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Fundamental shifts of central hardwood forests under climate change

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ABSTRACT

The Central Hardwood Region (CHR) of the United States constitutes one of the most diverse ecoregions in North America and the most extensive temperate deciduous forest in the world. Despite the economic and ecological significance of the CHR, the long-term effects of changes in climate and fire regime on forest structure remain largely unknown. In this study, we developed an integrated Climate-Sensitive Matrix framework to synchronously couple (1) forest dynamics, (2) mean fire interval, (3) population density, and (4) future climate scenarios to study the community and population structure of CHR forests under climate change and associated changes of fire regimes. Using Monte Carlo simulations and coupled forest dynamics-disturbance models, we projected that the CHR would undergo a major shift in forest community structure from the present to year 2100. The fundamental changes would consist of a transition of dominant species from oak and hickory to maple species, reduced species diversity (9.6–11.5%), and substantial declines in stand basal area (55.1–62.0%) and stand volume (56.3–62.4%). These projected changes will have profound ecological and economic implications. Ecologically, changes in tree species diversity favoring maples would alter ecosystem processing of nutrients and subsequent nutrient flows to drainage waters within the region. Habitat change would alter the broad spectrum of organisms relying on the forest, leading to a redistribution of wildlife species, further heightening the risks for endangered species. Economically, the total stumpage value throughout the CHR would be reduced by 54.5–59.8% from approximately $1317 billion to $529–599 billion. On the brink of these fundamental shifts, our study calls for ecologically- and economically-informed conservation and mitigation strategies to better prepare society for the associated changes in ecosystem services and economic benefits derived from CHR forests.

1. Introduction

The Central Hardwood Region (CHR) of the United States, covered by approximately 58 million ha of forests stretching from the upper southeast U.S. to Indiana and from Oklahoma to Pennsylvania (Fig. 1), constitutes the most extensive temperate deciduous forest in the world (Box and Fujiwara, 2015). The CHR is well known for its wide variety of oak-hickory forest resources that provide significant ecological and economic benefits to local, regional, and national communities. The CHR forms the headwaters for many major U.S. rivers and plays critical roles in improving and protecting soil and water resources as well as in mitigating flooding (Bernhardt and Palmer, 2011). It is home to a wide array of flora and fauna species (Schmidt and Mcwilliams, 2003) and is one of the most diverse ecoregions in North America (Mueller, 1996). The CHR supports ninety percent of hardwoods and one-third of the total forest growing stock in the continental United States (Hicks, 1998). The high quality hardwood timber resources play a vital role in regional employment and wood related industries.

A growing body of evidence suggests that global climate change will have significant impacts on forest ecosystems by affecting the distribution and variation of key environmental factors, such as CO_2, humidity, and incoming solar radiation (e.g., Aber et al., 2001; Allen et al., 2010; Boisvenue and Running, 2006; Latta et al., 2010; Lindner et al., 2010; Schoene and Bernier, 2012). These changes will affect species composition and the productivity of forest ecosystems in this region (Aber et al., 2001; Boisvenue and Running, 2006; Latta et al., 2010; Shugart et al., 2003; Smith et al., 1995) as well as

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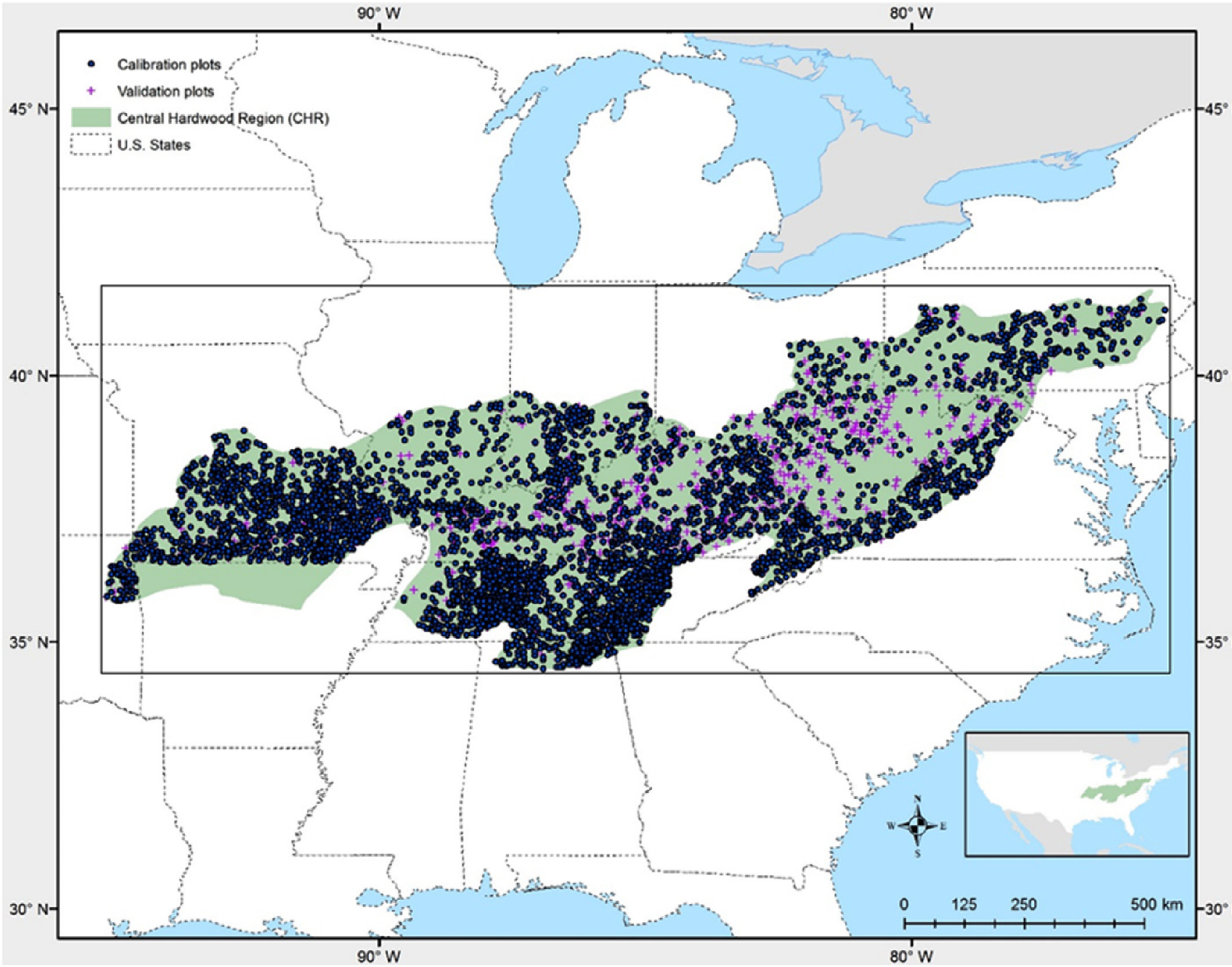

Fig. 1. Geographic distribution of the calibration (dots) and validation (+) plots, in the Central Hardwood Region (CHR). Inset shows the relative location of CHR in the contiguous United States. The box indicates the CHR region where the future relative changes of temperature and precipitation (trend ratio) were extracted for four future climate scenarios.

forest ecosystem processes through alterations in resource acquisition and resource utilization efficiency (Hansen and Dale, 2001; Hansen et al., 2001; Helmick et al., 2014; Juday et al., 2005). Precipitation and temperature, and their seasonality and extremes, may change species' ranges, inter-species relationships, fire frequency, and other ecosystem processes in the CHR, which will have broad ecological and economic implications across the region and beyond (Alexander and Arthur, 2010; Lafon et al., 2005; Parisen and Moritz, 2009). In addition, recent theoretical advances and empirical evidence (Cardinale et al., 2012; Liang et al., 2015; Naeem et al., 2012; Tilman et al., 1997) have revealed substantial impact of the loss of biodiversity on the functioning of ecosystems. The impact of climate change and biodiversity loss on CHR forests, however, has yet to be quantified.

Natural disturbances are a major factor affecting forest dynamics and composition (Fischer et al., 2013), and influence the development of effective ecosystem restoration and management practices (Foster, 2000; Zhou and Buongiorno, 2006). Throughout the CHR, forest dynamics have been driven historically by high intensity stand-replacing fires necessary for the successful regeneration of shade intolerant species (Albrecht and Mccarthy, 2006; Brose et al., 2013; Mcewan et al., 2007, 2011; Schuler et al., 2012; Signell et al., 2005). However, human intervention has reduced both the intensity and area of CHR forests burned since 1940, which has led to a widespread transition in dominant species from oak (*Quercus* spp.) and hickory (*Carya* spp.) to other early successional maple species (*Acer* spp.). This transition is termed the mesophication of the eastern hardwood forests (Fralish and Mcardle, 2009; Nowacki and Abrams, 2008). Accompanying this transition has been a reduction in area of bottomland hardwood forests and original oak savannas (Schmidt and Mcwilliams, 2003). In modeling fire impacts, fire regimes are typically based on the vegetation associations (Hann et al., 2004; Keane et al., 2002). Recent modeling efforts consider climate variables as predictors (Jiang et al., 2012; Parisen and Moritz, 2009; Westerling et al., 2006), and synthesize existing fire history information and mean fire intervals (MFI) based on physical mechanisms associated with dry climatic conditions (Guyette et al., 2010). Temperature, precipitation, and their interactions prove to be the most significant factors controlling fire frequencies and intensity in forest ecosystems (Morgan et al., 2001), and these environmental factors are predicted to change in the future.

Reliable forest growth models are lacking for the CHR. One of the first forest growth models for the region was established by Perkey (1985). This whole-stand model simulated stand-level attributes, but did not specify population structure. Later, the