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# Soil depth affects simulated carbon and water in the MC2 dynamic global vegetation model

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ABSTRACT

Climate change has significant effects on critical ecosystem functions such as carbon and water cycling. Vegetation and especially forest ecosystems play an important role in the carbon and hydrological cycles. Vegetation models that include detailed belowground processes require accurate soil data to decrease uncertainty and increase realism in their simulations. The MC2 DGVM uses three modules to simulate biogeography, biogeochemistry and fire effects, all three of which use soil data either directly or indirectly. This study includes a correlation analysis of the MC2 model to soil depth by comparing a subset of the model's carbon and hydrological outputs using soil depth data of different scales and qualities. The results show that the model is very sensitive to soil depth in simulations of carbon and hydrological variables, but competing algorithms make the fire module less sensitive to changes in soil depth. Simulated historic evapotranspiration and net primary productivity show the strongest positive correlations (both have correlation coefficients of 0.82). The strongest negative correlation is streamflow (−0.82). Ecosystem carbon, vegetation carbon and forest carbon show the next strongest correlations (0.78, 0.74 and 0.74, respectively). Carbon consumed by forest fires and the part of each grid cell burned show only weak negative correlations (−0.24 and −0.0013 respectively). In the model, when the water demand is met (deep soil with good water availability), production increases and fuels build up as more litter gets generated, thus increasing the overall fire risk during upcoming dry periods. However, when soil moisture is low, fuels dry and fire risk increases. In conclusion, it is clear climate change impact models need accurate soil depth data to simulate the resilience or vulnerability of ecosystems to future conditions.

## 1. Introduction

Climate change is an important driver of forest dieback and species migration with increases in drought, early snow melt, reduced snow depth, pest outbreaks, and fire risk (McKenzie et al., 2004; Mote et al., 2005; vanMantgem et al., 2009; Allen et al., 2010). In the North Pacific landscape of the USA, precipitation as rainfall is projected to increase in winter and spring, and decrease in summer, while temperatures rise from 2 to 5 °C by 2080 (Mote and Salathé, 2010). Vegetation models suggest that forest cover may increase at high elevations and latitudes in response to wetter winters, and dramatically decrease at lower elevations and latitudes due to severe competition for water from shrubs and grasses, even without consideration of future water needs from human land use (Climate Impacts Group (CIG), 2011). However, some vegetation models suggest possible vegetation shifts to lower elevations where water might be more readily available as higher elevations become drier (Crimmins et al., 2011).

Climate-related stress can also affect forests indirectly by increasing their vulnerability to pests and pathogens. Littell et al. (2009) projected a reduction of climate suitability for Douglas fir in the Puget Trough as well as increases in wildfires and mountain pine beetle outbreaks, which would affect tree growth and survival in the region. Lodgepole pines in British Columbia, Oregon, Washington and California have also shown increased vulnerability to climate change in recent decades and have been subject to well-documented beetle attacks (e.g., Raffa et al., 2008). Vegetation models indicate that lodgepole may disappear from most of its current range by the end of this century (Coops and Waring, 2011). Further North, Alaskan Yellow Cedar decline in southeast Alaska and portions of British Columbia has also been connected to warming air that melts snow and exposes roots to lethal subfreezing temperatures (D'Amore and Hennon, 2006).

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*Abbreviations:* ASW, available soil water storage capacity; DGVM, dynamic global vegetation model.

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Changes in available soil moisture are increasing tree vulnerability across many systems, and available soil water storage capacity (ASW) thresholds have now been documented beyond which forest decline starts to occur during multi-year droughts (Peterman et al., 2013; Mathys et al., 2014). Soil physical characteristics are important for assessing ASW, an essential component of ecosystem functions, including carbon and nutrient cycling, as well as succession through seedling establishment in post-disturbance forests (USDA NRCS Soil Survey Division Staff, 1993; Neilson and Drapek, 1998; Dale et al., 2001; Allen et al., 2010; Puhlick et al., 2012). Simulation results from vegetation models are used in global and regional assessments in an attempt to forecast ecosystem responses to climate change (Cramer et al., 2001; IPCC, 2007; Handler et al., 2013). The complex interactions between plants and pests or pathogens, often constrained by ASW can only be simulated if reliable soil data are available. Soil data have historically been a primary source of uncertainty for modelers who simulate belowground-processes such as root growth and decomposition as well as hydrological processes (Allen et al., 2010; Coops et al., 2012). In this paper, we report results from a correlation analysis of a dynamic global vegetation model (MC2) that demonstrates the importance of soil inputs in simulations of vegetation dynamics in the 21st century.

### 1.1. Background and model description

The MC1 dynamic global vegetation model (DGVM) was developed for the vegetation/ecosystem modeling and analysis (VEMAP) project (Bachelet et al., 2001). It consists of three component modules (Fig. 1): (1) a biogeography module derived from the static biogeography model MAPSS (Neilson, 1995), (2) a biogeochemistry module, derived from the CENTURY model (Parton et al., 1987), and (3) a dynamic fire model called MCFire (Lenihan et al., 1998). The MAPSS model is used solely to determine the potential life forms and vegetation types present on the landscape, using a twelve-month long-term average climate to characterize each grid cell during the equilibrium phase of the model (Bachelet et al., 2001). A modified version of the CENTURY model is then called to simulate the carbon and nitrogen pools associated with the potential vegetation types (Bachelet et al., 2001). These initial conditions are used to start the "spinup" phase during which the full DGVM simulates: (1) biogeography, using a set of climate and biomass threshold rules, (2) carbon and nitrogen cycling, using a modified version of CENTURY version 4 and (3) fire occurrence and effects, using the dynamic fire module. The DGVM is run iteratively for 600 years using a de-trended historical monthly climate until net ecosystem productivity nears zero and the fire return interval (FRI) nears historical estimates (Leenhouts, 1998). Once this "spinup" phase is completed, the DGVM is run with historical climate and future climate projections.

In the MC2 DGVM, the hydrology algorithms from CENTURY are used to calculate hydrological flows. The model uses soil depth, texture, rock fragment content and bulk density to estimate monthly available soil moisture. Because the MC2 DGVM uses these soil characteristics to regulate the water fluxes that directly affect plant growth and decomposition, we expect changes in these inputs to result in changes in simulated carbon and hydrology. However, to date, no formal analysis of the relationship between soil characteristics and model simulations has been performed.

Conklin (2009) used MC1 to simulate vegetation shifts in Yosemite National Park and observed that the model was overestimating carbon pools and simulating closed-canopy forests at the top of the Sierras. He found that the STASGO-based US soils map that had been used (e.g., Bachelet et al., 2008; Lenihan et al., 1998) included overestimated soil depths, especially at high elevations (Conklin, 2009). In the original data, he found deep soils at the top of Half Dome, where there should be no soil or vegetation. He used a modified soil dataset based on expert opinion for Yosemite and simulated the more realistic bare rock at the crest of the Sierras.

The NATSGO soil dataset (1:7.5 Million scale), originally used in MC1, was replaced by the STATSGO (1:250,000 scale) national soil dataset for the USA (personal communication Kern, 1994). Since then, the finer scale State Soil Geodatabase (SSURGO – average 1:24,000 scale) has been expanded to cover large areas at the state and county level (USDA NRCS, 2014), although the data do not yet provide full coverage of the U.S. For this paper, we conducted our correlation analysis using the MC2 model, the most recent C++ version of MC1, to evaluate whether substituting the soil depth layer from STATSGO with SSURGO data, where available, would result in significant changes in carbon cycling and hydrological flows.

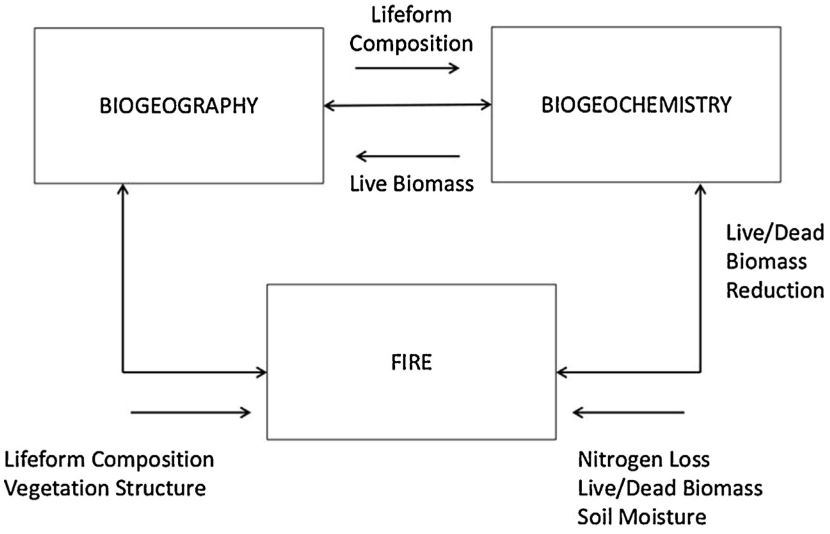

**Fig. 1.** Graphical representation of MC2 DGVM.The biogeography component, uses rules derived from the static biogeography model MAPSS (Neilson, 1995), the biogeochemistry component uses algorithms from a modified version of the biogeochemical model CENTURY (Parton et al. 1987) and the dynamic fire component includes both fire occurrence and effects (Lenihan et al. 1998).