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Uncertainty in carbon allocation strategy and ecophysiological parameterization influences on carbon and streamflow estimates for two western US forested watersheds

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ABSTRACT

Increasingly sophisticated process-based ecosystem models account for the ability of plants to vary the proportion of net photosynthate that is allocated to individual organs – such as leaves, stems and roots. Because the governing mechanisms are still not well understood, models differ in the strategies used to represent carbon allocation processes. Allocation schemes may have important implications for ecosystem structure and biogeochemical cycling, thus there is a need to better understand how different carbon allocation strategies influence estimates of variables that are of interest to model users. At the same time, uncertainty in other ecophysiological parameters that are commonly used in carbon cycling models may influence these estimates and interact with different carbon allocation strategies. We use a coupled ecohydrologic model to understand how uncertainty in three relatively simple allocation strategies affects carbon (C) and streamflow estimates in two case study forested mountain watersheds in the western United States: a relatively wet site located in the western Oregon Cascades, and a drier site in California's Sierra Nevada. Ecophysiological parameters controlling productivity rates, morphology, and nutrient requirements for growth are varied as well. The influence of specific ecophysiological parameters and allocation strategies on C sequestration and streamflow estimates differed between sites. At the wetter site, uncertainty in C cycling processes resulted in a three-fold difference in potential sequestered carbon, but had a negligible effect on annual and low monthly streamflow estimates. Conversely, at the drier site, C pool estimates showed limited sensitivity to ecophysiological parameter uncertainty, but considerable difference in annual and low monthly streamflow estimates across ecophysiological assumptions. At both sites, stemwood C pool estimates exceeded literature-derived field values when branch mortality—a surrogate for density thinning—was not included in addition to background mortality. Despite using site- and species-specific information, we are unable to invalidate any of the allocation strategies considered. Our results suggest that uncertainty in parameterization of ecophysiological parameters and assumptions about carbon allocation can strongly influence model estimates of both streamflow and forest carbon sequestration potential, but that influence is likely to vary with site bioclimatic characteristics.

1. Introduction

Carbon allocation is a fundamental part of forest ecosystem carbon cycling. An increase in the concentration of atmospheric CO_2 has stimulated interest in better understanding the forest ecosystem carbon cycle, forested landscape responses to changes in atmospheric drivers, and the role that forests play in global fluxes. Forest carbon cycling is particularly relevant in the design of low-cost mitigation strategies that utilize the potential of forests to act as carbon (C) sinks (IPCC, 2007; Pan et al., 2011). Biogeochemical ecosystem models are tools that are frequently used to understand and predict carbon cycling processes through physical representations of photosynthesis and allocation processes, e.g. BGC (Coughlan and Running, 1997), TEM (Raich et al., 1991), and 3-PG (Landsberg and Waring, 1997). These physically based models use meteorological moisture and energy inputs to calculate the exchange of water and carbon between vegetation and the atmosphere (i.e., evaporation, transpiration, photosynthesis, and

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respiration). Process-based and dynamic global vegetation models (DGVMs) demonstrate considerable uncertainty in their projections of the future terrestrial carbon balance (Ahlström et al., 2012; Friedlingstein et al., 2014). DGVMs in general agree that North America's mid-latitude forests will continue to act as carbon sinks (Ahlström et al., 2012), and forests in the Pacific Northwest and northern California in particular have the theoretical potential to store 46% more C than they are currently estimated to hold (Hudiburg et al., 2009).

Previous efforts have used observations to improve ecosystem models' representation of the C cycle (De Kauwe et al., 2014; Law et al., 2006; Siqueira et al., 2006) and have demonstrated considerable uncertainty in model estimates of net ecosystem exchange, evapotranspiration, and allocation (Mitchell et al., 2009; Wang et al., 2009). Discrepancies between observations and model estimates may be due to errors in measurements (i.e., flux towers), fundamental errors in model structure, or the difficulty in physically deriving these estimates using ecophysiological parameters measured at the leaf scale. Modeling studies focused on parameter uncertainty show that uncertainty in ecophysiological parameters can be greater than uncertainty in flux-tower measurements (Mitchell et al., 2009). This suggests that one of the first steps in improving ecosystem models' carbon cycling capabilities is to better understand the uncertainty introduced by ecophysiological parameterization and also investigate the role of C allocation parameters, which these prior studies did not include (Booth et al., 2012; Mitchell et al., 2009; Zaehle et al., 2005).

Allocation determines the partitioning of carbon fixed in photosynthesis to plant respiration or biomass, and whether C is fixed as biomass above or below ground in longer- or shorter-lived organs. Allocation thus influences not just tree growth, but terrestrial biogeochemistry via litter quality and decomposition rates (Friedlingstein et al., 1999), and forest uptake of water and nutrients from the soil. There is no consensus on how to model carbon allocation, and so it represents a primary limitation in our understanding of the carbon cycle. A number of approaches to modeling allocation exist, ranging in complexity from computationally efficient empirical methods – to allocation estimates based on competition for resources between individual trees (see Franklin et al. (2012) for a detailed review). Improving our ability to model forest C allocation will improve our understanding of forests' role in the terrestrial carbon balance.

How C allocation is modeled, both in model structure and parameterization, may be particularly important for estimating ecosystem carbon cycling response to drought and climate variability (Bloom et al., 1985; Farrior et al., 2015). In addition, hydrologic variables, including evapotranspiration and streamflow, may be highly sensitive to forest structure and its responses to climate. Drought stress is typically accompanied by declines in net C assimilation and most carbon cycling models account for this response. How reductions in net C assimilation are translated into changes in growth, however, can impact subsequent ecosystem function (De Kauwe et al., 2014; Litton et al., 2007). Declines in allocation to roots or leaves under increasing CO_2 levels could decrease subsequent forest access to water and C assimilation capacity (Farrior et al., 2015). Shifting the proportion of net assimilation allocated to roots in response to drought on the other hand, could alter subsequent sensitivity to drought and forest water use (Schenk and Jackson, 2002). Recent droughts in the Western US highlight the need for improved understanding and prediction of forest carbon cycling responses (Allen et al., 2015)and the local and downstream impacts of associated changes in forest water use (Asbjornsen et al., 2011; Grant et al., 2013). Hydrologic models have been used to estimate changes in evapotranspiration and streamflow, but do not account for potential changes in forest structure and its impact on water use. Coupled hydrology and ecosystem growth models provide a more mechanistically complete estimate by accounting for interactions among forest structure, climate, and water use (Abdelnour et al., 2013; Birkinshaw et al., 2011). To the authors' knowledge, however, little work has examined how ecophysiological parameter and allocation uncertainty in coupled ecohydrologic models might alter these estimates. This paper aims to characterize ecophysiological uncertainty by examining how it interacts with forest carbon allocation and to also provide a first order estimate of its influence on basin hydrology.

We apply a process-based, coupled ecohydrologic model to ask: (1) how do estimates of mature forest carbon stores vary across different assumptions about forest allocation of Net Primary Productivity (NPP); (2) how do uncertainties in ecophysiological parameters interact with differences in forest carbon allocation strategies to influence estimates of forest carbon stores; and (3) how do differences in carbon allocation strategies influence annual and low monthly streamflow estimates? To answer these questions, we assess the uncertainty of modeled carbon storage and streamflow estimates due to allocation assumptions and ecophysiological parameter uncertainty for relatively wet and dry forested regions. We limit this analysis to two conifer varieties that are widely studied in the western US: *Pinus ponderosa* (PIPO) and *Pseudotsuga menziessi* (PSME). By focusing on two well-studied conifers, we capitalize on existing field-based studies that provide a range of estimated ecophysiological parameter values and a variety of measurements for mature forest C pools of foliage, fine roots and stemwood. We use measured C pool estimates to assess whether vegetation models are reasonable and where possible, constrain model parameters. We investigate the implications of variability in C pool partitioning on low flow and annual streamflow estimates in the California Sierra Nevada (SIERRA) and the western Oregon Cascades (CASCADES), using well-instrumented case study watersheds in these two regions.

2. Modeling strategy

2.1. Approach

In order to examine uncertainty in vegetation parameterization and its effect on watershed scale streamflow estimates, we apply a coupled process-based carbon cycling and hydrology model for (1) a spatially lumped and (2) a spatially distributed representation of the landscape. In the lumped approach a single model patch is used to represent an average forest stand and allows us to perform computationally intensive parameter sensitivity analysis. The spatially distributed approach is then used to for a more limited sensitivity analysis of parameter effects on streamflow estimates that require accounting for within watershed heterogeneity and lateral water fluxes. We compare three carbon allocation strategies where partitioning of net assimilation is based on: (1) fixed coefficients (FIX), (2) allometric scaling (AGE), and (3) resource limitation (RESOURCE) (described in more detail below). All are relatively simple models of allocation strategies that may be appropriate for describing the average allocation behavior of a forest at the stand or regional scale (Franklin et al., 2012). At the stand-scale, we quantify the uncertainty in model estimates for foliage, fine root, and stemwood C pools to individual ecophysiological parameters for each allocation strategy and each species. Model estimates are also compared to field observations taken from literature for each organ. A subset of ecophysiological parameters whose stand-scale C pool estimates fall within the range of measured values are used to model watershed streamflow. We conduct this analysis focusing on two species located at two sites that have similar wet-winter/dry-summer climates, but have key climatic differences such as total annual precipitation and energy received.