# INCORPORATING CLIMATE INTO BELOWGROUND CARBON ESTIMATES IN THE NATIONAL GREENHOUSE GAS INVENTORY

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**Abstract—** Refined estimation of carbon (C) stocks within forest ecosystems is a critical component of efforts to reduce greenhouse gas emissions and mitigate the effects of projected climate change through forest C management. Recent evidence has pointed to the importance of climate as a driver of belowground C stocks. This study describes an approach for adjusting allometric models of belowground C with climate-derived predictions of belowground C stocks and quantifies the change in reported belowground C stocks applied to the US National Greenhouse Gas Inventory (NGHGI). Climate-adjusted predictions varied by region and forest type, but represented a 6.4% increase at the national scale when compared to current estimates. By combining allometric equations with trends in temperature, we conclude that climate variables can be used to adjust the US NGHGI estimates of belowground C stocks. Such strategies can also be used to determine the effects of future global change scenarios within a biomass and C accounting framework.

## INTRODUCTION

The logistical and methodological constraints associated with estimating forest carbon (C) in belowground pools have created a need for refined modeling approaches to quantify belowground C stocks. Although allometric equations are designed to account for a large portion of the apparent variability associated with belowground biomass (Litton and others, 2003), there are some drawbacks to this approach. Allometric equations lack the flexibility to incorporate climate information that integrates differences in ecosystem productivity and allows for evaluations of future climate change scenarios on global C cycles. Highlighting this concern, Reich and others (2014) recently compiled a global dataset and concluded that forest biomass found in coarse roots was inversely related to mean annual temperature, suggesting that climate may act as a driver of belowground C allocation.

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The objective of this project is to adjust belowground C estimation procedures for reporting in the US National Greenhouse Gas Inventory (NGHGI) through integrating climate information. Specific objectives are to (1) adjust estimates of belowground C by combining allometric and climate-derived approaches using current and projected climate attributes and (2) quantify the effect of the adjusted estimation approach on belowground forest C in the US NGHGI.

## METHODS

### FIA Data

All data were obtained from the publically-available Forest Inventory and Analysis (FIA) database (Woudenberg and others 2010; http://apps.fs.fed.us/fiadb-downloads/datamart.html). These data were accessed and compiled in May 2014. Publicly available data from the FIA database are regularly updated when data collection and/or processing anomalies are found and corrected. Additionally, new data are added regularly which may be reflected by small changes in the past or current estimates. If an FIA plot was remeasured at any point, only the most recent measurement was used in this analysis.

### Belowground Carbon in the US National Greenhouse Gas Inventory ($BGC_{NGHGI}$)

Here, as in the NGHGI, live belowground C is defined as all coarse living roots greater than 2 mm diameter (Smith and others 2013). In the current NGHGI, belowground carbon stocks are estimated in two stages. First, total aboveground biomass is estimated using allometric equations (Jenkins and others 2003; their Table 4). Second, a ratio of coarse root to total aboveground biomass is calculated (Jenkins and others 2003 [their Table 6]; Smith and others 2013), dependent on whether the species is a hardwood or conifer. As observations of belowground tree biomass and C are often limited (Zianis and others 2005), relying on allometric equations has been necessary to obtain estimates from national-scale forest inventories such as FIA's.

As outlined in Jenkins and others (2003), parameters indicate that the belowground ratio will decrease for larger diameter trees. For a fixed d.b.h., the belowground ratio will be larger for conifers compared to hardwood species. Belowground biomass was estimated for all FIA plots in the lower 48 states and coastal Alaska using the most recent inventory measurement by performing current NGHGI estimation strategies. Biomass was converted to C by multiplying by 0.5, assuming 50% of biomass is C. Estimates of belowground C were scaled to the plot level and are hereby abbreviated as $BGC_{NGHGI}$.

### Climate-adjusted Models of Belowground Carbon ($BGC_{ClimAdj}$)

Belowground C modeling approaches that incorporate climatic attributes may be used both to adjust our estimates of coarse root C stocks at the national scale (i.e., application in the US NGHGI) and to enhance evaluations of future climate change scenarios on forest C cycles. We estimated climate-sensitive predictions of belowground biomass ($BGB_{Clim}$) for all FIA plots as a linear function of the following explanatory variables: mean annual temperature, natural or planted stand, hardwood- or conifer-dominated stand, and stem biomass of live trees (Reich and others 2014). We assigned the hardwood/conifer variable using the FIA forest type code by separating conifer-dominated forest type codes (i.e., FORTYPCD <= 409) with hardwood-dominated codes (FORTYPCD >= 500). Values for $BGB_{Clim}$ were converted to belowground carbon ($BGC_{Clim}$) by multiplying by 0.5.

Adjustment factors were estimated to align allometric- and climate-derived estimates:

$$AdjFactor = BGC_{Clim}/BGC_{NGHGI}, \qquad [1]$$

where AdjFactor is the ratio of climate- to allometric-derived belowground C for a specific forest type found in a given geographic region. New climate-adjusted estimates of belowground C ($BGC_{ClimAdj}$) are then:

$$BGC_{ClimAdj} = BGC_{NGHGI} * AdjFactor \qquad [2]$$

## RESULTS AND DISCUSSION

Estimates of belowground carbon from the approaches currently employed in the US NGHGI suggest that C stocks are dependent on geographic region and forest type. Mean $BGC_{NGHGI}$ was largest in hemlock-Sitka spruce forests in the Pacific Northwest (40.76±0.96 Mg $ha^{-1}$ [mean±SE]) and redwood forests in the Pacific Southwest (59.27±7.06 Mg $ha^{-1}$). Climate-derived stock estimates of belowground C ($BGC_{Clim}$) were slightly smaller in magnitude when compared to $BGC_{NGHGI}$ estimates (e.g., hemlock-Sitka spruce [33.82±0.80 Mg $ha^{-1}$] and redwood forests [45.64±5.44 Mg $ha^{-1}$]) and generally showed decreasing C at lower latitudes (Figure 1). On average, $BGC_{Clim}$ estimates were 0.60 Mg $ha^{-1}$ greater than current $BGC_{NGHGI}$ models when considering all forest types.

The adjustment factors ranged from 0.77 to 1.60 with little variability within a region of interest. Compared to current NGHGI models, model differences showed greater belowground C stocks occurring in the Appalachian Mountain region and areas where northern hardwood forests are common, e.g., in the upper Midwest and northeastern US states.

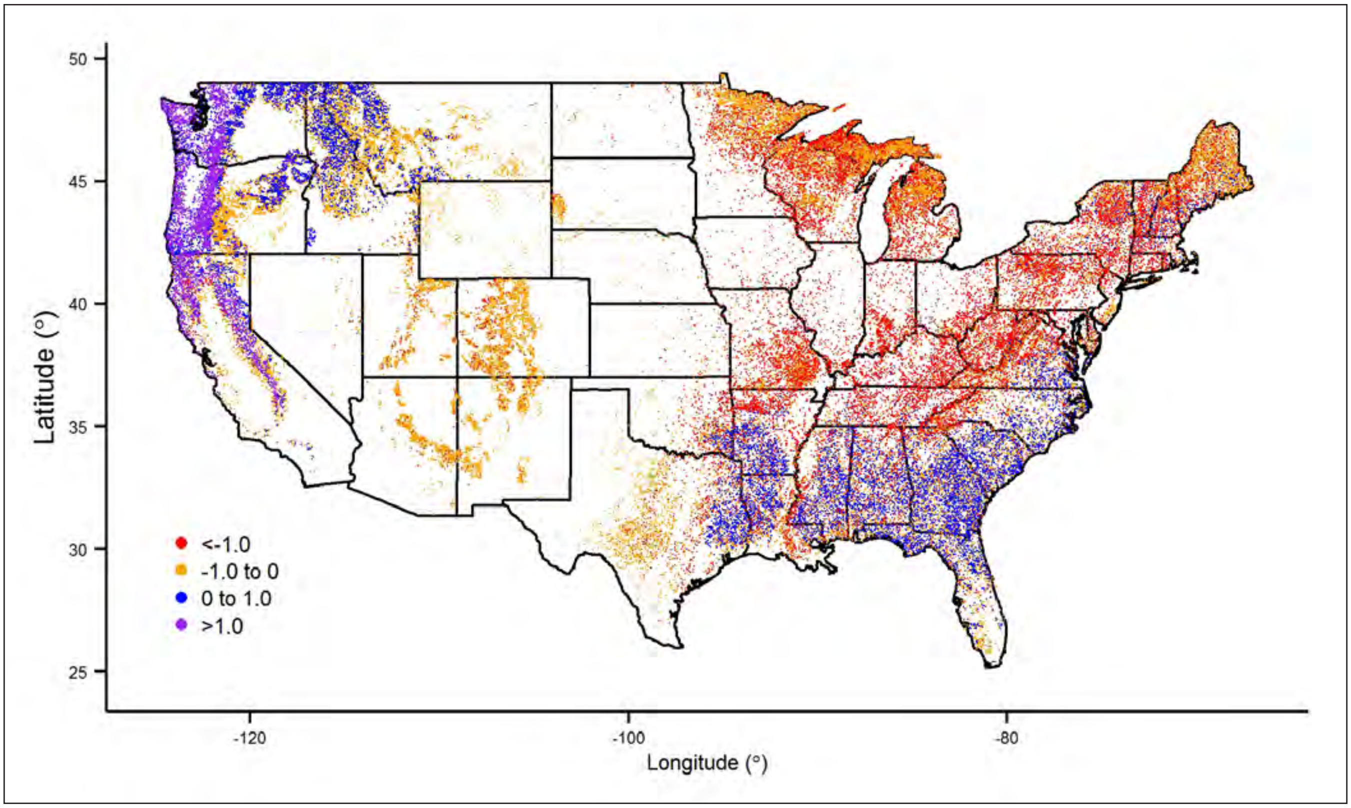


Figure 1—Distribution of differences between live-tree belowground C estimates from the National Greenhouse Gas Inventory and climate-adjusted estimates (BGCNGHGI - BGCClimAdj; Mg ha-1). Red colors indicate higher estimated belowground C and purple colors less belowground C.

Conversely, areas of smaller belowground C stocks were identified across the Pacific Northwest and Southeast US (Figure 1). The states of Oregon and Washington were predicted to display the largest negative mean difference in belowground C stocks (-10.6% and -10.7%, respectively). Comparatively, this region contains the largest belowground C stocks in the US, quantified using model imputation strategies (Wilson and others 2013). Conversely, the largest mean positive difference in belowground C stocks was in the states of Kentucky, Tennessee, and Oklahoma (28.0%, 26.7%, and 22.6%, respectively). Ultimately, this represented a total estimated increase of 368.87 Tg of belowground C across the US, or a 6.4% increase when compared to currently implemented NGHGI models (Table 1).

**Table 1—Largest mean  percent differences of belowground C by state for current US National Greenhouse Gas Inventory (BGCNGHGI) and climate-adjusted estimates (BGCClimAdj).**

| State | $BGC_{NGHGI}$ (SE) | $BGC_{ClimAdj}$ (SE) | Mean % difference |
|---|---|---|---|
| | *Population-level belowground C (Tg)* | | |
| Washington | 410.46 (1.29) | 366.61 (1.26) | -10.70% |
| Oregon | 478.52 (1.03) | 427.63 (0.99) | -10.60% |
| California | 456.22 (1.37) | 428.69 (1.27) | -6.00% |
| Oklahoma | 47.62 (2.54) | 58.36 (2.54) | 22.60% |
| Tennessee | 160.47 (1.27) | 203.39 (1.29) | 26.70% |
| Kentucky | 109.67 (1.83) | 140.42 (1.84) | 28.00% |
| All states | 5798.84 | 6167.71 | 6.40% |

The majority of forest types displayed negative mean differences between current NGHGI and climate-adjusted models, indicating greater live tree belowground C stocks when using the adjusted models. The larger stocks in climate-adjusted models are partially a reflection of the ability of this framework to account for temperature-related shifts in patterns of belowground allocation within a species; a relationship held constant in current NGHGI models.

## CONCLUSIONS

A number of findings emerged from our investigation of incorporating climate variables into the estimation of belowground C stocks. First, climate variables can be used to adjust the US NGHGI estimates of belowground C stocks. Specifically, adjustment factors were specified to amend current coarse root C stocks estimated from allometric equations by incorporating mean annual temperature at various locations across the US. Second, for the US NGHGI, incorporating mean annual temperature increased national belowground C stocks by 6.4%. Future work that integrates both climate and stand conditions (e.g., stand origin and forest type) will increase our ability to predict belowground C stocks across regions containing a mixture of management and climate regimes. Finally, as a means of refining NGHGIs, climate-adjusted models depicting belowground C stocks can be adopted to incorporate the impacts of future global change and management scenarios on C sequestration patterns and stocks. Adjusting current models so that they are sensitive to climate variables will aid modelers seeking to forecast forest C stocks by incorporating projected changes in climate variables such as temperature and precipitation.

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