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Modeling the effects of alternative management strategies on forest carbon in the *Nothofagus* forests of Tierra del Fuego, Chile

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ABSTRACT

The impact of forest management activities on the ability of forest ecosystems to sequester and store atmospheric carbon is of increasing scientific and social concern. The nature of these impacts varies among forest ecosystems, and spatially and temporally explicit ecosystem models are useful for quantifying the impacts of a number of alternative management regimes for the same forest landscape. The LANDIS-II forest dynamics simulation model is used to quantify changes to the live overstory and coarse woody debris pools under several forest management scenarios in a high-latitude South American forest landscape dominated by two species of southern beech, *Nothofagus betuloides* and *N. pumilio*. Both harvest type (clearcutting vs. partial overstory retention) and rotation length (100 years vs. 200 years) were significant predictors of carbon storage in the simulation models. The prompt regeneration of harvest units greatly enhanced carbon storage in clearcutting scenarios. The woody debris pool was particularly sensitive to both harvest type and rotation length, with large decreases noted under short rotation clearcutting. The roles of extended rotations and partial overstory retention are noted for enhancing net carbon storage on the forest landscape.

1. Introduction

The sequestration and storage of atmospheric carbon is being increasingly recognized as a valuable environmental service performed by forest ecosystems. As interest increases in the various physical and biological factors influencing climate change, so does interest in understanding how human activities relate to these factors. Human activities associated with forests, including forest management, have been recognized as significant forces in the terrestrial carbon cycle (Whittaker and Likens, 1975; Bramyrd, 1979). As carbon dioxide and other carbon-containing gases in the atmosphere have become recognized as greenhouse gases, the role of forests in sequestering and storing carbon has become an important element in the policy debate regarding anthropogenic climate change (Brown et al., 1996).

Forest management activities have the ability to influence the amount of carbon stored in forested stands and landscapes, through both intermediate stand interventions (Garcia-Gonzalo et al., 2007) and general timber harvest regimes (Harmon et al., 1990; Cohen et al., 1996). In regions of the world where intensive forest inventory has not been performed, approaches such as remote sensing and landscape models are necessary to scale stand-level carbon estimates to the landscape and region level (Cohen et al., 1996).

Much is known about management of the forest carbon resource in certain regions, such as the Pacific Northwest of North America (Harmon et al., 1990, 2004; Turner et al., 1995), but many ecosystems remain to be addressed in terms of understanding how different forest management regimes affect carbon storage. The rare combination of relatively large accumulations of downed woody debris (which store carbon), the relative paucity of fire events due to the moist, cool climate, and a highly variable wind disturbance regime in an equilibrium landscape warrant a unique effort to model forest carbon dynamics in Tierra del Fuego, Chile.

The objective of this research was to employ a simulation modeling approach to examine the effects of timber harvest activities on forest carbon storage at the landscape scale in the southern beech (*Nothofagus* Blume) forests of Tierra del Fuego, Chile, in terms of changes to two main forest carbon pools, the live overstory and coarse woody debris. The disturbance regime in these forests is dominated by small to medium-scale windthrow events (Rebertus and Veblen, 1993), creating a shifting landscape mosaic of even and unevenaged stands (Rebertus et al., 1997). The response of forest carbon pools to the addition of a forest harvest regime to this wind disturbance regime has not been quantified for this ecosystem.

The LANDIS-II model (Gustafson et al., 2000; Scheller et al., 2007) was used to simulate natural disturbance, timber harvest, regeneration, growth, decomposition, and other processes. One

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strength of the LANDIS-II model is that timber harvest can be superimposed onto the natural disturbance regime to show the additive effects of anthropogenic disturbance. The simulation modeling addressed the following hypothesis: increasing intensity of timber harvest will result in reduced forest carbon storage in both overstory and coarse woody debris pools (snags and downed wood) at the landscape scale when compared to the natural background disturbance regime. It was also hypothesized that, due to the extreme environment and the poor dispersal of *Nothofagus* species, clearcut harvesting will result in greater reductions of carbon than an overstory retention system.

2. Methods

2.1. Simulation landscape

The western portion of the Santa Maria peninsula (53°30′ S, 69°30′ W) in southwestern Tierra del Fuego, Chile was selected as the simulation landscape (Fig. 1). This high-latitude (53°–54°30′ S latitude) region hosts an assemblage of plant communities, including Patagonian shrub-steppe, Magellanic tundra, and sub-antarctic forests dominated by trees of the genus *Nothofagus* Blume (Moore, 1983). Forest soils are generally well-developed cryogenic podzols (Kalin-Arroyo et al., 1996). Forest vegetation is usually restricted to relatively well-drained areas below an altitudinal timberline at ~800 m elevation. Mean annual precipitation declines from the southwest coast, where it averages 3000 mm or more, to the shrub-steppe in the northern and eastern parts of the island, where it averages 800 mm or less. Mean monthly sea level temperatures average 9.5 °C and 0 °C for January and July, respectively (Tuhkanen, 1992). Forest management is still a relatively small-scale industry in Chilean Tierra del Fuego, but this may change in the future.

2.2. Generation of a land cover map using ASTER imagery

The LANDIS model is designed to accept classified imagery as a spatially explicit input for the modeling of actual landscapes. For this research, this input was derived from satellite imagery from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). This imagery was obtained from the Department of Earth and Space Sciences, University of Washington. ASTER is a remote sensing instrument that captures high-resolution earth-reflected radiation in three visible and near-infrared bands, six short-wave infrared bands, and five thermal bands (Abrams, 2000). In addition to these 14 nadir-looking bands, a 27.6° off-nadir, backward-looking radiometer captures a parallax image for the generation of high-resolution elevation datasets (Abrams, 2000).

An ASTER scene was utilized to provide image cover of the study area. Level 1B data were utilized, meaning that radiometric calibration and geometric co-registration were performed on images (ERSDAC, 2005). Topographic correction was performed on the visible, near infrared, and shortwave infrared ASTER bands using the SCS + C algorithm. This algorithm avoids the over-correction problems presented by the cosine correction and other topographic correction methods (Soenen et al., 2005). A square sampling grid of points (20 km by 20 km, with 1 km between points in each axis) was generated and used to extract the cosine of light incidence values (cos (i)) and grid values for each uncorrected band. The slope and intercept constants from linear regression models of uncorrected relectance in each band and cos (i) values were used as inputs for calculation of the correction constant C (Teillet et al., 1982). Correction was performed using ERDAS Imagine 9.1 (Leica Geosystems Geospatial Imaging, LLC) with the SCS + C algorithm implemented using the Spatial Modeling Language. Visual comparisons between corrected and uncorrected images confirmed the desired flattening of reflectance values.

An unsupervised classification (Lillesand and Kiefer, 1994) was performed to identify areas of *Nothofagus* forest and non-forest such as water, bare ground/rock, grassland (pampa), and Magellanic tundra. Non-forest cover types were masked with a Boolean process and a second unsupervised classification was performed on the masked imagery to identify distribution of *Nothofagus* forest types. These included stands dominated by coigüe (*Nothofagus betuloides*), lenga (*N. pumilio*), and ñirre (*N. antarctica*). This classification layer was used as a map of initial community distribution to parameterize LANDIS-II.

2.3. Description of the LANDIS-II model

The LANDIS-II model provides an environment in which the combined effects of timber harvest and the natural disturbance regime (wind, fire, and endogenous mortality) on forest biomass may be assessed (Gustafson et al., 2000; Scheller and Mladenoff, 2004). LANDIS-II is a spatially explicit, temporally discrete simulation model for forest disturbance dynamics (Mladenoff, 2004; Scheller et al., 2007) and incorporates extension modules for simulating many processes, including timber harvest regimes (Gustafson et al., 2000; Mehta et al., 2004) and wind disturbance (Scheller and Mladenoff, 2004). The extensible nature of LANDIS-II increases the number of ecology and management-oriented questions that can be addressed (Scheller et al., 2007). LANDIS-II operates on landscapes represented by a raster, or lattice of square

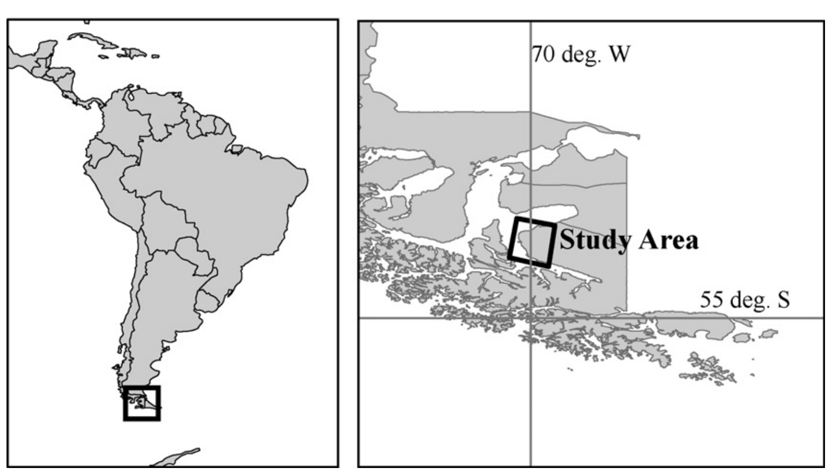

Fig. 1. Study site location.