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Equivalence among three alternative approaches to estimating live tree carbon stocks in the eastern United States

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ABSTRACT

Assessments of forest carbon are available via multiple alternate tools or applications and are in use to address various regulatory and reporting requirements. The various approaches to making such estimates may or may not be entirely comparable. Knowing how the estimates produced by some commonly used approaches vary across forest types and regions allows users of carbon stock estimates to make informed comparisons. Here, we focus on equivalence of alternate estimates of aboveground live tree carbon in eastern U.S. forests derived from the carbon reports output by the Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (FVS). Three approaches to estimating individual-tree carbon are compared by FVS variant and forest type. There are two approaches available in the FVS Fire and Fuels Extension (labeled FFE and Jenkins) and a third based on the U.S. Forest Service's forest inventory (component ratio method, labeled CRM).

We found that the two volume-based approaches, CRM and FFE, are most often identified as equivalent within forest type group or whole-variant relative to the other two pairs of approaches. Equivalence is common in the Northeast and Southern variants, but relatively infrequent in the Central States and Lake States variants. The underlying volume equations of the FFE and CRM approaches influence the carbon equivalence patterns as indicated by differences in volume estimates between FVS and the U.S. Forest Service's forest inventory. Aggregation, or expanding forest estimates to include increasingly larger areas, tends to reduce apparent differences between approaches – that is, they become more equivalent. This result is most evident with the CRM-FFE pair or in softwood forest type groups.

1. Introduction

The Forest Vegetation Simulator (FVS, Dixon, 2002) is a growth-and-yield modeling system developed and maintained by the U.S. Forest Service. This model and its carbon reports in the Fire and Fuels Extension have an established record of use among forest managers within the Forest Service but also other public and private land managers and researchers (Hoover and Rebain, 2011), and are approved for estimation in California's cap and trade system (California Environmental Protection Agency Air Resources Board, 2015). A number of alternate approaches to estimating tree carbon are in use, for example see Radtke et al. (2017). Of particular interest here are the estimations related to FVS simulations; specifically, these are: Rebain (2010), labeled here as FFE, Jenkins et al. (2003), described here as Jenkins, and Heath et al. (2009), referred to here as CRM (the component ratio method). The CRM approach to estimating carbon is not explicitly included in FFE calculations but is included here because it is the method currently used by forest carbon reports that rely on U.S. Forest Service data (e.g., U.S. EPA, 2017). Hoover and Smith (2017) investigated comparability and explicitly addressed statistical equivalence among these three alternate approaches to estimating live tree carbon for the 15 variants (FVS regions) in the western United States. That study, hereafter referred to as the western variants paper, focused on the question: where can FVS users expect results to align either within FVS across variants or with external independent forest carbon assessments? Information regarding the equivalence of estimates developed using different computational approaches is of interest to researchers, managers, and policymakers because multiple equations are in use and may produce estimates which are not strictly comparable. For example, a carbon offset registry may specify a particular method, but a regional protocol may employ another, neither of which may be congruent with other U.S. forest carbon estimation methods (e.g., U.S. EPA, 2017; USDA

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Forest Service, 2017a). Knowing how the estimates produced by some commonly used approaches vary across forest types and regions allows users of carbon stock estimates to better understand the comparability of such estimates. Zhou and Hemstrom (2009) and Domke et al. (2012) provide examples of such analyses.

This study addresses some questions about equivalence related to the contrasts between FVS variants and forest types of the eastern U.S. relative to those of western forests. The western variants paper focused on application of FVS in the western U.S. to predict carbon where forest carbon assessments could potentially include more than one of the multiple relatively small variants, which was one of the rationales for the focus on the West. Within the East, the FVS variants cover large areas and generally follow state boundaries, so it is less likely that FVS based forest carbon assessments will include multiple variants. Results from the western variants paper suggested that differences among the three approaches were less important at aggregate, or large extent, levels of forest carbon assessment. This appeared to be truer for the conifer forests than the hardwood groups. In addition, there was little consistency in equivalence identified among groups at the lower level of aggregation. That is, particular paired approaches were equivalent within certain forest type groups for some variants but not others, and within-variant consistency among softwood or hardwood type groups was not apparent. Again, this outcome was more pronounced in the hardwood type groups, which are a limited presence in the West.

The eastern variants are geographically large, and unlike the West, hardwood forest type groups are the majority. The purpose of this study is threefold. First, to inform users of FVS-based carbon assessments of equivalence or non-equivalence among these alternative approaches. That is, an extension to the East, following the western variants paper (Hoover and Smith, 2017). Second, to address the geographic size of the variant: is there a trend toward greater proportion of forest type groups and pairs of approaches being identified on these variants that encompass much larger forest areas? Third, to determine if patterns regarding western hardwood versus softwood forest types observed in the western variants paper continue in the East where hardwood type groups represent the majority of forests?

2. Methods

The goal here is to identify if, and possibly where, any of the three approaches to estimating live tree carbon can be considered equivalent within the four FVS eastern variants (Fig. 1). Equivalence tests applied to stand level carbon estimates obtained from both Forest Inventory and Analysis (FIA) inventory data and stands defined by FVS are pairwise comparisons; these are: Jenkins vs. CRM, Jenkins vs. FFE, and CRM vs. FFE. Methods are described in detail in Hoover and Smith (2017) and briefly outlined below.

Forest inventory data were obtained from the Forest Inventory and Analysis Data Base (FIADB), which is compiled and maintained by the FIA Program of the U.S. Forest Service (USDA Forest Service, 2017a). The specific data in use here were downloaded from <http://apps.fs.fed.us/fiadb-downloads/datamart.html> on 13 May 2016. The most recent evaluations – or cycle of the permanent inventory plots across each state – within each of the 37 states used for this analysis provided input data to FVS to establish simulations on plots identical to the FIADB plots. For consistency, only those plots representing a single forested condition were used in the FVS simulations (USDA Forest Service, 2017b). In addition, CRM carbon density (tonnes carbon per hectare, t C/ha, 1 tonne = 1 Mg) was calculated according to Appendix M of O'Connell et al. (2017) for aboveground portion of live trees in each of these FIADB plots.

We used FVS to establish stands identical to those obtained from the FIADB and provide the two FVS approaches to quantifying live tree carbon – FFE and Jenkins (see Rebain, 2010). Importing the FIADB data and establishing an FVS simulation is necessary to obtain the carbon estimates for the two alternate approaches; the model was run using default settings, since simulations were statewide. Note that the only part of the FVS simulation that is used here is the output from the initial year, which place all three approaches to carbon estimates as originating from identical data.

Equivalence tests are appropriate where the analysis addresses the question of whether the groups are effectively similar, which is in contrast to asking if they are different (Robinson et al., 2005; MacLean et al., 2014). The null hypothesis of equivalence tests states that the two populations are different (Parkhurst, 2001; Brosi and Biber, 2009), which can be viewed as the reverse of the

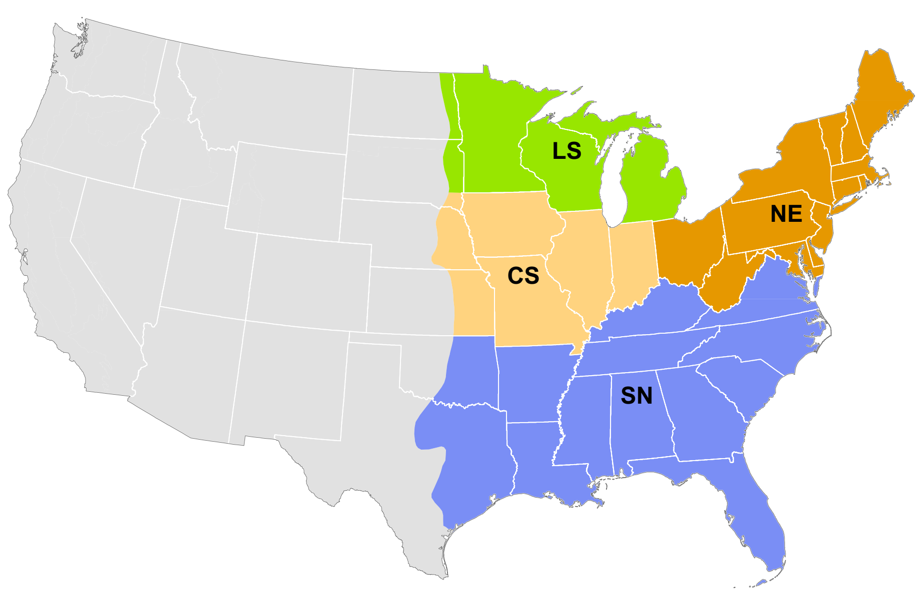

Fig. 1. Illustration showing the geographic extent of each FVS variant in the eastern U.S. Variant labels are: CS = Central States, LS = Lake States, NE = Northeast, and SN = Southern.