Remote Sensing of Environment 179 (2016) 162–169

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Improving the precision of dynamic forest parameter estimates using Landsat

Evan B. Brooks [a,*], John W. Coulston [b], Randolph H. Wynne [a], Valerie A. Thomas [a]

[a] Department of Forest Resources and Environmental Conservation, Virginia Tech, Blacksburg, VA, USA
[b] USDA Forest Service Southern Research Station, Forest Inventory and Analysis Unit, Knoxville, TN, USA

ARTICLE INFO

Article history:
Received 22 August 2014
Received in revised form 29 February 2016
Accepted 10 March 2016
Available online 8 April 2016

Keywords:
Harmonic regression
Hierarchical cluster analysis
FIA
Site index
Post-stratification

ABSTRACT

The use of satellite-derived classification maps to improve post-stratified forest parameter estimates is well established. When reducing the variance of post-stratification estimates for forest change parameters such as forest growth, it is logical to use a change-related strata map. At the stand level, a time series of Landsat images is ideally suited for producing such a map. In this study, we generate strata maps based on trajectories of Landsat Thematic Mapper-based normalized difference vegetation index values, with a focus on post-disturbance recovery and recent measurements. These trajectories, from 1985 to 2010, are converted to harmonic regression coefficient estimates and classified according to a hierarchical clustering algorithm from a training sample. The resulting strata maps are then used in conjunction with measured plots to estimate forest status and change parameters in an Alabama, USA study area. These estimates and the variance of the estimates are then used to calculate the estimated relative efficiencies of the post-stratified estimates. Estimated relative efficiencies around or above 1.2 were observed for total growth, total mortality, and total removals, with different strata maps being more effective for each. Possible avenues for improvement of the approach include the following: (1) enlarging the study area and (2) using the Landsat images closest to the time of measurement for each plot. Multitemporal satellite-derived strata maps show promise for improving the precision of change parameter estimates.

1. Introduction

The use of satellite and other remote sensing data to supplement in situ measurements of forest variables is a well-established practice (Fransson, 2000; Hansen et al., 2009; Katila & Tomppo, 2002; McRoberts & Hansen, 1999; Nilsson, Holm, Reese, Wallerman, & Engberg, 2005; Wynne, Oderwald, Reams, & Scrivani, 2000). There are many advantages to the use of satellite data, among them being increased coverage, reduced cost, and more frequent (and regular) measurement. These advantages make such data useful in assisting the scale-up of field observations to estimate population biophysical parameters of forests.

These parameters may be categorized into two groups. Status parameters define the condition of the forest at a point in time. Examples include total carbon stock, average canopy cover, and total species diversity. In contrast, change parameters define the manner in which the forest changes over time. Examples of these include total forest growth, total removals, total mortality, and total carbon flux.

The Forest Inventory and Analysis (FIA) program of the USDA Forest Service uses satellite data to augment its field measurements (McRoberts, 2010; McRoberts, Holden, Nelson, Liknes, & Gormanson, 2006; McRoberts, Wendt, Nelson and Hansen, 2002). By assigning the field plots to image-derived strata, the FIA program is able to obtain more precise estimates of forest parameters than would have otherwise been possible or financially feasible.

1.1. Post-stratification

Stratified sampling and post-stratification (PS) are standard methods for increasing the precision of estimates given a fixed sample size (Cochran, 1977). In stratified sampling, a population is divided into mutually exclusive strata, and within each stratum a random sample is taken. It is assumed that the strata represent distinct subsets of the population which are sufficiently different as to warrant the separate treatment. An example would be estimating a parameter based on the land cover type, in which case one would stratify along classes of land cover based on remote sensing data. The sample size of strata may be based on either proportionate allocation or disproportionate (optimum) allocation, the latter case being desirable when additional sampling is needed in strata exhibiting greater variability. In either case, one would expect increased precision from using stratified designs instead of a simple random sample (SRS) design (Cochran, 1977).

In the case of PS, the sample is not defined based on the strata. Instead, the sample is assigned to strata which have been generated

* Corresponding author.
E-mail address: evbrooks@vt.edu (E.B. Brooks).

http://dx.doi.org/10.1016/j.rse.2016.03.017
0034-4257/

via some other approach (often from ancillary data, as is the case in this study). When the strata effectively partition the sample according to the measured variables of interest, this approach can be nearly as precise as proportional stratified sampling (Cochran, 1977).

1.2. Post-stratification and the FIA program

PS estimation is used by the FIA program (Bickford, 1952; Chojnacky, 1998; LaBau, 2007; McRoberts, Gobakken, & Naesset, 2012; Scott et al., 2005; Westfall, Patterson, & Coulston, 2011). When considering continuous forest inventories with permanent plot locations, PS estimation is often used because strata boundaries change over time. The FIA has used PS, starting with aerial imagery, since 1952 (Bickford, 1952). Because of the cost, time and effort required to obtain and interpret aerial images and the relative temporal sparseness of such images, the FIA program transitioned to primarily using digital and satellite imagery around the turn of the millennium (Hansen & Wendt, 2000; McRoberts, Wendt, et al., 2002). In the decade that followed, researchers enjoyed success in cheaply improving the precision of many status forest parameter estimates using Landsat and its products (Hansen & Wendt, 2000; Hoppus & Lister, 2003; McRoberts, 2010; McRoberts, Nelson and Wendt, 2002; Musy, Wynne, Blinn, Scrivani, & McRoberts, 2006; Wayman, Wynne, Scrivani, & Reams, 2001; Wynne et al., 2000), such as the National Land Cover Database (Fry et al., 2011). The FIA program currently uses Landsat-based stratification methods to increase the precision of estimates for status parameters such as forest area and forest volume. One such method stratifies plots according to the number of forested pixels in a 5×5 neighborhood, resulting in a variety of strata based on the density of forested pixels around the target pixel (Hoppus & Lister, 2003). McRoberts, Wendt, et al. (2002) developed another approach that defines four strata of forest, forested edge, nonforested edge, and nonforest.

While there has been substantial work done with PS for status parameter estimates, published work has suggested that methods which are effective for status parameter estimation are less so for change parameter estimation (McRoberts et al., 2006). There is relatively little in the literature with regards to stratified estimation of change parameters. To develop strata maps related to forest growth from satellite data, multiple images through time are needed. Strata may be based on the time and severity of change or on the pattern of regeneration after a disturbance. Methods such as the vegetation change tracker (Huang et al., 2010), LandTrendr (Kennedy, Yang, & Cohen, 2010), exponentially weighted moving average change detection (Brooks, Wynne, Thomas, Blinn, & Coulston, 2014), and the continuous monitoring of forest disturbance algorithm (Zhu, Woodcock, & Olofsson, 2012) can produce stratification criteria for time and severity of disturbance, but they may not be able to provide sufficient regrowth information by themselves. Accordingly, the primary objective of this study was to test the effectiveness of using a Landsat-derived time series in PS estimation of forest area, total carbon stock, area of planting, area of cutting, total growth, total mortality, and total removals.

2. Data

The study area for this work was in west-central Alabama, USA (Fig. 1). The area is largely forested, and the dominant forest type is loblolly pine (*Pinus taeda*).

2.1. FIA plot data

We used FIA phase 2 plot data corresponding to the study area described above. The resulting 977 plots covered all land uses and ownerships.

The FIA sample locations are approximately systematic and are assumed to produce an equal probability sample (McRoberts et al., 2006). GPS positional accuracy of plot locations is approximately 8 to 20 m (McRoberts, 2010). The sample for this study is divided into seven rotating panels, giving a seven-year remeasurement period for a set of plots with remeasurements for this study covering the years 2004–2010.

The FIA phase 2 plot design is detailed in Bechtold and Scott (2005). The plot consists of four circular subplots of radius 7.3 m (24 ft) each, arranged with one subplot in the center and the remaining three equidistant from the central subplot at a distance of 36.6 m (120 ft) with azimuths of 0, 120, and 240°. The total extent of the four subplots is about 675 m^2 (1/6 acre). For each plot land use is determined, and for

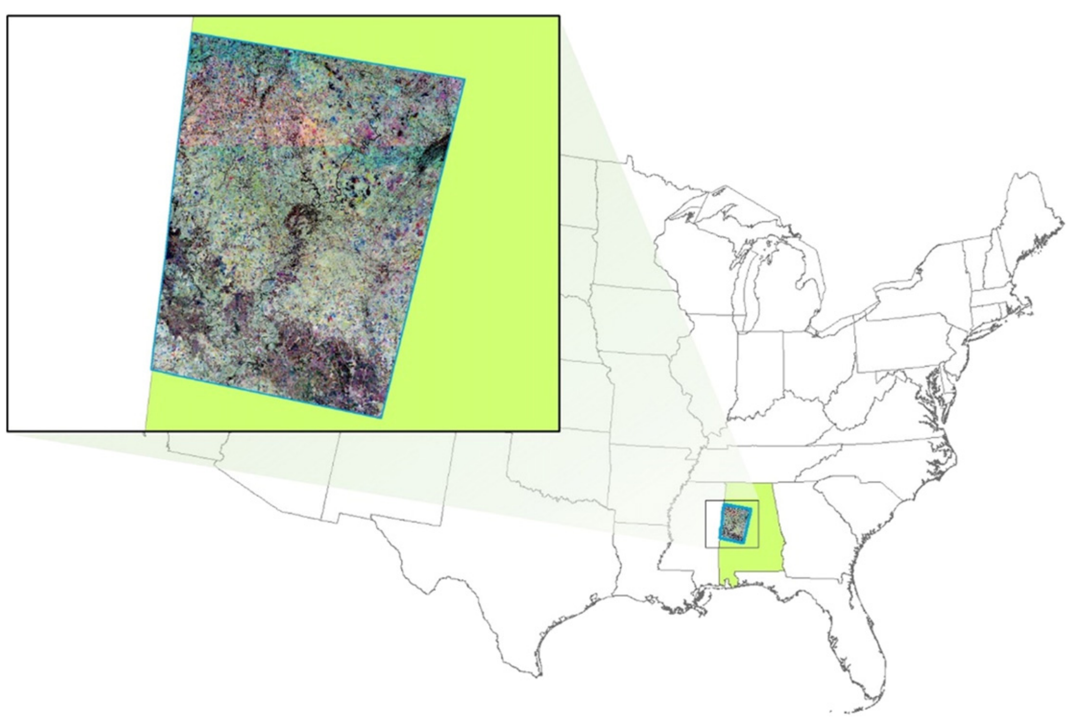

Fig. 1. Study area. Inset RGB are the mean normalized difference vegetation index (NDVI) values for 3-year groups centered on 1985, 1988, and 1991, respectively.