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Forest disturbance across the conterminous United States from 1985–2012: The emerging dominance of forest decline

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ABSTRACT

Evidence of shifting dominance among major forest disturbance agent classes regionally to globally has been emerging in the literature. For example, climate-related stress and secondary stressors on forests (e.g., insect and disease, fire) have dramatically increased since the turn of the century globally, while harvest rates in the western US and elsewhere have declined. For shifts to be quantified, accurate historical forest disturbance estimates are required as a baseline for examining current trends. We report annual disturbance rates (with uncertainties) in the aggregate and by major change causal agent class for the conterminous US and five geographic subregions between 1985 and 2012. Results are based on human interpretations of Landsat time series from a probability sample of 7200 plots (30 m) distributed throughout the study area. Forest disturbance information was recorded with a Landsat time series visualization and data collection tool that incorporates ancillary high-resolution data. National rates of disturbance varied between 1.5% and 4.5% of forest area per year, with trends being strongly affected by shifting dominance among specific disturbance agent influences at the regional scale. Throughout the time series, national harvest disturbance rates varied between one and two percent, and were largely a function of harvest in the more heavily forested regions of the US (Mountain West, Northeast, and Southeast). During the first part of the time series, national disturbance rates largely reflected trends in harvest disturbance. Beginning in the mid-90s, forest decline-related disturbances associated with diminishing forest health (e.g., physiological stress leading to tree canopy cover loss, increases in tree mortality above background levels), especially in the Mountain West and Lowland West regions of the US, increased dramatically. Consequently, national disturbance rates greatly increased by 2000, and remained high for much of the decade. Decline-related disturbance rates reached as high as 8% per year in the western regions during the early-2000s. Although low compared to harvest and decline, fire disturbance rates also increased in the early- to mid-2000s. We segmented annual decline-related disturbance rates to distinguish between newly impacted areas and areas undergoing gradual but consistent decline over multiple years. We also translated Landsat reflectance change into tree canopy cover change information for greater relevance to ecosystem modelers and forest managers, who can derive better understanding of forest-climate interactions and better adapt management strategies to changing climate regimes. Similar studies could be carried out for other countries where there are sufficient Landsat data and historic temporal snapshots of high-resolution imagery.

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1. Introduction

Disturbance is a major driver of forest ecosystem dynamics, with the legacy of disturbance history being largely responsible for the state of a forest stand at any point in time (Uuttera et al., 1996; Pflugmacher et al., 2012). Disturbances can alter the mix of species and stand structure in ways that depend on disturbance agent (e.g., fire, harvest, insects) and severity or magnitude, with variable and profound implications on fluxes of water, energy, and nutrients, biodiversity, and a host of other functions that strongly influence life on earth (Edwards et al., 2014). There is evidence that in the past several decades patterns of forest disturbance among disturbance causal agent classes have begun to shift both regionally and globally. For example, in the western US, timber harvesting on public lands has decreased (Oswalt et al., 2014) while forest fire frequencies have increased (Westerling et al., 2006). Across Europe, wildfire, wind, and bark beetle disturbances have steadily increased since the early 1970s (Seidl et al., 2014). Globally, incidents of both chronic and acute forest decline, purportedly related to climate change, have become increasingly common (Allen et al., 2010). Because of the importance of disturbance on forest function and implications for shifting dominance among classes of disturbance agent, ecological modeling and natural resource decision-making can benefit from improved national- to continental-scale monitoring and assessments (Running, 2008).

Currently, much of what we know about forest disturbance comes from disparate monitoring efforts that produce estimates that are challenging to compare and synthesize across disturbance agent classes, regions, and time periods. Further, estimates of disturbance rates produced by these efforts are often biased. For example, in the case of remote sensing based approaches if image spatial resolution is too coarse to capture small-scale disturbance these omission errors of disturbance will lead to bias in the area estimates. In general, map classification error, which is always present to some extent, also leads to biased area estimates (Olofsson et al., 2013). In the US several monitoring programs focus on forest disturbance but as a collection these are lacking in sufficient detail and temporal record length. US forest inventory data are able to resolve all major disturbance agent classes (Schroeder et al., 2014), but these data have only been collected in a nationally consistent manner for a little over a decade and have long remeasurement periods (i.e., 5 years in the east and 10 years in the west). The ForWarn system (Norman et al., 2013) is designed to detect and map an array of disturbance agent classes at a sub-monthly time step. ForWarn relies on MODIS data which has a spatial resolution (250 m) that is incapable of resolving many stand-scale events. Further, ForWarn extends temporally back only to 2000. Although the LANDFIRE program derives disturbance maps across disturbance agent classes at a 30 m nominal resolution, LANDFIRE also extends back only to 1999 (Vogelmann et al., 2011). Several other major monitoring programs report only a limited set of disturbance agent classes and often have significant measurement bias. For example, aerial insect and disease detection surveys (ADS) use visually defined polygons that only approximate area affected and are not collected everywhere every year (Meddens et al., 2012). The US fire mapping program, Monitoring Trends in Burn Severity (MTBS; Eidenshink et al., 2007), is based on Landsat data but maps only larger fire size events (~200 ha in the east, ~400 ha in the west).

The Landsat satellite remote sensing program holds great promise to satisfy monitoring needs because it provides one of the few datasets capable of quantifying diverse patterns and dynamics of forests at sub-stand scales and at sub-annual temporal resolution over the last several decades (Banskota et al., 2014). The spatial resolution of most Landsat data is 30 m, and with two satellites active over much of the life of the Landsat program (1972-present), data have been collected globally at either an 8- or 16-day interval, providing at least one clear view of the earth's surface during the growing season every year in most places (Roy et al., 2014). Data are free of charge and available from the archive in calibrated, georeferenced, and analysis-ready format (Woodcock et al., 2008). There are well-established protocols using Landsat data to map forest disturbance across all forest types globally (Cohen and Goward, 2004; Hansen et al., 2013) using data from the full temporal depth of the archive (Cohen et al., 2002). Moreover, there has been recent rapid development of sophisticated algorithms designed to use all available imagery in time series change detection analyses, offering great opportunities for the future of Landsat-based science (Huang et al., 2010; Kennedy et al., 2010; Brooks et al., 2014; Zhu and Woodcock, 2014). Additionally, we are now making good progress toward full integration of early Landsat data (MSS starting in 1972) in time series analyses (Braaten et al., 2015). This is important because the MSS data, despite presenting distinct challenges in time series analysis, would extend the record of forest dynamics backwards an additional 12 years.

Unfortunately, the full promise of automated Landsat disturbance mapping has yet to be realized. For example, Hansen et al. (2013) and Masek et al. (2013) provided national, annual data but quantified mostly moderate to high-severity, short-duration disturbances only and did not distinguish among disturbance agent classes. Meddens and Hicke (2014) and Meigs et al. (2015) targeted more gradual phenomena associated with insect disturbances, but these studies were limited in geographic scope. Zhu and Woodcock (2014) and Kennedy et al. (2015) evaluated a more comprehensive set of disturbance agent classes, but results were likewise spatially limited.

Recently, McDowell et al. (2015) described a comprehensive monitoring framework required for systematic quantification and analysis of disturbance that transcends limitations of current monitoring systems. The first two of the four primary framework components, detection and disturbance agent classification, emphasize a strong role for remote sensing. In this context, detection ranges from partial canopy loss to tree mortality and should be based on sub-patch scale observations at an annual or less time-step. Disturbance classification includes such agents as harvest, fire, insects, etc. Implied is that consistent (or at least harmonious) methods that allow comparison and integration of estimates should be used to detect disturbances across agent classes through time and over space. To improve the use of remote sensing for forest disturbance monitoring, we further suggest that the estimates of area and rates of disturbance be unbiased, include uncertainties, and have a long enough retrospective monitoring period to allow current trends to be contrasted against the recent past. Only then can we detect and quantify meaningful shifts in dominance among major causal agent classes.

The objective of our study is to characterize forest disturbance by major causal disturbance agent class for the conterminous US during the time period 1985–2012. We implement a disturbance monitoring strategy that is temporally and spatially consistent to allow comparisons of disturbance rates and agent classes across regions and time periods. In addition, we assess how the dominance among various disturbance agent classes has shifted, both nationally and regionally, between 1985 and 2012 across the full range of disturbance severities (or magnitudes). Rates of disturbance along with causal agent classes are quantified by visual interpretation of Landsat time series, and regional and national disturbance rates (by time period) are estimated from a probability sample of 7200 pixel-level observations distributed across the