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Assessing the effect of climate change on carbon sequestration in a Mexican dry forest in the Yucatan Peninsula

Z. Dai [a,b,*], K.D. Johnson [a], R.A. Birdsey [a], J.L. Hernandez-Stefanoni [c], J.M. Dupuy [c]

[a] USDA Forest Service, 11 Campus Blvd, Suite 200, Newtown Square, PA 19073, USA
[b] Commission for Environmental Cooperation, 393 rue St-Jacques Ouest, bureau 200, Montreal, QC H2Y 1N9, Canada
[c] Centro de Investigación Científica de Yucatán A.C., Unidad de Recursos Naturales, Calle 43# 130. Colonia Chuburná de Hidalgo, C.P. 97200, Mérida, Yucatán, Mexico

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ABSTRACT

Assessing the effect of climate change on carbon sequestration in tropical forest ecosystems is important to inform monitoring, reporting, and verification (MRV) for reducing deforestation and forest degradation (REDD), and to effectively assess forest management options under climate change. Two process-based models, Forest-DNDC and Biome-BGC, with different spatial modeling scales were evaluated to estimate the potential effect of climate change on carbon sequestration in a tropical dry semi-deciduous forest in the Yucatan Peninsula of Mexico. The results from the simulations using the two models show that carbon sequestration in this dry forest is highly sensitive to warming. Carbon uptake in this forest may increase or decrease slightly with a corresponding increase or decrease in precipitation; however, with an increase in temperature, carbon uptake may decrease significantly, showing that warming may be the main climate factor that impacts carbon storage in this tropical dry forest. Model performance evaluation indicates that both models may be used to estimate C stocks, but DNDC may be better than BGC for assessing the effect of climate change on C dynamics.

1. Introduction

Carbon (C) sequestration in forest ecosystems benefits the natural environment and contributes to the mitigation of global warming because forests are an important terrestrial C sink (Miehle et al., 2006; Trettin et al., 2006; Birdsey et al., 2007; Pan et al., 2011; Charman et al., 2013). The responses of terrestrial ecosystems to global warming can vary regionally. For example, projections from global climate models indicate the potential for more rain in middle and high latitude zones (Wentz et al., 2007; Zhang et al., 2007; Lambert et al., 2008), but not for low latitude areas (Zhang et al., 2007) and parts of subtropical areas (Dai et al., 2011). Understanding the regional differences in the response of forest ecosystems to global warming is fundamental to assess the role of forest ecosystems in reducing atmospheric CO_2 concentrations.

Climate change may have had a significant role in the collapse of the ancient Maya civilization in Mexico. Analyses of oxygen isotopes and chemical components in historical sediments in the Yucatan Peninsula indicate that historical air temperature and precipitation fluctuated greatly between 1300 and 1100 year BP (800–1000 A.D.), resulting in multiyear droughts (Hodell et al., 1995; Curtis et al., 1996; Haug et al., 2003; Medina-Elizalde and Rohling, 2012). These records imply that the current global warming trend may cause strong and long drought periods in the future, especially if rain decreases in this area (Zhang et al., 2007).

Understanding C dynamics in forest ecosystems is critical for assessing the impacts of deforestation and forest degradation, both of which are common in the tropical dry forests of Mexico. Specifically, quantifying C pools and sequestration rates (i.e. net CO_2 flux) informs strategies for Monitoring, Reporting and Verification (MRV) and reducing deforestation and forest degradation (REDD). The most common direct way to measure C sequestration is by using eddy flux measurement technology for small areas (Baldocchi, 2003; Hutley et al., 2005; Barr et al., 2006; Oren et al., 2006; Kurbatova et al., 2008). However, these studies have found that CO_2 fluxes are highly dependent on changing environmental factors, including topography, climate, hydrology, soil, vegetation and various disturbances (Pietch et al., 2003; He et al., 2012; Pacific et al., 2009). Therefore, flux measurements are inadequate by themselves to account for landscape heterogeneity

* Corresponding author at: USDA Forest Service, 11 Campus Blvd, Suite 200, Newtown Square, PA 19073, USA.
E-mail address: zdai@fs.fed.us (Z. Dai).

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and extrapolation over large regions. Additionally, spatially explicit and long-term carbon dynamics using only eddy flux measurements or field measurements are limited by personnel, equipment, and funds. These issues can be overcome with ecosystem models developed from expert knowledge of ecosystem processes, long-term experiences, and observations. Recent applications of biogeochemical carbon models for assessing forests response to land use change and natural and human disturbances highlight the merits of these methods (Miehle et al., 2006; He et al., 2012; Chen et al., 2003; Hanson et al., 2004; Mo et al., 2008; Hlasny et al., 2011; Miao et al., 2011; Dai et al., 2013). Thus, ecosystem models are important tools for understanding the responses of forests to climate change, and for assessing long-term C dynamics at the landscape level to aid in forest management decisions.

Many ecosystem C models such as MAESTRO (Wang and Jarvis, 1990) and Biome-BGC (Thornton et al., 2002), have been used for simulating C dynamics in forest ecosystems. Miehle et al. (2006) compared the performance of five forest C models, i.e., 3-PG (Landsberg and Waring, 1997), BIOMASS (Hingston et al., 1998), CABALA (Battaglia et al., 2004), Forest-DNDC (Li et al., 2000), and PROMOD (Battaglia and Sands, 1997), using observations from 93 plantations across southeastern Australia. Their results showed that most models performed reasonably well to predict forest C accumulation, and that, in particular, CABALA and Forest-DNDC performed better than others based on the model performance efficiency. Differences in performance efficiencies among models can be substantial, and in at least one study of 13 models (Hanson et al., 2004), efficiencies ranged from 0.17 to 0.73 for daily net ecosystem exchange (NEE), at least partly due to model structure. Also, since there are a variety of model structures developed from different natural environments, it is sometimes unclear which models are most appropriate for new environments. To help address these uncertainties, it is beneficial to experiment with more than one model, which allows for additional model evaluations against field observations and also evaluations of agreement between modeled output trends. In this study we chose to apply two models, Forest-DNDC which requires more data inputs and has a more sophisticated soils submodel, and Biome-BGC which has a simpler structure and is more widely applied.

Most of Mexico is located in the northern tropical zone, with a high diversity of forest types ranging from deciduous to evergreen based primarily on moisture availability. Responses of these forests to climate change are likely to be very different. For example, the climatic and hydrogeological conditions in the Yucatan Peninsula are very different from the rest of the country (Perry et al., 2003; Brienen et al., 2009; Dai et al., 2014). Global warming may increase air temperature in this area at a rate of $\geq$0.1 °C per decade (based on data beginning in 1960; Met Office, 2011), but may not bring more rain (Zhang et al., 2007), potentially impacting the carbon dynamics in these dry tropical forest ecosystems (Brienen et al., 2009). In addition, Mexican tropical dry forests cover more area, and are more threatened by climate change than other tropical ecosystems (Hernandez-Stefanoni et al., 2011; Dupuy et al., 2012). Accordingly, it is important to consider the responses of carbon dynamics in tropical dry forests when exploring climate change mitigation options.

The aims of this study were threefold: (1) to evaluate the Forest-DNDC and Biome-BGC models for a Yucatan dry semi-deciduous forest using biomass, soil and climate observations, (2) to apply the two models for estimating the effect of climate change on carbon dynamics in the forest, and (3) to evaluate the performance of the models. To achieve the first and third objectives we used field observations from 276 plots from Kaxil Kiuic in the Yucatan Peninsula collected by Hernandez-Stefanoni et al. (2011) and Dupuy et al. (2012). Four quantitative model performance evaluation variables were also used to evaluate the model performance. To achieve the second objective, a daily climate dataset for a 43-year period (1970–2012) was used, based on the climate data recorded at six weather stations in this area.

2. Data and methods

2.1. Study site

This site is located in the Yucatan Peninsula, Mexico, 20.02–20.16°N and 89.39–89.60°W (Fig. 1). It is a tropical dry semi-deciduous forest landscape of about 350 km^2, which is mainly comprised of forestlands (93.9%) with scattered croplands (about 5.35%) and urban areas (about 0.75%) at present (Fig. 2). The land use has historically been swidden agriculture for over two thousand years (Hernandez-Stefanoni et al., 2011; Dupuy et al., 2012; Rico-Gray and Garcia-Franco, 1991; Turner et al., 2001). The current forest is regenerated after deforestation and cropland abandonment.

The landscape topography consists of mosaics of low and moderate hills with small flat areas. The slope ranges between 0 and 90%, with an average slope of 7%. The elevation ranges from 70 to 176 m above mean sea level, with a mean of 116 m. The climate is tropical, with a summer rain period from June to October and a dry season between November and May. The mean annual precipitation is 1190 mm during the 38-year period from 1970 to 2007, based on the available climate data observed at the weather

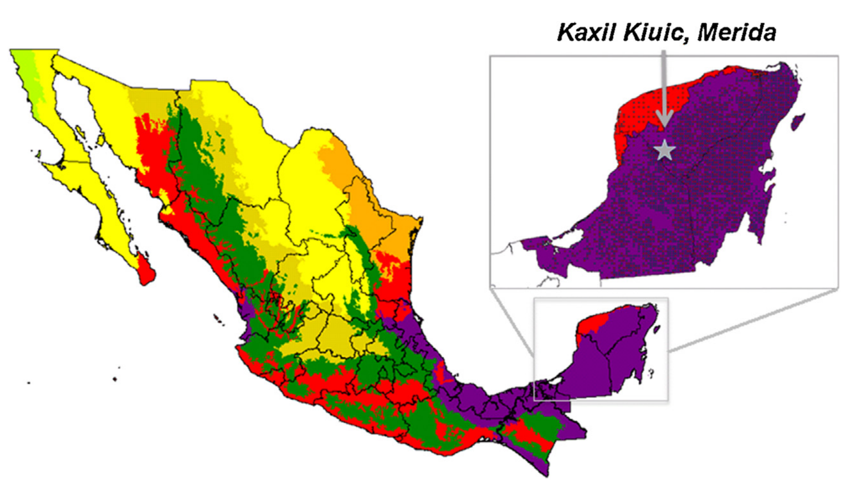

Fig. 1. Kaxil Kiuic forest in the Yucatan Peninsula, Mexico.