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# Restoring forest landscapes for biodiversity conservation and rural livelihoods: A spatial optimisation model

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A B S T R A C T

Conserving nature in the presence of humans is especially challenging in areas where livelihoods are largely based on locally available natural resources. The restoration of forests in such contexts calls for the identification of sites and actions that improve biodiversity protection, and ensure the provision of and accessibility to other forest-related ecosystem services. This paper introduces an integer-linear programming (ILP) approach to identify reforestation priorities that achieve such goals. Applications of ILP to nature conservation are many, but only a few of them deal with the problem of restoration, and none of the available models considers the basic needs of the local population. Given constraints on a restoration budget, the potential conversion of productive lands and the travel time to reach harvestable forest, the model maximises the amount of reforestation area (weighted by priority values) and minimises the harvesting of existing forest, while ensuring the conservation of landscape diversity, the satisfaction of timber demands and the stabilisation of erosion-prone land. As an input, suitability maps, generated through a combination of ecological criteria, are used to prioritise the selection of reforestation sites. An application to a 430 km$^2$ area in Central Chiapas (Mexico) resulted in compact patches and thus a manageable reforestation plan. Acceptable trade-offs were found between the amount of soil stabilisation possible and the prioritisation goals, while uncertainty in the prioritisation scores did not significantly affect the results. We show that restoration actions can be spatially designed to benefit both nature and people with minimal losses on both sides.



## 1. Introduction

Over the last three decades, conservation biologists have focused considerable attention to the dilemma of how to select natural reserves (see for example, 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 have taken advantage of advanced techniques from operations research and heuristics. While several studies have paid minimum attention to the actual economic feasibility of a conservation plan or model solution, an increasing number of authors have been investigating the strict inter-connections between biological and economic benefits (Calkin et al., 2002; Nalle et al., 2004; Polasky et al., 2005, 2008). Other studies (Ruliffson et al., 2003; Önal and Yanprechaset, 2007) have shown that it is possible, and needed, to plan effective conservation actions in areas where people live and work (Miller and Hobbs, 2002). Consistent with that, models and software packages have been developed that enable planners to account for socioeconomic issues in conservation planning (Watts et al., 2009; Huang et al., 2010).

Despite the excellent work conducted, these studies, usually based on large-scale economic revenues, disregard the issue of local people's livelihoods. This is perhaps a negligible issue in developed 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. In subsistence economies, establishing a conservation area often results in precluding the use of easily accessible

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resources by indigenous and local populations, thereby forcing most of the conservation costs to be effectively paid by the local subsistence population (Roe and Elliott, 2004). This is actually an important but missing theme in the modelling debate: models give pixels or habitat units a conservation status but do not effectively account for the occurrence and needs of human settlements in or around those pixels or habitat units. Unfortunately, neglecting such an important issue will undermine the success of the conservation effort: areas in proximity of a village will only be protected if villagers are given alternatives for obtaining the resources they need. The sustainability of conservation projects is likely to be achieved only 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 necessity in order to enhance conservation values and protect biodiversity from further degradation (Hobbs and Norton, 1996). Models have been developed to help determine cost effective actions (Crossman and Bryan, 2006; Westphal et al., 2007; Bryan and Crossman, 2008; Stralberg et al., 2009; Lethbridge et al., 2010). Among all threatened ecosystems, forests are disappearing at a rate of around 13 million hectares per year on a global scale (FAO, 2006). Not only is such degradation leading to significant losses of biodiversity worldwide, but it is also reducing the provision of a number of forest-related ecosystem services (e.g. soil stabilisation, watershed protection). Forest restoration actions must be taken that enhance biodiversity conservation, while preserving livelihoods (Lamb et al., 2005). This concept has been incorporated in an official restoration approach proposed by the IUCN and the WWF in 2001 known as the Forest Landscape Restoration (FLR) approach (Lamb and Gilmour, 2003). By definition this approach is not aimed at bringing the ecosystem back to a pristine state but rather at building up a forest-based landscape that benefits both nature and people (Maginnis and Jackson, 2002). From a planning perspective this approach rests on answering the following types of questions: where to act first, which interventions to carry out, which proportion of the landscape to restore, and how to satisfy the communities' need of forest products. The underlying concept is that only a sound re-configuration of the landscape mosaic is likely to produce an acceptable trade-off between conservation and human well-being (Lamb et al., 2005). 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 enhance other kinds of ecosystem services.

When it comes to conservation and restoration planning models, it is common to define whether a landscape unit has been allocated for restoration by the use of a binary decision variable ('yes' or 'no'): that is a unit can either be assigned for restoration or not. Mathematical optimisation models which are based upon a set of binary decision variables are known as Integer-Linear Programming (ILP) problems (Underhill, 1994; Csuti et al., 1997). The main advantage of this type of optimisation model, when compared to other methods such as heuristics, is that specific algorithms are available to solve many problems and applications of reasonable size to guaranteed optimality. When problem sizes are too large then a heuristic must be used where no such guarantee of optimality is possible (Underhill, 1994). The need of generating a provable optimal solution in a conservation planning problem has been questioned in the light of the main advantages of sub-optimal/heuristic approaches, namely fast 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 packages allow modelers/analysts to process significantly larger datasets and models to optimality than what was possible in the past. Applications of ILP to conservation planning are many (see for example 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; Bryan and Crossman, 2008). However, none of these models considers the basic needs of the local population. Failing to account for the location of villages and the needs to the villagers will likely result in a solution that will be difficult at best to implement, or even be thwarted by continuing local activities.

To address the basic problem raised above, we propose an ILP-based model to set forest restoration priorities that are designed to enhance the conservation value of a landscape, while allowing human communities to harvest accessible forest stands and while stabilising a given amount of erosion-prone land. Opportunity costs related to the conversion of agriculture and the conversion of 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 timber. Suitability maps, generated through spatial multi-criteria analysis, are used to drive the prioritisation process and ad hoc constraints ensure that the 'harvestable forest' is accessible to/from villages. The model is tested on a study area in the state of Chiapas (Mexico).

## 2. Methods

Forest restoration is usually implemented under two main circumstances: the occurrence of a degraded forest which is to be brought back to a pre-disturbance state or the presence of a cleared area that is to be reforested. For the purpose of this study, we concentrated our efforts on the latter case: this assumption limits the areas potentially selectable for restoration to non-forested areas only. In our framework the above-mentioned uses ('protection' and 'harvest') apply to both the existing forest and the reforested lands, and harvested forest is expected to be re-established after harvest. This results in four forest categories: existing forest for protection (F), existing forest for potential harvest (E), reforested land for protection (Z) and reforested land for potential harvest (R). The model focuses on the latter three categories and is raster-based where 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 locations respectively. Villages and biophysical surrogates are assigned indices $k$ and $m$, respectively.

### 2.1. Modelling the human-forest link

Livelihoods of rural communities within poor countries are based on locally available natural resources. Our 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. That is, we wish to make a solution feasible within the perspective of each village. We consider that the forest provides villages with just timber: no other forest-related resources are considered in the model, although other services could be easily included (e.g. carbon sequestration, wild foods).

The Classical Transportation Problem (CTP), introduced by Hitchcock (1941), aims to minimise the costs associated with transporting materials/goods from a number of sources (points of supply) to a number of destinations (points of demand). In our application we assume the forested cells can serve as potential sources of fuelwood and timber, and the villages are the destinations of those goods. Consistent with the CTP, each supply has an upper limit (*i.e.* each forested cell can only provide a given amount of timber if it is allocated for serving local economic demand) and each demand has a lower limit (i.e. a minimum amount of timber that should be guaranteed to each village). Timber demand at each village location ($D_k$) is estimated by means of the following equation:

$$D_k = n \times pop_k \times y \quad \forall k \tag{1}$$

where: $n$ 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 their designated source, an allocated forest stand and return to their village. We consider this cost 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 maximum travel time to reach surrounding forest stands that have been allocated for such purposes is