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Improving estimates of forest disturbance by combining observations from Landsat time series with U.S. Forest Service Forest Inventory and Analysis data

Todd A. Schroeder [a,*], Sean P. Healey [a], Gretchen G. Moisen [a], Tracey S. Frescino [a], Warren B. Cohen [b], Chengquan Huang [c], Robert E. Kennedy [d], Zhiqiang Yang [e]

[a] U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station, Ogden, UT 84401, USA
[b] U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Corvallis, OR 97331, USA
[c] Department of Geography, University of Maryland, College Park, MD 20742, USA
[d] Department of Earth & Environment, Boston University, Boston, MA 02215, USA
[e] Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR 97331, USA

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ABSTRACT

With earth's surface temperature and human population both on the rise a new emphasis has been placed on monitoring changes to forested ecosystems the world over. In the United States the U.S. Forest Service Forest Inventory and Analysis (FIA) program monitors the forested land base with field data collected over a permanent network of sample plots. Although these plots are visited repeatedly through time there are large temporal gaps (e.g. 5–10 years) between remeasurements such that many forest canopy disturbances go undetected. In this paper we demonstrate how Landsat time series (LTS) can help improve FIA's capacity to estimate disturbance by 1.) incorporating a new, downward looking response variable which is more sensitive to picking up change and 2.) providing historical disturbance maps which can reduce the variance of design-based estimates via post-stratification. To develop the LTS response variable a trained analyst was used to manually interpret 449 forested FIA plots located in the Uinta Mountains of northern Utah, USA. This involved recording cause and timing of disturbances based on evidence gathered from a 26-year annual stack of Landsat images and an 18-year, periodically spaced set of high resolution (~1 m) aerial photographs (e.g. National Aerial Image Program, NAIP and Google Earth). In general, the Landsat data captured major disturbances (e.g. harvests, fires) while the air photos allowed more detailed estimates of the number of trees impacted by recent insect outbreaks. Comparing the LTS and FIA field observations, we found that overall agreement was 73%, although when only disturbed plots were considered agreement dropped to 40%. Using the non-parametric Mann–Whitney test, we compared distributions of live and disturbed tree size (height and DBH) and found that when LTS and FIA both found non-stand clearing disturbance the median disturbed tree size was significantly larger than undisturbed trees, whereas no significant difference was found on plots where only FIA detected disturbance. This suggests that LTS interpretation and FIA field crews both detect upper canopy disturbances while FIA crews alone add disturbances occurring at or below canopy level. The analysis also showed that plots with only LTS disturbance had a significantly greater median number of years since last FIA measurement (6 years) than plots with both FIA and LTS disturbances (2.5 years), indicating that LTS improved detection on plots which had not been field sampled for several years. Next, to gauge the impact of incorporating LTS disturbances into the FIA estimation process we calculated design-based estimates of disturbance (for the period 1995–2011) using three response populations 1.) LTS observations, 2.) FIA field observations, and 3.) Combination of FIA and LTS observations. The results showed that combining the FIA and LTS observations led to the largest and most precise (i.e. smallest percent standard error) estimates of disturbance. In fact, the estimate based on the combined observations (486,458 ha, +/−47,101) was approximately 65% more than the estimate derived solely with FIA data (294,295 ha, +/−44,242). Lastly, a Landsat forest disturbance map was developed and tested for its ability to post-stratify the design-based estimates. Based on relative efficiency (RE), we found that stratification mostly improved the estimates derived with the LTS response data. Aside from insects (RE = 1.26), the estimates of area affected by individual agents saw minimal gain, whereas the LTS and combined FIA + LTS estimates of total

* Corresponding author. Tel.: +1 801 625 5690.
E-mail address: tschroeder@fs.fed.us (T.A. Schroeder).

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disturbance saw modest improvement, with REs of 1.43 and 1.50 respectively. Overall, our results successfully demonstrate two ways LTS can improve the completeness and precision of disturbance estimates derived from FIA inventory data.

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1. Introduction

In addition to being one of the primary drivers of the net terrestrial carbon budget (Harmon, 2001; Kasischke et al., 2013), forest disturbance also plays a critical role in affecting biodiversity (Dornelas, 2010), wildlife habitat (Gibson et al., 2013) and the surface energy balance (O'Halloran et al., 2011). With rising global temperatures (Easterling et al., 2000; IPCC, 2014) and an ever growing human population (Raftery, Li, Ševčiková, Gerland, & Heilig, 2012) poised to alter the frequency and severity of disturbance regimes across the globe (Bradford, Jensen, Domke, & D'Amato, 2013; Dale et al., 2001; Westerling, Hidalgo, Cayan, & Swetnam, 2006), improved monitoring of forest disturbance, especially at the landscape scale has become increasingly important. Because forest disturbance manifests at a variety of spatial and temporal scales (Asner, 2013) and has varying impacts which affect the canopy, understory and forest floor, effective monitoring will likely require a hybrid approach, where detailed field measurements collected in a probabilistic sample are combined with frequent, repeated observations made by remote sensing satellites.

In the United States, the Forest Service Forest Inventory and Analysis (FIA) program (http://www.fia.fs.fed.us/) collects detailed field measurements which are used to produce timely and accurate estimates of a wide range of forest attributes. These attributes, which include forest area and volume, are used to provide information on the current status and health of forests over varying geographical extents. Typically, a probabilistic sample of inventory plots is used to estimate amount of forest area while maps derived from remote sensing have been used both as strata applied to reduce variance (i.e. for "post-stratification", see McRoberts, Wendt, & Liknes, 2005) and to delineate forest location and extent (McRoberts & Tomppo, 2007). Reporting population estimates at the state and county level has long been a primary function of FIA. However, with increasing stress on forested ecosystems (van Mantgem et al., 2009; Weed, Ayres, & Hicke, 2013), a new emphasis has been placed on improving FIA's capacity to report on how much forest is changing, where it is changing and what is changing it. This includes developing a flexible monitoring system which can estimate annual trends, report on different geographic areas (e.g. administrative units, watersheds, or ecoregions), as well as incorporate different spatial layers for use in post-stratified variance reduction.

Presently, monitoring the status and trends of forest disturbance can be challenging for inventory programs as they often have long temporal gaps (e.g. several years to decades) between plot measurements. For example, in the western U.S., a 10 year cycle of measurements is required for the network of FIA plots to fully sample the entire forested landscape. Since forest disturbance and recovery dynamics vary irregularly (annual rates < 3% per year; Masek et al., 2013) over space and time, both the frequency (time) and spatial coverage (space) of observation determine how well a sample captures a rare event like disturbance (Patterson & Finco, 2011). Therefore, it would greatly benefit FIA if all of its plots could be monitored and updated annually, thus providing estimates of disturbance which better reflect the current condition of the forest landscape. This would be especially beneficial in the western states, where annual updating would give FIA better capacity to track and respond to episodic insect outbreaks and fires. Based on this need, there is potential for FIA to improve its change monitoring capabilities by incorporating more frequent observations from optical remote sensing satellites such as Landsat.

With a 40+ year historical archive and a 16 day repeat cycle, Landsat imagery offers an excellent data source for monitoring forest disturbance over large areas (Hansen & Loveland, 2012). The 30 m spatial grain and 6 reflective bands are capable of capturing many types of forest disturbance, especially those that impact the upper canopy (Cohen & Goward, 2004). Now that the entire Landsat archive is freely available it has become economically feasible to monitor disturbance over large areas using satellite time series. The increased accessibility of Landsat data has led to the emergence of several new automated algorithms which are capable of mapping historical disturbance using the spectral response from multiple image dates (Huang et al., 2010; Jin et al., 2013; Kennedy, Yang, & Cohen, 2010; Zhu, Woodcock, & Olofsson, 2012). Thanks in part to greater access to supercomputers such as the NASA Earth Exchange (NEX, https://nex.nasa.gov/nex/), these algorithms are now being run over increasingly larger areas (Hansen et al., 2013). For example, the North American Forest Dynamics (NAFD) project (Goward et al., 2008; Masek et al., 2013) is currently using the Vegetation Change Tracker (VCT, Huang et al., 2010) algorithm to produce a wall-to-wall forest disturbance map for the conterminous U.S. With the availability of Landsat-based disturbance maps on the rise, it is important to determine their utility for improving the precision of FIA estimates through post-stratification.

In addition to stratification, Landsat data have also recently emerged as an effective backdrop for collecting plot-level reference information on disturbance and land cover change. Visualization tools such as TimeSync (Cohen, Yang, & Kennedy, 2010) demonstrate how a trained analyst can use the spectral and temporal information from Landsat along with other spatial data to record timing and cause of most natural and anthropogenic disturbance events. Such ancillary data include high spatial resolution photos from NAIP and Google Earth; fire polygons from Monitoring Trends in Burn Severity (MTBS, www.mtbs.gov; Eidenshink et al., 2007); and disturbance grids compiled by the Landfire program (www.landfire.gov; Vogelmann et al., 2011). Because of Landsat's long historical record, the analyst interpretation approach has surfaced as one of the best (and only) methods for collecting reference data over the full range (20–40 years) and interval (annual) of most time series maps. In addition to validation, analyst-based LTS observations can also be used for design-based estimation if collected over a statistically-based set of sample locations such as FIA plots. In fact, it is possible that combining the improved frequency and spatial coverage of LTS observations with the detailed, but less frequently acquired FIA field data might provide the most complete picture of where and how disturbance is impacting the greater landscape. In general, combining LTS and field-based observations in a design-based framework is an emerging technique for estimating (or predicting) landscape scale disturbance dynamics (e.g. see Plugmacher, Cohen, Kennedy, & Yang, in press) and for validating maps of disturbance (Olofsson, Foody, Stehman, & Woodcock, 2013). Although our focus here is on FIA data, it is important to recognize that LTS observations, both in the form of maps and analyst-interpretations can be similarly applied to other sets of probabilistically collected field measurements.

Traditionally, Landsat data and its derivatives (e.g. National Land Cover Dataset, NLCD) have been used by FIA for post-stratification, a statistical technique for using spatial data to reduce the variance of design-based parameter estimates (McRoberts, Tomppo, & N sset, 2010). The literature suggests that static parameters such as forest area and volume have typically gained the greatest benefit from stratification (McRoberts et al., 2006; Nelson, McRoberts, Liknes, & Holden, 2002), while dynamic parameters reflecting forest change (e.g. growth, mortality and removals) have had much more limited success (Brooks, Coulston, Wynne, & Thomas, 2013; Gormanson, Hansen, & McRoberts, 2003). It is possible that stratification (which is based on agreement between map and sample plots) could improve if the FIA response variable