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Sustainability of forest management under changing climatic conditions in the southern United States: Adaptation strategies, economic rents and carbon sequestration

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A B S T R A C T

The impacts of climate change on profitability and carbon storage in even-aged forest stands of two dominant commercial pine species, loblolly and slash pine, in the southern United States were assessed under alternative assumptions about the impact of climate change on forest productivity and catastrophic disturbance rates. Potential adaptation strategies to reduce losses from disturbance included: 1) alternative planting densities, and 2) planting slash pine instead of loblolly pine. In addition, the amount of sequestered carbon was used to develop an index of economic efficiency for carbon sequestration, which further helps rank the suitability of alternative adaptation strategies. Our results indicate that greater economic rents from forests occur with lower planting densities and the substitution of slash pine for high density loblolly pine. However, less carbon is sequestered by low density loblolly pine compared to slash pine and high density loblolly pine. Both adaptation strategies are economically more effective in terms of carbon sequestration compared to the baseline since they generate more economic revenues per Mg of sequestered carbon.

1. Introduction

Increased emissions of greenhouse gases generated by human activities, particularly carbon dioxide (CO_2), are considered one the main causes of climate change. Climate models consistently predict that the Earth's temperature will increase in the 21st century (Christensen et al., 2007). In the southern United States (U.S.), the increase in temperature is expected to be between 2 °C and 3 °C (Christensen et al., 2007). Precipitation patterns are expected to change depending on the location, with the southern U.S. becoming drier (Karl et al., 2009). Climate change is also expected to play a significant role in the increased severity of natural disturbances such as wildfires, pests and hurricanes (Dale et al., 2001).

Forestlands provide numerous critical ecosystem services such as timber, carbon (C) sequestration, aesthetics, and biodiversity. The southern U.S. provides 57% of the national volume of roundwood harvested and nonindustrial private forest landowners own approximately 68% of private timberlands (49 million hectares) (Smith et al., 2009). This suggests that private landowners will likely play a crucial role in meeting future demand for wood products. Southern forests have the potential of sequestering 23% of regional total greenhouse gas emissions (Han et al., 2007). Forests are also critical to water supply and water quality protection, with forest watersheds providing eighty percent of freshwater in the U.S. (USEPA, 2000), and reducing water treatment costs (e.g., de Groot et al., 2002). Although climate change will likely have a major impact on forestlands, the implications are not fully known. For example, the understanding of increased multiple natural disturbances is mainly qualitative (Vose et al., 2012). This uncertainty is mainly

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related to the degree in which climate change will affect forestlands[1] and the response of forest ecosystems to climate change (Yousefpour et al., 2012).

Increased drought intensity in the southern U.S. has caused significant decreases in net primary productivity (up to 40%) and resulted in C sources in forest ecosystems (Chen et al., 2012). Warming conditions and decreased precipitation are expected to stress southern pines and increase the impacts of bark beetles which are also expected to move northward (Duerr and Mistretta, 2013); and introduced pests such as cankers and emerald ash borer will likely have a significant impact on southern forests over the next 50 years, threatening the ecological viability of their hosts (Duerr and Mistretta, 2013). Furthermore, droughts will increase the wildfire potential in the region at higher rates (50%) compared to the national average with future climates (Liu et al., 2010), and with climatic changing conditions, the severity of wildfire events is predicted to increase in the Coastal Plain Appalachian mountains impeding successful forest regeneration and causing shifts in vegetation types over time (Stanturf and Goodrick, 2013).

Risk from hurricanes, which are a major natural disturbance to southern U.S. forests, is also expected to increase due to climate change. The Atlantic basin in particular is expected[2] to see higher frequency of intense hurricanes, which are particularly destructive to commercially-important pine trees in the southern U.S. (Bender et al., 2010). Hurricanes have a compounding multiplying effect on forestlands; sequestered C can be lost to downed biomass (McNulty, 2002), accumulated dead fuels may increase wildfire hazard (Liu et al., 2008), and damaged trees and those with reduced vigor are susceptible to pest outbreaks (Stanturf et al., 2007). Furthermore, hurricanes cause major forest-related economic losses. For example, losses of US$ 2 to 3 billion were caused by hurricanes Katrina and Rita in 2005 (Stanturf et al., 2007).

The various climate change-related impacts on forestlands (increased abiotic disturbances and changes in forest productivity) make it difficult to predict the net impacts. As such, forest managers might consider alternative adaptation management approaches in light of climate change-related risks. These include silvicultural activities such as thinnings, changes in tree planting density, and harvest age that can ameliorate the negative effects of increased disturbance events due to climate change (D'Amato et al., 2011). Indeed, managing tree spacing due to thinnings or initial tree planting density becomes critical to reduce hurricane damage (Oswalt and Oswalt, 2008). For example, Stanturf et al. (2007) reported that winds up to 128 km hour^{-1}caused no damage to loblolly pine for 20-m and 25-m-tall stands with tree spacings of 2.5, 5 and 7.5 m, although it is generally thought that taller trees with wider spacing are prone to stem breakage during hurricanes (Oswalt and Oswalt, 2008). Stand density management through reduced tree planting density followed by prescribed burning is a widely used treatment to reduce the accumulation of forest fuels (Stanturf and Goodrick, 2013), and the influence of wildfires (Amacher et al., 2005) in the southern U.S. Furthermore, the management of stand density will reduce the vulnerability to insects and pest attacks in the region (Duerr and Mistretta, 2013). Finally, planting a different tree species may reduce the impacts of disturbance events. Loblolly pine, which is currently the dominant commercial species in the southern U.S., is more susceptible than slash pine and longleaf pine to breakage, uprooting and deterioration by insect and diseases (Barry et al., 1998).

Understanding the timber and C-related impacts of climate change adaptation strategies becomes critical for landowners' and land managers' forest management objectives. Emerging C markets represent another avenue for forest landowners' income diversification. For example, with payments for C sequestration typically ranging between \$5 and \$15 ton^{-1} CO_2e (carbon dioxide equivalent), around 30–137 Teragrams (Tg) of additional CO_2e can be sequestered on U.S. timberlands (Nepal et al., 2013). The South has the annual potential sequestration of 400 Tg CO_2e due to low management cost and high timber volumes (Galik et al., 2013). Under changing climatic conditions, however, the decomposition of soil organic matter and release of CO_2 from forestlands could increase (Vose et al., 2012) making forestlands a carbon source rather than a carbon sink (Hicke et al., 2012).

With the exception of Goetz et al. (2013), profitability analysis and C sequestration at the forest stand level under climate change have not been readily explored. In this paper, we analyze the economics of two alternative climate change adaptation strategies – reduced planting density and planting a different pine species – on economic rents and C sequestration in southern U.S. commercial forests. Given their commercial dominance in the southern U.S., we focus on loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliotti*), and simulate the impacts of disturbance risk (i.e., hurricanes, wildfires and pest outbreaks) and salvageable portion for a representative site that could be planted with loblolly pine at high density (baseline approach), planted with loblolly at low density, or planted with slash pine at high density. Compared to the baseline (high-density loblolly pine), we evaluate changes in economic rents and C sequestration given different assumptions about forest productivity, disturbance risk, and salvageable portion of the forest stand remaining after a disturbance.

Further, we assess the sustainability of the climate change adaptation strategies by defining an index of sequestered C and economic efficiency – the economic efficiency of C sequestration (EECS) – which is the ratio of economic returns (land expectation value LEV \$ ha^{-1}) to sequestered carbon (Mg ha^{-1}). In the following sections, we present a conceptual economic model of forest disturbances and apply this model for a representative southern U.S. forest site. Results are compared for the adaptation alternatives, and we discuss their implications for landowners.

2. Model specification

We capture the influence of climate change on forest disturbance and subsequent economic rents within a Reed model framework (Reed, 1984), which can determine the impact of a risk of a disturbance event and salvageable portion of the forest stand on optimal forest management at the hectare level. This model assumes that: disturbance events follow a Poisson process, i.e., they are independent and occur at the same average probability per unit of time, and the waiting time X between successive destructions (and hence represents the age of the stand at the time of a disturbance event) is a random variable. It is also assumed that X follows an exponential distribution, thus the probability of a stand being affected by a disturbance event before the optimal rotation

[1] Climate change is also likely to have a significant impact on forest productivity. An increase of 23–28% in forest productivity is expected, worldwide, until 2050 with increased levels of CO_2 (Kallarackal and Roby, 2012). Increased levels of CO_2 and temperature will improve loblolly pine (*Pinus taeda*) growth (Wertin et al., 2012), although the positive impacts of elevated CO_2 levels on growth may be offset by other factors, including soil water availability (Wertin et al., 2010). Forecasted precipitation regimes are expected to vary significantly across the southern U.S. with climate change (Wear and Greis, 2012), and to occur in less frequent, more intensive events that decrease the overall availability of water for trees due to less infiltration (Allen and Ingram, 2002). In the southern U.S., a 10–20% increase of forest productivity is forecasted yet a significant reduction in precipitation would definitely decrease forest productivity (Robert Teskey, personal communication, University of Georgia, June 2012).

[2] Hurricanes will have different frequencies in the southern U.S., depending on location. For example, increased regional frequencies for larger hurricanes in East Coast States are expected compared to those for Gulf States (Parisi and Lund, 2008).