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Traditional fire use impact in the aboveground carbon stock of the chestnut forests of Central Spain and its implications for prescribed burning

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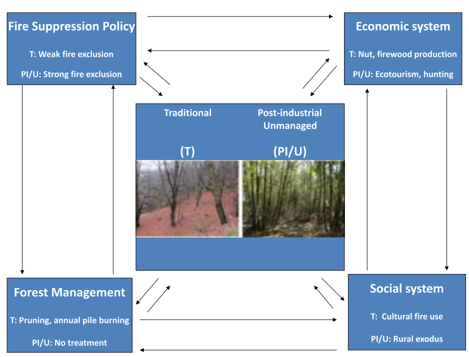
HIGHLIGHTS

- Traditional cultural fire use is essential for the conservation of chestnut forest ecosystems
- Traditionally managed chestnut forest stands accumulate on average 2.6 times more carbon than unmanaged sites
- Traditionally managed chestnut forest stands present 4.4 times more understory species that unmanaged sites
- Due to land use changes, fire exclusion policies and rural demographic trends traditional fire use is declining.
- Surrogate prescribed burning plans based on traditional fire use should be developed to offset this decline.

GRAPHICAL ABSTRACT



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ABSTRACT

Chestnut forest ecosystems have a complex fire ecology; a result of centuries of co-evolution with pre-industrial era, cultural fire use by local communities based on Traditional Ecological Knowledge (TEK). As the "forest transition" unfolds throughout Europe however, and the traditional role of chestnut forest ecosystems as producers of edible nuts and firewood declines, chestnut forest resilience may be endangered due to disturbance regime changes driven by transformations in land use linked to the rural exodus, state fire exclusion policies and climate change. In this study we compared the aboveground carbon stocks of two chestnut forests located in Central Spain which can be considered representative of divergent Europe-wide management trends. In the first site of Casillas traditional understory burning is still widespread and its impacts on forest stand structure can be characterized as maintaining "open canopy", low density stands dominated by old growth chestnut trees. In the second site of Rozas de Puerto Real traditional fire use has declined and natural ecological succession processes have resumed resulting in high density, "closed canopy" stands dominated by young chestnut tree saplings and increasing pine, oak and shrub encroachment. For both sites we used in-the-field monitoring methods to estimate aerial carbon stock using allometric equations. Our results suggest that carbon sequestration and species richness is greater in the traditionally managed chestnut forest stands. Since present demographic trends present difficulties for the maintenance of traditional fire use by local communities, we argue that future fire management of

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unmanaged chestnut stands and maintenance of traditional forest stands ought to be implemented through surrogate prescribed burning plans that replicate the seasonal timing and ecological effects of TEK based controlled burning.

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1. Introduction

The Forest Transition Model (FTM) theorizes that forest cover tends to expand as societies undergo industrialization and urban development (Mather, 1992). This expectation arises from the untested hypothesis that as rural population density declines forests expand and biomass per hectare and carbon uptake should also necessarily increase (Mather, 1992; Mather and Needle, 1998; Walker, 1993; Houghton et al., 2000; Rudel et al., 2005; Angelsen and Rudel, 2013). On the basis of the conventional wisdom generated by theories such as FTM, policy networks linked to European climate change mitigation efforts have sought to incentivize reforestation and afforestation policies. These policies have become firmly established as one of the key "low cost" strategies in the global climate change mitigation regime for the foreseeable future though empirical evidence supporting the FTM has been obtained from only a few European and Asian experiences (Rudel et al., 2005; Stern, 2007; Barbier et al., 2008; Angelsen and Rudel, 2013). European countries, in particular, experienced substantial expansions in forest cover as they industrialized and urbanized thus seemingly corroborating the main tenets of the FTM (Fuchs et al., 2014; European Environmental Agency, 2015). Though, there is no doubt that the FTM provides valuable insights into the relationship between large-scale socio-economic development processes and forest cover trends it also seems to show some limitations regarding the potential increases in carbon sequestration to be derived from net expansions in forest cover (Oliveira et al., 2017). These limitations are often related to the omission of the role played by fire as a disturbance regime in many of the Earth's terrestrial ecosystems (Chapin et al., 2000; Hurteau et al., 2008; Oliveira et al., 2017). Some studies, in fact, have begun to empirically test the hypothesis that as forest cover expands so does the frequency and intensity of fires which may result in unintended positive feedback loops with climate change, increased landscape fuels and state led fire exclusion policies (Seijo and Gray, 2012; Stephens et al., 2014). These changing feedbacks could potentially contribute to an increase in greenhouse gas emissions from the forestry sector in spite of net expansions in forest cover (Chapin et al., 2008; Hurteau et al., 2008; Batllori et al., 2013; Stephens et al., 2014; Oliveira et al., 2017).

Chestnut forests in Spain, and by extension Europe, are currently experiencing a forest transition (Conedera et al., 2016). During the 20th century many chestnut forests were abandoned as a result of the gradual decline of pre-industrial forms of land use and management that require continued cultural, labour intensive inputs (Grund et al., 2005; Krebs et al., 2012; Pezzatti et al., 2013; San Roman et al., 2013; Zlatanov et al., 2013; Seijo et al., 2015, 2017; Conedera et al., 2016). Chestnut forest cover however, as the FTM predicted, expanded overall, though old growth formations are increasingly encroached upon by younger saplings from both chestnut and other deciduous and conifer tree species growing in dense, closed canopy formations as natural ecological succession processes resume (San Roman et al., 2013; Zlatanov et al., 2013; Conedera et al., 2016; Seijo et al., 2017). As a result researchers and managers have become concerned with the continued ability of chestnut forest ecosystems to provide valuable ecosystem services, such as the conservation of biodiversity and carbon sequestration, under the new circumstances generated by the rural exodus, land use transformations, climate change and changing fire regimes (Pezzatti et al., 2013; San Roman et al., 2013; Seijo et al., 2017).

Much of this uncertainty centers around the potential resilience, or lack thereof, of chestnut forest ecosystems to changing disturbance regimes, especially fire (Zlatanov et al., 2013; Conedera et al., 2016; Seijo et al., 2017; López-Sáez et al., 2017). Like many other Mediterranean species, chestnuts have a complex fire ecology often linked to annual, low intensity, non-vegetative season, anthropogenic traditional fire use (Grove and Rackham, 2000; Pausas and Keeley, 2009; Seijo et al., 2015, 2017; López-Sáez et al., 2017). These pre-industrial era forms of cultural burning based on Traditional Ecological Knowledge maximizing the exploitation of food products and firewood, may have in fact augmented chestnut tree resilience to fungal and insect pests while modifying some key fire regime attributes that, in turn, may have helped prevent large fires and conflagrations by reducing landscape fuel beds and ladder fuels (Seijo et al., 2015, 2017).

The half a century long application of state policies of fire exclusion, climate change and recent transformations in land use may however lead to important fire regime transformations in Mediterranean type ecosystems where fire events may be getting larger and more severe (Moreira et al., 2011; Fernandes et al., 2013; Stephens et al., 2014; Oliveira et al., 2017). Studies based on the evolution of land use and land cover trends during the last 20th century have confirmed that traditional activities (i.e. agriculture and animal husbandry) were abandoned in Mediterranean rural areas when they were depopulated (Grove and Rackham, 2000; Viedma et al., 2006, 2016; Moreira et al., 2011). These socioeconomic changes along with the expansion of wildland-urban interface areas and the aforementioned factors may be accentuating the coupling of fire regimes with climate (Pausas and Fernández-Muñoz, 2012). These general fire regime trends could have important consequences for the ability of chestnut forest ecosystems to continue sequestering carbon and provide other key ecosystem services in the near future in spite of their relatively recent net expansion.

In this article we will explore these hypotheses about the chestnut forest transition through the empirical evidence obtained from one such process taking place in two chestnut forest ecosystem sites in Central Spain that can be considered representative of Europe-wide trends (Conedera et al., 2016). Specifically we compared carbon aboveground vegetation stocks and species richness in two contrasting chestnut forest ecosystem with diverging fire regimes and management strategies associated with human systems exhibiting markedly different levels of economic development (Seijo and Gray, 2012). We make the case that our findings can inform and offer valuable insights into the unintended ecological consequences of the FTM in terms of carbon balance, species richness and, indirectly, fire risk. These insights could in turn provide useful social-ecological criteria for the formulation of climate change mitigation and adaptation strategies that take into consideration the potential use of prescribed burning inspired by traditional fire use to help abate landscape fuels while simultaneously favouring chestnut forest ecosystem resilience to fire and insect disturbances, conserving biodiversity and enhancing local rural economies through high added value nut production (Seijo et al., 2015, 2017).

2. Methods

2.1. Study area, site characteristics and fire regimes

This study was conducted in sweet chestnut (*Castanea sativa* Mill.) forest stand sites of Casillas and Rozas located in the foothills of the mountains of Gredos (Central Spain) (Fig. 1). Data collection was carried out at 900–1100 m·a.s.l. range of elevation hillside forests, with south-southeast orientation and the same slope ranges in Casillas (40°19′N

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