Forest Ecology and Management 385 (2017) 236–253

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Equivalence of live tree carbon stocks produced by three estimation approaches for forests of the western United States

Coeli M. Hoover *, James E. Smith

USDA Forest Service, Northern Research Station, 271 Mast Road, Durham, NH 03824, USA

ARTICLE INFO

Article history:
Received 19 October 2016
Accepted 23 November 2016
Available online 9 December 2016

ABSTRACT

The focus on forest carbon estimation accompanying the implementation of increased regulatory and reporting requirements is fostering the development of numerous tools and methods to facilitate carbon estimation. One such well-established mechanism is via the Forest Vegetation Simulator (FVS), a growth and yield modeling system used by public and private land managers and researchers, which provides two alternate approaches to quantifying carbon in live trees on forest land – these are known as the Jenkins and Fire and Fuels Extension (FFE) equations. A necessary consideration in developing forest carbon estimates is to address alternate, potentially different, estimates that are likely available from more than one source. A key to using such information is some understanding of where alternate estimates are expected to produce equivalent results. We address this here by focusing on potential equivalence among three commonly employed approaches to estimating individual-tree carbon, which are all applicable to inventory sampling or inventory simulation applications. Specifically, the two approaches available in FVS – Jenkins and FFE – and the third, the component ratio method (CRM) used in the U.S. Forest Service's, Forest Inventory and Analysis national DataBase (FIADB).

A key finding of this study is that the Jenkins, FFE, and CRM methods are not universally equivalent, and that equivalence varies across regions, forest types, and levels of data aggregation. No consistent alignment of approaches was identified. In general, equivalence was identified in a greater proportion of cases when forests were summarized at more aggregate levels such as all softwood type groups or entire variants. Most frequently, the FIA inventory-based CRM and FFE were determined to be equivalent.

Published by Elsevier B.V.

1. Introduction

With the implementation of offset protocols such as those included in the Regional Greenhouse Gas Initiative (RGGI, https://www.rggi.org/design/overview) and California Assembly Bill 32 (California Global Warming Solutions Act, 2016; California Environmental Protection Agency Air Resources Board, 2015), forest carbon estimation and management have become increasingly important areas of research and discussion. In addition, there is an active market in voluntary forest carbon credits (Forest Trends, 2016). The increased focus on forest carbon estimation is fostering the development of multiple tools and methods to facilitate carbon estimation. The diverse set of approaches for quantifying forest carbon can result in a range of possible values ascribed to a given subset of forest. That is, available tools produce alternate answers, largely because the underlying data and mathematical equation forms often vary among the approaches. Despite the potential for differences, the approaches addressed here all attempt to estimate the same quantity – whole tree biomass from inventory-like individual tree measurements. In this study, we assess the different estimation approaches to see if they produce carbon stock estimates that are statistically equivalent. Because alternate published routes to forest carbon are in use for carbon reporting (Heath et al., 2009; Jenkins et al., 2003; Rebain, 2010), a key to successfully using such information is some understanding of where alternate estimates are expected to produce equivalent results, or where they are not likely to be equivalent. We address this by focusing on potential equivalence among three commonly employed individual-tree carbon estimates applicable to inventory sampling or inventory simulation applications.

Methods for estimating aboveground live tree biomass, one of the two largest forest carbon stocks (soil being the other), fall into two main approaches when considering individual tree estimates: volume-based versus whole-tree based allometric relationships. In the first, the primary focus of the model estimate is on forest wood production. Bole volume is then converted to biomass or carbon, and the estimate is extended to account for the balance of the tree. This approach relies on local or regional equations for tree volume

* Corresponding author.
E-mail addresses: choover@fs.fed.us (C.M. Hoover), Jsmith11@fs.fed.us (J.E. Smith).

http://dx.doi.org/10.1016/j.foreco.2016.11.041
0378-1127/Published by Elsevier B.V.

(in the Forest Vegetation Simulator, known as FVS, these are generally regional equations from the National Volume Library, Dixon, 2002). With the second approach, the allometric relationships are intended to directly relate individual tree measurements, such as diameter and height, to estimates of biomass or carbon, usually through destructive sampling of a limited number of trees. These individual tree biomass equations generally are developed for local or regional applications. Choice of approach (volume-to-carbon or allometric biomass equation) depends on many factors including the type of data and equations available as well as the scale of the project and the needs of the manager or investigator. Because local and regional volume equations may be constructed quite differently from place to place, a set of ten generalized biomass equations was developed (Jenkins et al., 2003) to produce consistent national-scale estimates for U.S. reporting purposes. Due to concerns about the broad species groups used for the equations, the component ratio method (CRM) was developed in 2009 (Heath et al., 2009) and combines the Forest Inventory and Analysis (FIA) regional volume equations with component ratios from the Jenkins et al. (2003) method for calculating components of tree biomass. The CRM method (a volume-based approach) is now used to compute forest carbon estimates arising from FIA's forest inventory (USEPA, 2016).

The Forest Vegetation Simulator, or FVS (Dixon, 2002) is a growth and yield modeling system that is used by U.S. Forest Service managers for forest planning purposes, as well as other public and private land managers and researchers. FVS consists of 19 main geographic variants and can simulate a wide range of management scenarios. Simulations developed within FVS produce a series of intermediate results in the form of explicitly defined stand and tree structures, which are amenable to the inclusion of individual tree biomass equations. In 2006, carbon estimation capability was added to the Fire and Fuels Extension (FFE) of FVS (Rebain, 2010) to enable managers to assess the carbon implications of various management scenarios. The FFE includes two methods (one volume-based, one allometric) for estimating carbon in live tree biomass: the FFE default methods (FFE) based on equations from the National Volume Library, and the Jenkins et al. (2003) method described above. For more detail on carbon estimation using FFE, consult Hoover and Rebain (2011).

Each of these three approaches to estimating carbon in live tree biomass has strengths and weaknesses. For an excellent overview of the CRM and Jenkins estimates, see Zhou and Hemstrom (2009). Each method, using the same dataset, will produce a somewhat different carbon stock estimate. Chojnacky (2012) and Domke et al. (2012) reported that the CRM method generally produced lower biomass estimates than those calculated using the Jenkins et al. (2003) equations. This calls for caution when comparing studies or estimates which have been developed using different approaches since the results may not be genuinely comparable. With the advent of voluntary and compliance carbon markets, understanding these differences becomes a matter of some importance. The California Compliance Offset Protocol, for example, specifies one method for use in California, Oregon, and Washington, and another for the rest of the conterminous U.S. (California Environmental Protection Agency Air Resources Board, 2015). In addition, the Protocol allows for use of a set of approved growth and yield models (of which FVS is one) for certain purposes, and these employ still different computation methods. The FFE carbon reports have been used by a variety of investigators to examine the carbon implications of fuels reduction treatments, beetle outbreaks, and various harvesting scenarios (Hurteau and North, 2009; Caldwell et al., 2013; Kelsey et al., 2014).

MacLean et al. (2014) compared aboveground live carbon stock estimates and growth projections on a subset of states in the Northeast variant of FVS. Equivalence testing was used to compare estimates at a county level based on the biomass estimation approaches of CRM, FFE, and Jenkins. In this study, we build on that approach and compare aboveground live biomass carbon stock estimates produced from the three methods (CRM, FFE, and Jenkins) for each of the 15 major variants that cover the western U.S. We focus on the West because more variants are available, the Western variants compute total tree volume slightly differently than Eastern variants (Rebain, 2010), and west-versus-east is a common divide for forest inventories and populations.

We have three major objectives in this study where our focus is on the equivalence of alternate approaches when applied to a common set of inventory data:

(1) To test if estimates of live aboveground carbon stocks produced from the CRM, FFE, and Jenkins methods are statistically equivalent.
(2) Determine if the relative differences between the estimates are consistent across each of the geographic variants, or are variant-specific.
(3) Within variants, identify equivalence or patterns in equivalence by forest type groups (as defined by the Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service, USDA Forest Service, 2016a).

2. Methods

2.1. Forest inventory data

Forest inventory data are used to provide a common input for calculations using each of the three approaches to estimating forest carbon, and these data are from the network of FIA permanent inventory plots (USDA Forest Service, 2016a). Inputs for calculating aboveground carbon vary among the Jenkins, CRM, and FFE approaches, and in some cases inputs vary from region to region (Jenkins et al., 2003; USDA Forest Service, 2016a; Hoover and Rebain, 2011). However, all necessary information for the three approaches are included in the FIA plot level data, which provides the basis for consistent comparisons.

Inventory data were obtained from the Forest Inventory and Analysis Data Base (FIADB), which is compiled and maintained by FIA (USDA Forest Service, 2016b). The data are based on continuous systematic annualized sampling of permanent plots over all land within individual states so that a portion of the survey data is collected each year on a continuous cycle, with remeasurement at 5 or 10 years depending on the state. The portion of the data used here represents U.S. forest lands of the western conterminous United States, and the approximately 12 percent of Alaska forest land of southern coastal Alaska that currently has the established permanent annual survey (Fig. 1). The specific data in use here were downloaded from http://apps.fs.fed.us/fiadb-downloads/datamart.html on 13 May 2016.

The forest inventory data were used to directly calculate stand level tree carbon and to initiate identical stands within FVS. Plot level estimates of carbon were calculated for CRM (USDA Forest Service, 2016a) directly from the FIADB. The Jenkins and FFE estimates include foliage, while the CRM estimates provided in the FIADB do not. For consistent comparison, an estimate for foliage following Jenkins et al. (2003) is added to the CRM estimate; this is consistent with the other Jenkins-based component ratios used within CRM (USDA Forest Service, 2016a). The same set of FIADB data – from the plot, condition, and tree tables (USDA Forest Service, 2016b) were input to FVS in order to establish simulations on plots identical to the FIADB's (see additional discussion of FVS in Section 2.2). Stand level estimates were resolved to carbon in the aboveground portion of all live trees greater or equal to 2.5 cm d.