Forest Ecology and Management 349 (2015) 45–54

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Historical agriculture and contemporary fire frequency alter soil properties in longleaf pine woodlands

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ARTICLE INFO

Article history:
Received 20 December 2014
Received in revised form 6 April 2015
Accepted 9 April 2015
Available online 24 April 2015

Keywords:
Disturbance
Fire suppression
Land-use legacy
Pinus palustris
Reforestation

ABSTRACT

Historical agriculture and contemporary disturbances such as fire can each affect soil properties, but the relative impact of their separate and combined effects is poorly understood. We investigated the effects of historical agriculture and contemporary fire frequency on soil properties of longleaf pine woodlands in the Southeastern United States. We sampled 24 pairs of sites from adjacent former agricultural and remnant longleaf pine woodlands based on high ($\geqslant$ four since 1971) and low (< four since 1971) fire frequency. We found no evidence for interactive effects between agricultural history and fire frequency on measured mineral soil properties, yet each disturbance independently affected different aspects of the soil. Effects of past agricultural use were most apparent in the top 15 cm of the mineral soil, with post-agricultural woodlands characterized by increased phosphorus and bulk density, as well as decreased organic matter and soil water holding capacity, compared to remnant woodlands. Some effects of past agricultural use, such as increased phosphorus, were also apparent as deep as 30 cm into the soil profile. However, when expressed as stocks (to account for differences in bulk density) we found that organic matter content was similar among post-agricultural and remnant woodlands. With respect to contemporary fire frequency, less frequently burned sites had thicker O-horizons (litter and duff layers) and showed a trend of greater inorganic nitrogen in mineral soil, relative to frequently burned sites. Overall, our results indicate that agricultural legacies in soils persist 60 years after agricultural abandonment and have impacts that may extend deep into the soil profile. Fire suppression additionally affects soils, resulting in additive effects of historical and contemporary disturbances. Additional research is needed to better determine if and how the combined effects of past and present disturbances will affect ecological systems. These combined and long-lasting impacts of historical and contemporary disturbances may help explain why restoration of native understory vegetation remains challenging.

1. Introduction

Within the last century, abandonment of agricultural lands has increased worldwide (Cramer et al., 2008). In the late 19th century, rapid expansion of agriculture across the United States resulted in the clearance of up to 40% of the nation's forests and woodlands (Houghton and Hackler, 2000). After 1920, forested land increased by 14 million ha as marginal agricultural lands (e.g., low fertility soils), mostly in the Eastern United States, were abandoned and reverted back to forest (Hart, 1968; Houghton and Hackler, 2000). Long after agricultural abandonment, legacies of previous land use on afforested land may linger (Foster et al., 2003; Flinn and Vellend, 2005). Decades after the cessation of agriculture, recovering forests may remain distinct from undisturbed (in recent time) forests in their plant species composition and richness (Hermy and Verheyen, 2007; Veldman et al., 2014) and soil properties (McLauchlan, 2006; Brudvig et al., 2013). With respect to soils, tilling, nutritional amendments, and biomass removal during agricultural activities dramatically alter soil physical and chemical properties (McLauchlan, 2006). Compared to forests without recent agricultural history, soils of post-agricultural forests often contain lower soil organic matter (Flinn and Marks, 2007; Matlack, 2009), increased soil phosphorus (Compton and Boone, 2000; Dupouey et al., 2002; Brudvig et al., 2013), increased pH (Grossmann and Mladenoff, 2008; Matlack, 2009), and greater soil bulk density (Compton et al., 1998; Maloney et al., 2008). In some cases, agricultural legacies in soil properties persist for thousands of

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http://dx.doi.org/10.1016/j.foreco.2015.04.006
0378-1127/

years (European deciduous forest: Dupouey et al., 2002); in other cases, soil nutrients may recover within two centuries to levels observed in remnant forest never used for agriculture (New England sand plain forest: Compton et al., 1998).

What remains less clear is whether and to what degree these legacies from agriculture interact with contemporary disturbances, such as fire, that also impact soil properties (Foster et al., 2003; Flinn and Vellend, 2005). The effects of fire on soil properties are dependent on intrinsic properties of the burned site as well as properties of the fire itself (Wan et al., 2001; Certini, 2005). Pre-fire site conditions such as fuel load and soil organic matter content can influence fire intensity (i.e., fuel consumption rate) and severity (i.e., degree of change to ecosystem properties), which in turn affect post-fire conditions of soil properties (Neary et al., 2005). For instance, low-intensity surface fires influence soils in the short-term (with recovery to pre-fire levels within 1–5 years) by increasing pH (Certini, 2005) and inorganic, plant-available nitrogen (NO_3 and NH_4) (Wan et al., 2001), and by decreasing soil organic matter and soil carbon (Neary et al., 1999; Certini, 2005). In contrast, high-intensity fires typically result in nitrogen losses due to oxidation (Binkley and Fisher, 2013) and larger releases of inorganic nitrogen due to leaching (Neary et al., 1999; Certini, 2005). Given the lasting effects of historical agriculture on soil and vegetation, the degree to which contemporary fires influence soil properties may be contingent upon the pre-fire condition of the soils as influenced by a site's agricultural history (Duguy et al., 2007). For example, soil carbon losses due to historical agriculture may be exacerbated by additional soil carbon losses due to organic matter combustion from fires. Alternatively, soil carbon losses due to fire may be smaller in post-agricultural sites compared to remnant sites due to larger amounts of fuel (organic matter) in remnant sites (Duguy et al., 2007).

While the impacts of individual disturbances have been widely studied, our understanding of the interactions between multiple disturbances and their cumulative effects on ecosystems remains limited (Turner, 2010). Recent studies examining the interaction between past and present disturbances, specifically agriculture and fire, have found that agricultural history affects the impact of contemporary fire on post-fire recovery of plant community richness and composition (Duguy and Vallejo, 2008; Puerta-Piñero et al., 2012), similarity among plant communities (Mattingly et al., 2015), and soil carbon dynamics (Duguy et al., 2007). More research is needed to better determine if and when the combined effects of past and present disturbances on ecological systems will be additive, synergistic, or offsetting. In this study, we examine the effects of agricultural history and contemporary fire frequency on soils from longleaf pine (*Pinus palustris*) woodlands.

Longleaf pine ecosystems (variably referred to as savannas, woodlands and forests; hereafter woodlands) of the Southeastern US have been greatly impacted by both land-use history and changes to fire regimes. Less than 3% of this habitat remains intact following wood harvesting, turpentining, and clearing for tillage agriculture in the late 19th to early 20th centuries (Frost, 2006). The remaining habitat has been further degraded by changes to its historical fire regime, namely, a long history of fire suppression (Frost, 2006). Similarly, many other fire-maintained ecosystems around the world are also experiencing drastic alterations to their fire regimes (Pausas and Keeley, 2009). In longleaf pine woodlands, a major focus of current restoration efforts is reintroducing historical fire regimes to re-create the open woodlands that support high understory plant diversity and endangered species such as the red cockaded woodpecker (Kirkman et al., 2004; Varner et al., 2005; Gilliam and Platt, 2006). Yet reinstatement of historical fire regimes alone may not always restore fire-suppressed ecosystems (Stephenson, 1999; Varner et al., 2005). Because understory plant richness in longleaf pine woodlands is also strongly linked to variation in soil properties (Kirkman et al., 2001; Brudvig et al., 2013) and because soil properties, in turn, are impacted by agricultural history (McLauchlan, 2006), understanding the interactive effects of previous agriculture and contemporary fire on soils will likely lead to improved management for habitat recovery in longleaf pine woodlands and other fire-maintained ecosystems.

Our study focuses on the influences of historical agriculture and contemporary fire management on soil properties in longleaf pine woodlands. Agricultural fields are typically selected based on soils being suitable for farming (Flinn and Vellend, 2005); thus, comparing properties of soils that differ in agricultural history requires an approach that controls for underlying soil variation. We used a paired-plot design, whereby pairs of post-agricultural and remnant woodlands were immediately adjacent in space and located on the same soil series to avoid potentially confounding issues of past land-use decisions. To date, few studies take this paired-plot approach (but see Brudvig et al., 2013) or account for soil type to understand the effects of agricultural history. In this study, we address the following questions: (1) What is the effect of historical agricultural land use on soil physical and chemical properties 50+ years after agricultural abandonment? (2) Does contemporary fire frequency affect soil properties? (3) Do contemporary fire frequency and historical agriculture have additive, synergistic, or offsetting impacts on soil properties? Based on published work in other sandy-soiled forested ecosystems, we predict soil properties in post-agricultural longleaf woodlands will have less soil carbon and nitrogen, and greater phosphorus and bulk density compared to remnant woodlands, even after 50 years since abandonment (Compton et al., 1998; Maloney et al., 2008). We expect fire frequency to have the greatest effect on soil organic matter and carbon (Neary et al., 1999). If both predictions above hold true, then higher fire frequency will exacerbate the effect of agriculture on some—but not all—soil properties in longleaf pine woodlands.

2. Materials and methods

2.1. Study site

We conducted the study at the Department of Energy's Savannah River Site (SRS), an ~80,000 ha National Environmental Research Park near New Ellenton, South Carolina, United States (Fig. 1). The SRS is located on the border of the Sandhill and Upper Coastal Plain ecoregions and is characterized by a humid subtropical climate (Blake et al., 2005). Of the soil types historically supporting upland longleaf pine woodlands at SRS, the most common soil association is the Blanton–Fuquay–Dolton (47% of SRS area; Kolka et al., 2005). The Blanton series (Loamy, siliceous, semiactive, thermic Grossarenic Paleudults) is the most abundant at SRS, followed by the Fuquay series (Loamy, kaolinitic, thermic Arenic Plinthic Kandiudults) (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Official Soil Series Descriptions. Available online at http://soils.usda.gov/technical/classification/osd/index.html (Accessed 11 March 2015)). Our work occurred on these two soil series alone. Both the Blanton and Fuquay series are sandy, well-drained, and flat to gently sloping (0–10% grade) soils with low organic matter content (Kolka et al., 2005).

Prior to European settlement, the SRS uplands were longleaf pine woodlands heavily influenced by Native American fire regimes (White, 2005). Historically, these woodlands experienced frequent (every 1–6 years), low intensity surface fires (Frost, 2006). In 1951, SRS was established and the United States Forest Service was contracted to manage existing woodlands and to reforest abandoned farmland and cutover woodlands in the area (Blake, 2005). At the time of government purchase, 38% of the land was in