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Land use change effects on carbon and nitrogen stocks in the Pyrenees during the last 150 years: A modeling approach

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ABSTRACT

In the southern Pyrenees, human population and therefore land uses have changed from forests to pastures, then crops, and back to pastures and secondary forests during the last two centuries. To understand what such rapid land use changes have meant for carbon (C) and nitrogen (N) stocks, we used data from two forest sites in the western Pyrenees, combined with regional data on pastures and crop production (potato, cereal), to calibrate the ecosystem-level model FORECAST. Then, we simulated 150 years of land use for each site, emulating historical changes. Our estimates show that the conversion from forests into pastures and crops created C and N deficits (378–427 Mg C ha^{-1}, 4.0–4.6 Mg N ha^{-1}) from which these sites are still recovering. The main ecological process behind the creation of these deficits was the loss of the ecological legacy of soil organic matter (SOM) created by the forest, particularly during conversion to farming. Pastures were able to reverse, stop or at least slow down the loss of such legacy. In conclusion, our work shows the deep impact of historical land use in ecosystem attributes, both in magnitude of removed C and N stocks and in duration of such impact. Also, the usefulness of ecological modeling in absence of historical data to estimate such changes is showcased, providing a framework for potential C and N stocks to be reached by climate change mitigation measures such as forest restoration.

1. Introduction

Nowadays it is becoming apparent that we are at the onset of a new geological era named the Anthropocene, due to human-induced changes in biodiversity, topography, hydrological and geochemical cycles, and even climate (Zalasiewicz et al., 2008). All these changes together constitute the so-called global change, which is already having important consequences on different ecological patterns and processes (Vitousek, 1994; Steffen et al., 2011).

Opening new lands for farming has been identified as one of the factors generating net C releases to the atmosphere, especially when forests or bogs are converted into arable land due to the large amounts of C contained in their soils. On the other hand, when farming ceases and the land reverts to forest or other uses (through natural succession or as part of ecological restoration plans) the land could become a net sink of atmospheric C (Dixon et al., 1994). Land use history is therefore tightly linked to human-related release or fixation of atmospheric C.

Land-use change has a long history around the world in any region where human population practiced natural resource management tasks other than hunting and gathering. In particular, the Mediterranean region has more than 10,000 years of landscape changes since the establishment of arable farming. Since then, farming has become the most widespread form of land use in Europe (Stoatte et al., 2001).

In the Pyrenees, the historical events caused alternating periods of expansion and contraction of pastures, croplands, and forests (see Supplementary material). However, despite the importance of land-use change in dominating long-term net terrestrial fluxes of C, estimates of the annual flux are uncertain relative to other terms in the C budget (Prentice et al., 2001). Knowing such rates of C fluxes would be useful to identify the most likely and promising strategies for climate change mitigation through land-use actions, such as forest and grassland management. The direct estimation of historical influences of human activities in forest through Europe is considered as an extremely difficult task, due to the long history and overlapping effects of human activities. However, one indirect method that can be applied is scenario modeling (Herold et al., 2011).

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Clearing and farming of forest lands have clear implications in many ecosystem attributes, and especially on soils. These effects include, but are not limited to: (1) substantial nutrient removals in harvested timber, influencing the balance of remaining plant-available nutrients in the long term (Blanco et al., 2005); (2) physical effects of ploughing, which changes soil structure, influencing soil oxygenation, water retention, and water flow, which in turn affects mineralization rates of soil organic matter (SOM) (Ballard, 2000); (3) canopy removal during thinning or harvesting, affecting soil temperature and moisture regimes (Blanco, 2004); (4) prescribed fire or slash burning, resulting in substantial nutrient pulses (Canals et al., 2014), which may be used by the new vegetation or may be lost from the system through volatilization (notably of N and S) and, in some cases, fly-ash losses (Kimmins, 1997); and (5) changes in nutrient content and availability by fertilization, which is some cases could result in soil acidification from nitrification (Ballard, 2000). All these effects have a direct translation into reducing soil fertility in the long-term, affecting ecosystem productivity and C storage capacity (Morris et al., 1997; Wei and Blanco, 2014).

C stocks in the Pyrenees Mountains have gone through important fluctuations in the latest decades (Álvaro-Fuentes et al., 2011), but there is little quantitative information on the changes that have occurred in longer time spans, specifically in the latest century and a half. Therefore, our ultimate goals were: (1) to estimate the potential deficit in C and N pools caused by historical land-use change; (2) to identify which type of land use (crop, pasture or forest) has been mainly responsible for such deficit; and (3) to identify which ecological processes could have been more implicated in generating this deficit. Knowing such information could provide a better framework for C sequestration and storage management plans focused on climate change mitigation, including reforestation, afforestation, improved grassland management or low-impact farming. To provide an initial estimation of the magnitudes of such changes, we have used the ecosystem-level model FORECAST. The model is specially designed to examine the impacts of different management strategies or natural disturbance regimes on long-term site productivity and C sequestration. A detailed description of the FORECAST model can be found in (Kimmins et al., 1999, 2010) and a brief description of the algorithms simulating C sequestration and N limitation will be presented in the next section. This model has been tested in boreal, temperate, subtropical and tropical forests (Bi et al., 2007; Blanco et al., 2007; Blanco and González, 2010; Seely et al., 2010; Wang et al., 2013; Wei and Blanco, 2014), including the Pyrenees (Castrillón et al., 2013), as well as in agroforestry (Welham et al., 2007, 2010) and restoration applications (Welham et al., 2012).

2. Materials and methods

Supplementary materials provide the extended data on the research sites and calibration parameters. Here we provide a description of the most important data sources.

2.1. Research sites

Given the variety of environments existing in the Pyrenees, we have calibrated the model FORECAST to simulate forests, crops and grasslands in two sites of the western Pyrenees region that could be considered as archetypical sites: a "low elevation" site (elevation below 1000 m.a.s.l., close to the human population centers), and a "high elevation" site (elevation above 1000 m.a.s.l., far from the human population centers). Therefore, we used data from two contrasting experimental forest sites that have been monitored since 1999, representing the two extremes of a site quality gradient throughout the western Pyrenees, in the province of Navarre (northern Spain). The lower elevation site represents highly productive *Pinus sylvestris* forests in Navarre, with higher soil N than in the other site (Table 1). The higher elevation site is an example of a low production *P. sylvestris* forest in Spain. Tree densities are similar at both sites, but tree size is significantly higher in Aspurz. Both sites are pine-dominated stands, with a minor presence of broadleaves (less than 10% of the total stand density) of broadleaves. *Pteridium aquilinum* (L.) Kuhn and *Rubus* spp. are the two dominant species in the understory at both sites. Soil at the low elevation site is Haplic Alisol, and Dystric Cambisol at the low elevation site (Table 2). Supplementary Material provides a location map (Fig. S1) and ombrothermic diagrams (Fig. S2).

2.2. The FORECAST model

FORECAST is a management-oriented, deterministic, non-spatial, stand-level forest growth and ecosystem dynamics simulator that operates at annual time steps. The model simulates the dynamics of all forest carbon stocks required under the Kyoto Protocol (aboveground biomass, belowground biomass, litter, dead wood and soil organic carbon). It complies with the carbon estimation methods outlined by the IPCC (Penman et al., 2003). The model uses a hybrid approach to vegetation growth modeling, as it merges the use of empirical data (i.e. growth and yield tables and field data, among others, see Section 2.3) modified by the simulation of the most important ecological processes (Kimmins et al., 1999; Landsberg, 2003). This hybrid approach assumes that the best predictor of vegetation growth for a site with a given combination of climate and nutrient limitation is the observed vegetation growth itself. In other words, vegetation productivity for a given site depends on the combination of climatic, topographic and edaphic features of that site. Therefore, observed vegetation productivity is a variable that implicitly has already taken climate effects into account. This approach, combined with the annual time step, reduces the need of meteorological or climate data, which are not used as input variables in FORECAST, but assumes that climate for the simulated scenario is similar to the climate during the time when empirical data were recorded. A detailed discussion of this approach and the full model have been described in before (Kimmins et al., 1999, 2010; Penman et al., 2003) and therefore only a summary of the main driving function to calculate vegetation growth is provided here.

The model uses a mass balance approach to estimate how nutrients circulate in the ecosystem, and how their availability limits vegetation growth (trees, plants and bryophytes) together with available light in the canopy (Fig. 1). Detailed descriptions of decomposition, tree uptake and biogeochemical cycles can be found in (Kimmins et al., 1999; Kimmins, 1993). FORECAST has three application stages: (1) assembling calibration data and generating historical rates of key ecosystem processes; (2) model initialization by establishing the ecosystem condition for the beginning of a simulation run; and (3) simulation of tree and plant growth.

2.2.1. Generation of historical rates of ecological processes

Projection of stand growth and ecosystem dynamics is based upon a system of equations that links the rates of key ecological processes regulating the availability of, and competition for, light and nutrient resources with vegetation growth. The rates of these processes are calculated from a combination of historical bioassay data (biomass accumulation in component pools, stand density, etc., see Kimmins et al., 1999 for a detailed description of input parameters needed) and measures of certain ecosystem variables (e.g. decomposition rates, photosynthetic saturation curves, etc.) by relating biologically active components (foliage and small roots)