that very often an existing forest stand, due to its position and characteristics, might have a lower importance than a cleared land that gets reforested. Moreover, at the beginning of the time horizon, existing forest is the only one thing that can be harvested, while waiting for planted trees to grow for the satisfaction of future needs. The way this "potential species richness" index was computed is also dependent on contingent conditions. On the one hand, scarce data imposed the analysis of just those species that were representative of main forest types and for which available data were at least sufficient to obtain reliable outputs from the distribution model. On the other hand, an information was needed that could be easily transferred from forested lands (in the case of E) to cleared lands (in the case of Z and R). Although Maxent generates robust outputs even with extremely small sample sizes (less than 10 occurrence localities) (Pearson et al., 2007) and several runs were performed with varying parameters, the obtained potential species richness map may be affected by quite large errors that leave room for improvements. However, the results are likely to provide the biogeographical information that was looked for: identifying where a species can maintain populations. Criteria referring to fragmentation and pre-forested areas were selected for their ability to detect the problem of connectivity and degradation of current forest cover, respectively. R and E were also identified on the basis of criteria referring to accessibility. Distance from village is likely to produce compact patches around settlements, whereas distance from edge (in the case of E) reduces the risk of having people cross a protected forest to get timber. Neither the ability of harvested forest to protect biodiversity nor the effects of plantations on biodiversity were specifically accounted for. Nevertheless, R and E forest types are expected to be managed in a sustainable way, by programming a sound harvest schedule and promoting sustainable cutting techniques. Moreover, plantations can be effective in conserving indigenous biodiversity by bridging gaps in the original forest cover and protecting indigenous remnants (Norton, 1998).

Modelling the supply of timber to local communities needed several assumptions to be made. First of all, all people were supposed to need the same amount of timber for their lives, no matter other economic activities they might be involved in. In the real world instead it is likely that the largest villages (e.g. Guadalupe Victoria, Roblada Grande) significantly rely on agriculture and pasture and buy timber from elsewhere. Secondly, no particular attention was paid to the fact that different tree species may result in quite different outputs in terms of timber productivity and also different time to achieve the same productivity. Thirdly, the collection of timber was assumed to be entirely done by foot, while it is credible that also cars and trucks are used. All assumptions allowed the overall model complexity to be low, but the model is quite adaptable to incorporate different settings.

The cost of reforestation, though based on likely plantation costs, is largely hypothesized and may be very different from the real one. Nevertheless, the model accounts for costs to vary from place to place, just like it happens in the real-world.

This model is an innovative one that can respond many questions that still remain unanswered regarding how to re-shape a landscape to reconcile conservation with the support of livelihoods. To this extent, it seems to go in the direction identified by Rosenzweig (2003) and his ‘reconciliation ecology’ and may represent a first step towards integrating nature protection and poverty reduction in marginalised countries (Brockington et al., 2006). The model is an attempt to make the Forest Landscape Restoration approach a more tangible technique. It seems widely applicable to all those areas of the world where an exceptional biodiversity value is threatened by bad land use practices, while the presence of humans makes the strict ‘protected area approach’ inapplicable. In these contexts, a more accurate mix of conservation, restoration and sustainable use must be identified and translated into land use decisions.

Chapter 6

Conclusions

The main goal of this research was to develop and test spatial tools to support the application of the Forest Landscape Restoration approach. The work was driven by three specific objectives:

- the identification of criteria and indicators for the identification of forest restoration priorities;
- the definition of a multicriteria methodology to set reforestation options and evaluate them;
- the definition of a spatial optimization model to design the landscape mosaic.

The implementation of the FLR actually requires clear ecological indications about which areas should be accorded priority for forest restoration. A literature review of forest-related criteria highlighted a substantial lack of information on that. To tackle this problem an expert survey was conducted to verify whether consensus can be achieved and relevant criteria and indicators defined.

The multicriteria methodology was a first attempt to incorporate some of the key-concepts of FLR into a spatial decision support tool . Using basic GIS and mathematical techniques, it was possible to generate reforestation options that are expected to improve the overall landscape functionality, and eventually to assess their ecological and socioeconomic performance.

Finally, spatial optimization techniques were applied to re-design the landscape mosaic such that its conservation value is enhanced and the provision of ecosystem services to people guaranteed.

In this chapter the main findings of the research, grouped by the three specific objectives, are discussed by reviewing their strengths and weaknesses and proposing some recommendations for future research.

6.1 Criteria and Indicators

6.1.1 Main findings

This part of the research has focused on a topic that is oten disregarded in most restoration (and conservation) studies: the identification of criteria and indicators. Most of the studies indeed start from an arbitrary set of criteria which are then applied without discussion on their relevance. This research instead took advantage of expert knowledge to explore the issues that are likely to be most relevant towards the identification of forest restoration priorities. The elicitation of experts'opinion resulted in a total of 380 criteria and more than 600 related indicators. The criteria were grouped into 20 and 18 clusters referring to the need for restoration and its feasibility, respectively. The second round of the Delphi survey allowed clusters to be reduced to 8 and indicators to around 90. During the final face-to-face meeting the 8 criteria, 5 referring to the need for restoration and 3 to the feasibility of restoration, were assumed to be describable by means of 22 indicators, 14 for the first group and 8 for the second one. The final list of criteria was supported by a significant higher consensus than that obtained by rejected ones, showing that some concepts are likely to be more significant than all the others. Important concepts are stressed in the list, such as: fragmentation and connectivity, degradation, disturbance, natural regeneration potential and species richness. The latter, which is also appearing in the WCMC's list (2000), was further differentiated between diversity at the species level and diversity at the ecosystem/landscape level. It is interesting to note that 'degradation' and 'disturbance' appear both in the list referring to the need for restoration (B) and that referring to the feasibility of restoration (F). This is a strong confirmation of the hypothesis that the actual feasibility of the restoration process plays a major role in deciding where to concentrate the efforts first. This result leads to suppose that when it comes to practice, restoration practitioners and decision-makers will seek for a sensitive balance between the actual need for restoring and the probability that the restoration can take place in a reasonable time frame.

6.1.2 Strengths and weaknesses

Strengths

This has been the first attempt to apply the Delphi technique to the elicitation of expert's judgement on the definition of C&I for identifying restoration priorities. The results were quite encouraging on the effectiveness of the method towards obtaining a final compact result. This kind of problems is hardly manageable through other methodologies, in that no empirical knowledge exists but the expertise of people who have been working on the topic for several years. The proposed approach is a slight evolution of the traditional Delphi survey technique. It involves two classical Delphi rounds and a final face-to-face meeting with a restricted number of participants. This structure proved to be effective in handling what is commonly known as the main drawback of the Delphi technique, namely the time needed to get to the final results (Gordon, 1994). The face-to-face meeting allowed final list to be more compact and readily applicable. This was particularly relevant to this case, which did not just involve a selection procedure, but rather a design and selection procedure. A traditional Delphi approach would have required an additional round which would have caused a significant loss of participants. The two Delphi rounds had prepared the ground so that the face-to-face discussion could start on solid roots and be as fruitful as possible. The first main result, that is the two extended lists of criteria and indicators, provides restoration practitioners with a wide range of concepts that deserve attention when planning a restoration action. The final short list instead represents a ready-to-use tool for the practical implementation of restoration plans. The main added value of the final criteria and indicators is represented by their spatial and operational character. Most of the proposed indicators can actually be computed with basic GIS operations and possibly allow a decision-maker to rapidly visualize on a map where the restoration action is more urgent and/or feasible.

Weaknesses

The major shortcoming is the perceived arbitrariness of the selcted C&I. Some may argue that the Delphi is guaranteed to provide an answer that may or may not have any meaning. It is also true that this could have been said also of a different approach based on the analysis of a vast literature review of restoration projects around the world. The basic problem is that when no empirical knowledge is available, expert judgement is often the only possibility to obtain an insight into a topic. In this context, the effectiveness of the Delphi is supported by substantial literature (Crance, 1987; Hess and King, 2002). Moreover, the size of the adopted sample of experts (37) and their varied expertise in forest restoration worldwide was supposed to minimize such risks. Again, it should be remembered that the real limitations of the Delphi are mainly two: the time needed for its application, and its poor effectiveness when dealing with issues requiring minimal judgement and for which better solution techniques exist (Gordon, 1994). Arbitrariness is also perceived as a consequence of the simplifications and assumptions (e.g. clustering) that were made during the process. These were needed for re-arranging the huge amount of data collected (i.e. hundreds of criteria and indicators) and make them suitable for analysis at the next Delphi round. Such simplifications may actually have affected the final results and in particular they may have led to loss of information. At the same time, obtaining a final short list was more than just an efficiency goal; rather it was an attempt to make the results actually manageable by restoration practitioners. A question is also emerging: would different C&I have been identified had a different group of experts participated in the survey? The answer is: yes, they would. Of course, there could have been some differences, but the consensus rates that were measured on the finally selected criteria suggest that those specific concepts have an outstanding importance towards the definition of priority sites for forest restoration.

6.1.3 Recommendations for future research

The identification of C&I does not ensure, by itself, that these are meaningful and effective in identifying forest restoration priorities. While raising issues that do matter towards identifying restoration priorities, their effectiveness must be necessarily tested on the ground. An initial problem is redundancy: some indicators may be already explained by others and therefore not contributing to the final result. To address this issue indicators should be computed at several potential restoration areas and their relative independence checked by means of multivariate statistics. This is expected to result in a minimum set of independent criteria and indicators to be applied. Such set is not likely to be the same across any possible forest landscape. The second major field of improvement concerns the evaluation of indicators. This refers to the task of evaluating the desirability of each criterion level towards the prioritisation goal. This point can be clarified through an example. If we consider the indicator ‘distance from nearest forest patch’, a basic evaluation is summarised by the question: is the restoration priority higher near the forest patch or far from it? A more thorough analysis should assess how the priority changes at varying distances from the forest patch in this case. Talking to experts involved in the ReForLan project has shown that this task is not an easy one at all, as views on some topics may be opposite. While there is a wide consensus on a given indicator, there are different opinions on how to evaluate it. We should say that forest restoration is naturally characterised by different views. Nevertheless, for a specific restoration plan, a shared vision has to be searched for to actually implement the plan. At the very least, this vision should involve a shared opinion about whether, for a given indicator, restoration priority is likely to increase when the indicator score increases or vice versa. Finally, there is the problem of combining criteria and indicators to provide a unique information about the restoration priority of a given site. Multi-Criteria Decision Analysis provides a number of different methods (e.g. weighted linear combination, multiplicative functions) to combine criteria, but their effectiveness must be tested in the field. Both the evaluation and the combination of criteria and indicators are heavily affected by uncertainty. However, uncertainty is somehow physiological of this topic, and it is hardly reducible. Too many opinions and experiences are involved in defining whether or not a site is a priority. What can be done is actually to deal with uncertainty and turn it into a useful indication rather than a mere limit. In Chapters 4 and 5, some techniques to deal with uncertainty were investigated. In general terms, the future development of this research theme is the testing of the proposed C&I. Only their actual measurement on different locations can provide sufficient information to assess redundancies, while field work can help evaluating them. Applications to several case studies can suggest which set is the most reliable and widely applicable one.

6.2 Multicriteria methodology

6.2.1 Main findings

In Chapter 4, a GIS-based methodology was proposed to identify reforestation priorities, to design a number of landscape-scale reforestation options and to evaluate them with respect to a set of ecological and socioeconomic criteria. In the end, 14 reforestation options were obtained that ensure sufficiently high reforestation priority and feasibility according to the proposed prioritisation criteria. The options also satisfied the reforestation demand (i.e. the total area that the decision-maker is willing to reforest) and presented compact patches. The reforestation options covered a total area of around 28,000 ha of which one fourth was selected by all options. This emphasised some considerable differences among options, but also the existence of a core area, whose extension is half the reforestation demand, that has a 100% probability of being selected for reforestation. In terms of socio-ecological performance, the options showed some significant variations, but two of them (9 and 10) seemed to be guaranteeing higher standards under any evaluation perspective. The study showed that it is possible to design reforestation options that ensure ecological benefits (e.g. increased connectivity), while not harming livelihoods (e.g. low conversion costs).

6.2.2 Strengths and weaknesses

Strengths

The proposed methodology is among the first attempts to turn the FLR principles into planning tools. In particular, the concepts of restoration priority, provision of ecosystem services and protection of livelihoods are taken into account. The methodology enables the potential user to generate relevant reforestation options by defining only three parameters: the total reforestation demand and two thresholds defining what can be considered a priority. This seems coherent with the role of a decision-maker, who knows how much he will be able to reforest and which areas he wants to accord more priority to. The approach does not limit to the simple selection of the best reforestation sites, but it starts from the actual design of such sites. This is fundamental when implementing the FLR, as very often small variations in the shape of reforestation sites can bring huge modifications on the final output. The idea of just looking at available sites and selecting the supposedly best ones is simply a non-sense. The use of basic GIS operations and mathematical concepts make the methodology user-friendly. The lack of time-consuming computations allow large datasets to be easily processed, which can be a common issue when planning restoration actions at the landscape scale. The threshold-based method is an innovative one in that it allows a non-compensatory principle to be implemented (e.g. a given area is a priority if it is sufficiently in need for restoration and sufficiently likely to make the restoration succeed) and uncertainties to be dealt with. The application of geostatistics allowed an information about poverty to be extrapolated and poverty trends across the region to be simulated. This shows how advanced spatial tools can be applied to socioeconomic data to generate an information that can be easily coupled with ecological data (Goodchild et al., 1993).

Weaknesses

A major limit of the approach is that it does not allow the user to a priori define targets on both conservation and livelihood standards. It might arise that the higher (or the lower) is always the better. Conservation practice instead is often about allocating a given amount of land for the protection of a given species or habitat. On the socioeconomic side, no constraints can be established such that, for example, the conversion of agricultural fields is not beyond a given limit. The methodology allows a set of options to be identified that satisfy some basic requirements (high restoration priority, high expected restoration feasibility, satisfaction of a given reforestation demand), and then it enables the user to judge which option is the best one. This problem might partly be addressed by paying great attention during the assessment of value functions. The final non-spatial multicriteria analysis might take advantage of goal-based value functions. That is, each option should be evaluated on the basis of minimum targets to be achieved. In general terms the assessment of value functions is a critical part of the methodology and the related uncertainty is likely to heavily affect the final results. Several assumptions have been made to make the implementation easier and some of them might be seen a bit simplistic. First of all, restoration is not just reforestation. Only the latter was considered here to have an unequivocal information about which land is available for restoration (i.e. unforested areas out of urban centres). Restoration should also occur on degraded forest, but data on degradation (e.g. NDVI) were not available. The proxy for species richness is actually an extreme choice, but I was forced to that as no information was available at a fine enough scale and other data on the presence of species (e.g. plots) were unavailable or insufficient. The massive use of distance-based proxies is also a limiting factor of this approach, but one that allows information to be generated at each cell location. It is also very common in problems of spatial decision-making. The final multicriteria analysis falls short of exploring the link between poverty and forest. The assumption is that reforesting poorest regions means providing forest-related services in those areas where people need them more. This is maybe true, but the ways through which to deliver these services should be studied more in detail to assess the effectiveness of the plan towards poverty reduction.

6.2.3 Recommendations for future research

The methodology has great potential for turning the FLR principles into an applicable plan on the ground. In order for this to be possible however, some further effort is needed to prepare a robust dataset, evaluate the proposed criteria and involve stakeholders. Data preparation is often a big issue in poor regions, as information has low quality or it is missing. Investing some considerable resources into data collection and preparation would actually allow the users to apply those criteria and indicators that are expected to better explain the system. The evaluation of criteria should take advantage of the contribution of experts. Restoration practitioners would provide an invaluable contribution to the assessment of value functions that account for the characteristics of the specific context. The involvement of stakeholders (e.g. administrators, community representatives) can give great contribution to the social sustainability of the restoration project. The third step of the methodology (i.e. the selection of the best reforestation option) might be modified for integrating the expectations and views of stakeholders. Participatory techniques should be implemented that enable stakeholders to comment on the maps of potential options and their opinions to be integrated to select the best option. This approach would split the methodology in two parts: the first one primarily involving experts for the identification of restoration priorities based on ecological criteria, and the second one involving stakeholders to identify the most acceptable option. Finally, more attention should be paid to the forest-poverty link. On the one hand, survey and census data should be handled carefully to obtain a reliable description of the type and entity of poverty over the landscape (Minot, 2000). On the other hand, an in-depth analysis should be carried out to assess how a given type of poverty is affected by forest conditions and how it contributes to modifying forest conditions. To this purpose, the problem of accessibility to forest resources is a relevant one, both in terms of opportunity (e.g. use) and threat (e.g. degradation). The involvement of stakeholders is again crucial to the achievement of these objectives.

6.3 Spatial optimization model

6.3.1 Main findings

In Chapter 5, a spatial optimization model for the restoration of forest landscapes was presented. The model is an original piece of work with respect to current literature in that it integrates the approach of land allocation models (Aerts et al., 2003) with the concept of in-site use of natural resources (Allen, 1985). The results of an application in central Chiapas showed that designing the landscape mosaic proposed by the FLR theory is actually feasible by considering also the preservation of the livelihoods systems. This was achieved by devoting about 60% of the total reforested area to protection and leaving the remaining part available for harvest. Also, a very small portion of the existing forest (around 6% of the total reforestation area) had to be given up for satisfying the timber need of local human communities. It was shown that it is possible to find new configurations of the landscape that ensure accessibility to harvestable forest stands, provision of ecosystem services (e.g. soil stabilisation) and the conservation of a region's environmental classes. All of this was possible by converting to forest, in the worst case, as much as 10% of a village's agriculture or pasture areas. Trade-off analyses highlighted that moderate increases in the amount of erosion-prone land to be stabilised do not dramatically affect the ability of the model to allocating a reforestation use to highly suitable areas. Only when the stabilisation objective is raised at the highest levels, the trade-off is strongly unbalanced and a considerable amount of the existing forest has to be given up for harvest. The analysis conducted to account for the uncertainty of the input data (e.g. weighting of criteria) highlighted the stability of the final result. In particular, more than 50% of the cells selected for reforestation have a 100% probability of being selected, at varying input. The model also provided a confirmation about the effectiveness of suitability maps in generating compact outputs.

6.3.2 Strengths and weaknesses

Strengths

The model provides a credible solution to the problem of conserving biologically diverse areas in the presence of human communities. This is possible because the identification of accessible forest stands from which to collect timber helps protecting forests of higher conservation value. This is the first attempt to include the accessibility issue from the point of view of local people who reach the forest stands by foot. Existing models are suitable when new land use allocations should be identified, but would not provide any answer about how to satisfy people's needs of natural resources. This makes the model widely applicable in a number of regions of the world where conservation efforts must be made in the presence of small human communities dependent on locally available natural resources. The model also accounts for the economic sustainability of the reforestation plan. On the one hand, the budget constraint limits the total reforestation size. On the other hand, the conversion to forest of economically strategic land uses (i.e. agriculture, pasture) is limited around each village. The model is optimal, which means that, in the region of feasible solutions, it always finds the optimal one. The decision of using a set formulation and the relaxation problem ensured high speeds to the model, despite the size of the dataset (more than 160,000 variables and 115,000 constraints). This is obviously a great advantage in the practical implementation for having quick feedbacks.

Weaknesses

Among the major problems of the proposed method is the lack of an analysis about how the harvestable forest contributes to the goal of nature conservation. We assumed that the sustainable management of the forest is likely to provide ecological benefits and this is the reason why the prioritisation of R is based on the same criteria as the prioritisation of Z. The idea is that financial resources should be devoted to the reforestation of the more ecologically important areas, no matter if these areas will then be protected or available for harvest. Then, of course, conservation entities must be reforested by a minimum amount of protected forest and all financial resources exceeding the satisfaction of communities' needs are devoted to reforestation and protection. Some assumptions have made the implementation of the model easier but also less coherent with the real-world dynamics. Probably most of these assumptions refer to the supply-demand modelling. Timber needs were estimated on the basis of only one tree species, while in the real-world several species contribute to a person's own need. Another assumption was that all the people in the village rely on timber in the same way and that the transportation of timber is entirely done by foot. Fixed amounts of trees per hectare were assumed to be harvestable from all existing forests across the landscape, because no previous analyses on the productivity of forest had been conducted. This problem was partly addressed by considering very low harvestable amounts (200 trees/ha) on existing forest, which is then expected not to be heavily degraded. Finally, the model, besides biodiversity and timber, considers only one ecosystem service, namely soil stabilisation, thus providing a partial response to the issue of optimizing benefits for people and nature.

6.3.3 Recommendations for future research

The major area for improvement refers to the inclusion of the time component into the model. The forest landscape is obviously a dynamic entity. In this application an 8-year time horizon was considered, and all computations were based on that. Further research is needed to build up a time step approach, and to provide a clearer information about what to do at each time step and what the landscape will be like at the same step. In particular, harvest schedules should be designed to develop an exploitation plan that can be sustainable by forests and people. Space and time are two keywords of the FLR approach: conservation and livelihood benefits can be achieved if a set of technical solutions are applied at different sites over the landscape and different steps through time. In extremely poor regions a crucial issue is that of giving livelihoods a strong push at the beginning to actually make people capable of taking care of nature. To this purpose, models are needed that provide decision-makers with a sort of road map describing the technical solutions to be applied at each site and each time step for achieving multiple benefits in a reasonable time frame. The model provides a sound basis for this development and, most of all, it delivers an important and sometimes neglected concept: that nature conservation and human well-being should be embraced together in order to have biodiversity protected in the long run.

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Appendices

Appendix 1 contains the questionnaire distributed among experts during the first round of the Delphi survey described in Chapter 3.

Appendix 2 contains the questionnaire distributed among experts during the second round of the Delphi survey described in Chapter 3.

Appendix 1

Delphi survey: part one

TASK 1. Your geographical expertise

Please enter your work experience in the geographical regions of the world by checking the relevant boxes.

	None	Moderate	Good	Very good
Europe				
North America				
Caribbean				
Latin America				
Africa				
Asia				
Middle East				
Oceania				

Comments:

TASK 2. Your ecological expertise

Please enter your work experience in different habitats* by checking the relevant boxes.

	None	Moderate	Good	Very good
Boreal coniferous forest				
Boreal mountain				
Boreal tundra woodland				
Temperate continental forest				
Temperate mountain				
Temperate oceanic forest				
Temperate steppe/prairie				
Subtropical desert				
Subtropical dry forest				
Subtropical humid forest				
Subtropical mountain				
Subtropical steppe				
Tropical desert				
Tropical dry forest				
Tropical moist deciduous forest				
Tropical mountain				
Tropical rain forest				
Tropical shrubland				
Mangrove				

* The classification of forest habitats is the one proposed by the Forest Restoration Information Service of UNEP-WCMC (http://www.unep-wcmc.org/forest/restoration/).

Comments:

TASK 3. Attributes and measures that lead to the identification of areas that should be accorded priority for biodiversity restoration.			
Please list the attributes that you consider to be important, and if possible justify your choice, provide a rating of importance in a 1-4 scale (1 = weakly important; 2 = moderately important; 3 = quite important; 4 = extremely important), and associate to each attribute one or more measures.			
Attributes	**Important because**	**Rating (1-4)**	**Measures**
1.			
2.			
3.			
If you need more space, just add new rows to the table.			
Comments:			

TASK 4. Attributes and measures that influence whether or not restoration is feasible on a particular site.			
Please list the attributes that you consider to be important, and if possible justify your choice, provide a rating of importance in a 1-4 scale (1 = weakly important; 2 = moderately important; 3 = quite important; 4 = extremely important), and associate to each attribute one or more measures.			
Attributes	**Important because**	**Rating (1-4)**	**Measures**
1.			
2.			
3.			
If you need more space, just add new rows to the table.			
Comments:			

Appendix 2

Delphi survey: part two

TASK 1. Attributes and measures that lead to the identification of areas that should be accorded priority for biodiversity restoration.				
Attributes	**Check the most important attributes** **(up to 8)**	**Measures**	**Check the most important measures (up to 3 per attribute)**	**Comments** (e.g. measurement units, sampling methods, etc.)
1.Climatic conditions		1.1 Humidity		
		1.2 Precipitation		
		1.3 Temperature		
2. Disturbance		2.1 Amount of area logged (ha)		
		2.2 Area of vegetation type after disturbance / area of vegetation type before disturbance*		
		2.3 Area / Perimeter		
		2.4 Density of stream crossings		
		2.5 Distance from roads		
		2.6 Disturbance classification (natural, human induced, current, potential)		
		2.7 N. of people depending upon the ecosystem		
		2.8 N. of people living within the ecosystem		
		2.9 Natural Disturbance Type (NDT) classification		
		2.10 Road density		
		2.11 % of agricultural area		
		2.12 % of area logged by slope class		
		2.13 of invasive species		
		2.14 % of populated area		
3. Connectivity - Corridors		3.1 Amount of interior habitat within a unit		
		3.2 Corridor length		
		3.3 Corridor width		
		3.4 Distance from protected sites		
		3.5 Linkages between habitat units		
		3.6 Presence or absence of wild areas connected to the restoration area		
		3.7 Types of linkages		

Attributes	Check..	Measures	Check..	Comments (e.g. measurement units, sampling methods, etc.)
4. Diversity (ecosystem and landscape level)		4.1 Altitudinal variation		
		4.2 Amount of dead wood		
		4.3 Amount of deciduous trees		
		4.4 Azimuthal variation		
		4.5 Canopy cover		
		4.6 Diversity of soils		
		4.7 Landscape functional diversity		
		4.8 Landscape structural diversity		
		4.9 Presence or absence of diverse ecosystem at the landscape scale		
		4.10 Presence or absence of water		
		4.11 Quality of dead wood		
5. Diversity (species level)		5.1 Abundance		
		5.2 Age		
		5.3 Beta diversity (complementarity of species communities)		
		5.4 Evenness		
		5.5 Fisher's Alpha		
		5.6 Forest density		
		5.7 N. of birds		
		5.8 N. of endemic species		
		5.9 N. of interactions among species		
		5.10 N. of keystone species		
		5.11 N. of keystone species lost		
		5.12 N. of major vegetation types		
		5.13 N. of native species / N. of exotic species		
		5.14 N. of TER species		
		5.15 Presence or absence of non-game species		
		5.16 Shannon diversity		
		5.17 Species richness		
		5.18 % live / dead (mortality)		

Attributes	Check..	Measures	Check..	Comments (e.g. measurement units, sampling methods, etc.)
6. Diversity (genetic level)		6.1 Adaptive traits		
		6.2 Canopy cover		
		6.3 Genetic diversity among populations		
		6.4 Isozymes		
		6.5 N. of stems / ha by size class		
		6.6 Neutral markers		
		6.7 Nuclear inheritance		
		6.8 Species-specific microsatellites		
7. Ecosystem services		7.1 Carbon sequestration / Productivity		
		7.2 Distance from water		
		7.3 Elevation		
		7.4 Slope		
		7.5 Soil retention (mass/ha)		
		7.6 Water provision (yield)		
8. Fragmentation		8.1 Area of the fragments		
		8.2 Core area		
		8.3 Forest patch density		
		8.4 Isolation		
		8.5 N. of fragments		
		8.6 Proximity		
		8.7 Representativeness of the ecosystem in the world (%)		
9. Habitat availability		9.1 % ecosystem type by habitat type by region (medium filter)		
		9.2 % ecosystem type by habitat type by watershed (500-5000 ha) (fine filter)		
		9.3 % habitat type by region (coarse filter)		
10. Historically forested area		10.1 Areas that were historically forested		
11. Landscape degradation		11.1 Deforestation rate		
		11.2 Fire frequency		
		11.3 Freq. of landslides		
		11.4 Land use change (%)		
		11.5 N. of landslides		
		11.6 Pollution indices		
		11.7 Road density		
		11.8 Soil erosion		
		11.9 Volume of sediment-debris		

Attributes	Check..	Measures	Check..	Comments (e.g. measurement units, sampling methods, etc.)
12. Protected areas		12.1 Distance from protected areas		
		12.2 Presence or absence of protected areas		
13. Rarity		13.1 Presence or absence of rare species		
		13.2 Representation of biotype in the broader landscape		
		13.3 Uniqueness index		
14. Remnants		14.1 Amount of primary and secondary forest at varying distances		
		14.2 Distance from edges of forest		
		14.3 Distance from forests of certain size		
		14.4 Distance from remnant vegetation		
		14.5Distance from seed sources		
		14.6 Presence or absence of adjacent areas with land use types suitable for restoration		
		14.7 Presence or absence of remnant vegetation		
		14.8 Presence or absence of seed dispersers		
		14.9 Tree and shrub density		
15. Size		15.1 Area		
		15.2 Area needed for restoring a vegetation type		
16. Soil conditions		16.1 N soil content		
		16.2 Organic matter content of upper soil horizon		
		16.3 P soil content		
		16.4 Soil macrofauna abundance		
		16.5 Soil respiration		
		16.6 Soil texture		

Attributes	Check..	Measures	Check..	Comments (e.g. measurement units, sampling methods, etc.)
17. Vegetation structure		17.1 Height distribution		
		17.2 Horizontal structure: coarse woody debris-amount, size, level of decay		
		17.3 Plant – strata diversity		
		17.4 Structural stage		
		17.5 Tree diameters		
		17.6 Vertical structure: plant species composition, snags/wildlife trees-level of decay, cavity trees		
18. Degree of threat		18.1 Area with threatened species		
		18.2 N. of red list species		
		18.3 Presence or absence of red list species		
		18.4 % of endangered forest		
		18.5 % of remained forest		
19. Water ecosystem		19.1 Alkalinity		
		19.2 Bank height		
		19.3 Channel depth		
		19.4 Channel width		
		19.5 Dissolved O_2		
		19.6 Distance from large rivers		
		19.7 Hardness		
		19.8Length of water courses in the restoration areas		
		19.9 Peak flow		
		19.10 pH		
		19.11 Water clarity		
		19.12 Wetness index (Russell *et al.*, 1997)		
		19.13 Width of active floodplain		
20. Recreation		20.1 Amenity value		
		20.2 N. of people visiting the area		
		20.3 Visual impact assessment		

* The measures expressed as “…” / ”…” are ratios.

Comments

TASK 2. Attributes and measures that influence whether or not restoration is feasible on a particular site.				
Part a. Ecological attributes				
Attributes	**Check the most important attributes** (up to 4)	**Measures**	**Check the most important measures** (up to 3 per attribute)	**Comments** (e.g. measurement units, sampling methods, etc.)
1. Accessibility		1.1 Distance from centres of appropriate capacities		
		1.2 Distance from transport infrastructures		
		1.3 Distance from cities		
		1.4 Geomorphology		
		1.5 N. of available vehicles		
		1.6 Type of roads		
		1.7 Type of vegetation		
2. Climate		2.1 Climate change parameters		
		2.2 Rainfall		
		2.3 Relative humidity		
		2.4 Wind		
3. Land use conflicts		3.1 Differential land cover use transformation rates		
		3.2 Land use		
		3.3 Landscape development plans		
		3.4 Presence or absence of abandoned lands		
		3.5 Presence or absence of private properties		
		3.6 Presence or absence of utilities (power lines, etc.)		
		3.7 Suitability of land for alternative land uses		
		3.8 Transformation matrix for each land cover type		
4. Degradation level		4.1 Amount of old-growth trees		
		4.2 Amount of remnant vegetation		
		4.3 Amount of seed dispersers		
		4.4 Compaction		
		4.5 Erosion of topsoil		
		4.6 N. of pioneer species		
		4.7 N. of remnant tree species		
		4.8 Nutrient depletion		
		4.9 Soil fertility		
		4.10 Species richness		

Attributes	**Check..**	**Measures**	**Check..**	**Comments** (e.g. measurement units, sampling methods, etc.)
5. Disturbance		5.1 Amount of herbivory		
		5.2 Fire frequency		
		5.3 Land use		
		5.4 Livestock data		
		5.5 N. of invasive species		
		5.6 People / Km^2 *		
		5.7 Presence or absence of invasive species		
		5.8 Presence or absence of noxious weeds		
		5.9 Presence or absence of pests and diseases in the region		
		5.10 Regeneration ability of invasive species		
		5.11 Road density		
		5.12 Type of livestock		
6. Forest characteristics		6.1 Calliper – diameter		
		6.2 Diversity		
		6.3 Historical forest composition and structure		
		6.4 Landscape Biological Survey of Vegetetion (LaBiSV)		
		6.5 N. of exotic species		
		6.6 N. of forest patches		
		6.7 N. of stems or ha by size class		
		6.8 Patch distribution		
		6.9 Presence or absence of desired plant species		
		6.10 Presence or absence of mycorrhizae		
		6.11 Presence or absence of old growth forest		
		6.12 Presence or absence of secondary forest		
		6.13 Species richness		
		6.14 Tree height		
		6.15 Uneven-aged / even aged forest		
		6.16 % live / dead		
		6.17 % threatened plants		
		6.18 % tree - plant species composition as a deviation from a baseline such as site series or late-seral plant community		

Attributes	Check..	Measures	Check..	**Comments** (e.g. measurement units, sampling methods, etc.)
7. Natural regeneration potential		7.1 Distance from natural forest		
		7.2 Distance from protected areas		
		7.3 Distance to seed sources		
		7.4 Growth potential		
		7.5 N. of birds		
		7.6 N. of seed trees and shrubs		
		7.7 Pests and diseases adaptability		
		7.8 Presence or absence of minimal biotic structures		
		7.9 Presence or absence of biological corridors		
		7.10 Presence or absence of unique genetic variants at populations using neutral markers, such as isozymes, microsatellites or DNA sequences		
		7.11 Rhizomes and root material		
		7.12 Seedling density		
		7.13 Survival capacity		
		7.14 Syndromes classification of the landscape unit		
		7.15 Wind direction		
		7.16 % of species with different dispersal modes		
8. Size of habitat		8.1 Area		
		8.2 N. of fragments		

Attributes	Check..	Measures	Check..	**Comments** (e.g. measurement units, sampling methods, etc.)
9. Soil		9.1 Acidification of the substrate		
		9.2 Altitude		
		9.3 Aspect		
		9.4 Bedrock type		
		9.5 Bulk density		
		9.6 Cation exchange capacity		
		9.7 Compaction		
		9.8 Concentrations of heavy metals		
		9.9 Concentrations of pesticides		
		9.10 Daily and annual temperature fluctuation		
		9.11 Depth		
		9.12 Erosion		
		9.13 Fertility		
		9.14 Microbial communities		
		9.15 Organic matter (%)		
		9.16 pH		
		9.17 Plant-available P		
		9.18 Precipitation		
		9.19 Presence or absence of toxic chemicals		
		9.20 Presence or absence of toxins		
		9.21 Slope		
		9.22 Slope below 35 %		
		9.23 Soil type		
		9.24 Structure		
		9.25 Total N		
10. Water availability		10.1 Annual precipitation		
		10.2 Aridity and humidity index		
		10.3 Distance from rivers		
		10.4 Elevation above the average groundwater level		
		10.5 Field capacity of the soil		
		10.6 Infiltration rate		
		10.7 Precipitation distribution		
		10.8 Soil depth		

Part b. Socio-economic attributes				
Attributes	**Check the most important attributes** **(up to 4)**	**Measures**	**Check the most important measures (up to 3 per attribute)**	**Comments** (e.g. measurement units, sampling methods, etc.)
11. Economic sustainability		11.1 Amount of food provided		
		11.2 Amount of wood provided		
		11.3 N. of economically important species		
		11.4 Price of products		
12. Forest governance		12.1 Inspections		
		12.2 Laws and regulations		
13. Land ownership		13.1 Area of ownership		
		13.2 Pattern of land ownership and tenure		
		13.3 Public or private owner		
14. Monitoring		14.1 Amount of funds		
		14.2 Partnerships		
15. Political will		15.1 Amount of incentives		
		15.2 Amount of resources invested		
		15.3 N. of institutions involved		
		15.4 Presence or absence of incentives		
		15.5 Subsidies or fines to stimulate or discourage restoration activities		
16. Restoration costs		16.1 Area to be restored		
		16.2 Cost of fences		
		16.3 Economic value of land		
		16.4 Labour cost		
		16.5 Monetary cost		
		16.6 Perimeter		
		16.7 Seedling production cost		
17. Technical knowledge		17.1 Presence or absence of technical information		

18. Willingness of locals		18.1 Amount of community investment		
		18.2 Degree of interest (assessed via surveys)		
		18.3 N. of NGOs working in the area		
		18.4 N. of people interested		
		18.5. N. of programs of environmental education		
* The measures expressed as "…" / "…" are ratios.				
Comments				