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Simulating the potential for ecological restoration of dryland forests in Mexico under different disturbance regimes

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ABSTRACT

Examining the potential for ecological restoration is important in areas where anthropogenic disturbance has degraded forest landscapes. However, the conditions under which restoration of degraded tropical dry forests (TDF) might be achieved in practice have not been determined in detail. In this study, we used LANDIS-II, a spatially explicit model of forest dynamics, to assess the potential for passive restoration of TDF through natural regeneration. The model was applied to two Mexican landscapes under six different disturbance regimes, focusing on the impact of fire and cattle grazing on forest cover, structure and composition. Model results identified two main findings. First, tropical dry forests are more resilient to anthropogenic disturbance than expected. Results suggested that under both a scenario of small, infrequent fires and a scenario of large, frequent fires, forest area can increase relatively rapidly. However, forest structure and composition differed markedly between these scenarios. After 400 years, the landscape becomes increasingly occupied by relatively shade-tolerant species under small, infrequent fires, but only species with both relatively high shade tolerance and high fire tolerance can thrive under conditions with large, frequent fires. Second, we demonstrated that different forms of disturbance can interact in unexpected ways. Our projections revealed that when grazing acts in combination with fire, forest cover, structure and composition vary dramatically depending on the frequency and extent of the fires. Results indicated that grazing and fire have a synergistic effect causing a reduction in forest cover greater than the sum of their individual effects. This suggests that passive landscape-scale restoration of TDF is achievable in both Mexican study areas only if grazing is reduced, and fires are carefully managed to reduce their frequency and intensity.

1. Introduction

The tropical dryland forests (TDF) of Mexico are recognised as a global conservation priority, being centres of species richness and endemism, as well as providing a range of benefits to local communities (Gordon and Newton, 2006a,b; Miles et al., 2006). However, in recent decades these forests have been degraded and fragmented at an alarming rate. At the national scale, a recent study reported an annual TDF deforestation rate of 1.6% (177,000 ha) during 1976–1993, and 0.5% (44,416 ha) during the following decade (Challenger and Dirzo, 2009). This study also indicated that only 26% of the original TDF cover remained as intact forest by 2002 and that the remaining areas were characterised by different degrees of human disturbance. The development of effective restoration programs of TDF is therefore an urgent priority (Trejo and Dirzo, 2000; Quesada et al., 2009). Ecological restoration of TDF can potentially occur naturally through the processes of dispersal, migration, colonization and succession if the causes of ecological degradation can be removed or controlled (Kennard, 2002; Lamb et al., 2005). Such 'passive' restoration is probably the most common forest restoration approach implemented in tropical regions (Lamb et al., 2005). However, if disturbances have severely altered the composition, structure and dynamics of TDF, the capacity for natural recovery may be dramatically reduced or eliminated altogether (Lamb and Gilmour, 2003).

Among anthropogenic disturbances, fire and grazing by livestock have caused the most serious degradation of TDF in Mexico. For example, Maass (1995) reported that cattle ranching has expanded rapidly during the past 50 years, and is now considered to be the main cause of TDF degradation. Roman-Cuesta et al. (2007) reported that in recent decades fire has become one of the most important threats to the conservation of TDF. In 1998, Mexico experienced fires which burned the largest area of forest ever affected in a single season (Cedeño, 2001). In addition, during the period

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2003–2007, ecoregions in Mexico with TDF had an intermediate to high density of detected fires compared with other ecoregions in the country (Manson et al., 2009).

Information on the rate of ecological recovery under different disturbance scenarios is required to evaluate the feasibility of passive restoration efforts (Vieira and Scariot, 2006). Ideally such information should be spatially explicit, given that forest restoration should be undertaken at the landscape scale in order to address the problem of forest fragmentation and to restore connectivity (Mansourian et al., 2005). Although a number of studies have analysed TDF recovery after disturbance (Guariguata and Ostertag, 2001; Vieira and Scariot, 2006; Griscom et al., 2009), very little information is available regarding the processes of recovery of TDF at the landscape scale.

This study addresses the information needs for ecological restoration of TDF by applying a spatially explicit model (LANDIS-II), which was designed to simulate the dynamics of forested landscapes through the incorporation of ecological processes, including succession, disturbances and seed dispersal over long time domains (Scheller et al., 2007). The LANDIS-II model is an elaboration of the LANDIS family of landscape disturbance and forest succession models. Although the architecture has changed since the initial version and new features have been added, LANDIS-II retains many principles from earlier versions that have been widely tested and applied in different parts of the world (He and Mladenoff, 1999; Wang et al., 2006; Swanson, 2009). However, we are not aware of any previous attempt to apply LANDIS-II, or any other spatially explicit model of forest dynamics, to tropical dry forest landscapes.

The aim of this investigation was to test the following hypotheses; (1) ecological disturbances (grazing and fire) at landscape level can have synergistic effects in altering the cover, structure and composition of TDF; (2) expansion of TDF cover in degraded landscapes could be achieved without complete prevention of anthropogenic disturbance. In particular, we explored the application of LANDIS-II for modelling TDF dynamics in two Mexican case studies, to examine the individual and combined impacts of fire and grazing on forest cover, structure and composition at the landscape scale. The overall objective was to use this modelling approach to identify restoration approaches with broad applicability and to examine the conditions under which passive restoration of degraded TDF might be optimized in practice.

2. Methods

Research was undertaken in two study areas dominated by TDF, namely the Tablon, Chiapas, and the Central Veracruz, Mexico (Fig. 1). Both study areas are global conservation priorities, being identified as global biodiversity hotspots (Myers et al., 2000), and in recent decades both have been degraded at a high rate owing to the effects of human disturbances (Challenger and Dirzo, 2009). Both study areas cover similar areas, but they differ in the percentage of forest cover. According to CONABIO (2006) both areas have a high degree of marginalisation, and an average of 23 inhabitants km^{-2} and 14 inhabitants km^{-2} respectively were recorded in 2000 in Central Veracruz and Tablon.

2.1. Study areas

2.1.1. Tablon, Chiapas

The Tablon study area covers 24,735 ha and is situated between 675 and 1537 m altitude in the municipalities of Villaflores and Jiquipilas, state of Chiapas (16°11′38″ and 16°22′29″N, and 93°31′57″ and 93°44′31″W). The climate is defined as warm sub-humid, with an average annual rainfall between 1200 and 2800 mm concentrated from late May to early November (Aguilar-Jiménez, 2008). According to the land cover map produced for this study (see Section 2.2 for a description), 88.6% of the entire Tablon area is covered by forests and 9.9% by pasture; 0.9% is represented by arable land and 0.6% by urban areas. The natural vegetation of Tablon forms a gradient of forest types ranging from low-stature deciduous tropical forest in the lower elevations of the study area, through dry oak and pine-oak with increasing elevation, and with pine forests on the highest ridges. Owing to its steep topography and sandy soils, Tablon is susceptible to severe soil erosion if the natural vegetation is removed by subsistence agriculture and extensive cattle ranching.

Tablon falls within the La Sepultura Biosphere Reserve, which was designated in 1995 for its high number of endemic species, high biodiversity value and species richness. It is also an important water catchment for the region. Government bodies and NGOs are actively promoting more sustainable forms of land use in the region (Lillo et al., 1999).

2.1.2. Central Veracruz

The Central Veracruz study area, with an area of 29,468 ha, is situated between 10 and 507 m altitude in the state of Veracruz, Mexico (19°07′45″ and 19°21′18″N, and 96°21′33″ and 96°41′12″W). The climate is defined as warm sub-humid (minimum and maximum average temperatures are 20 °C and 31 °C, respectively) with rainfall of 800–1500 mm, occurring primarily from June to September followed by an extended dry season. Areas on the eastern side of Central Veracruz have a warm-humid climate, whereas those on the western side are characterized by a warm-dry climate. Soil types are predominantly Feozems, Litosols and Vertisols (INIFAP and CONABIO, 1995; CONABIO, 1999). According to the land cover map produced for this study area (see Section 2.2 for a description), 43% of the entire Central Veracruz area is represented by pasture, 23% by shrubland (locally know as acahual), 21% by arable land, 5.5% by tree plantation, and 3% by urban areas and only 4.4% covered by undisturbed forest. The original vegetation was predominantly tropical dry forest (Rzedowski, 1990). None of the remaining forest fragments are under protection. The primary land use is cattle ranching, which is generally undertaken on a relatively small scale by private landowners. For common land tenants (know as ejidatarios), the main activities are cultivation of maize and sugar cane.

2.2. Input data

2.2.1. Spatial layers

The LANDIS-II model is designed to accept raster imagery as a spatially explicit input to simulate landscape dynamics, as described below.

In Tablon, input raster data included a Digital Elevation Model (DEM) and QuickBird satellite imagery, from which a series of secondary maps were derived. The DEM (50 m cell-size) was derived from the 30 m resolution national DEM (INEGI, 2003), resampled to a 50 m grid using regularized spline with tension (Mitasova and Mitas, 1993). A direct beam solar radiation map (50 m cell-size) was calculated using the formulae proposed by Rigollier et al. (2000) and implemented in the GRASS module r.sun (Neteler and Mitasova, 2008). An ecoregion map was produced from the combination of the DEM with the beam solar radiation map (Table 1).

Three QuickBird scenes acquired in November–December 2004 were obtained as a mosaic to cover the study area. These data consisted of a panchromatic band (0.61 m spatial resolution) and four multispectral bands (2.44 m resolution) covering the visible blue to near infrared wavelengths (450–900 nm). A basic land cover map (50 m cell-size) (Fig. 2), which identified forest, pasture, roads, urban areas and permanent agricultural areas was derived from the QuickBird imagery. The production of the basic land cover map