Regional dynamics of forest canopy change and underlying causal processes in the contiguous U.S.

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[1] The history of forest change processes is written into forest age and distribution and affects earth systems at many scales. No one data set has been able to capture the full forest disturbance and land use record through time, so in this study, we combined multiple lines of evidence to examine trends, for six US regions, in forest area affected by harvest, fire, wind, insects, and forest conversion to urban/surburban use. We built an integrated geodatabase for the contiguous U.S. (CONUS) with data spanning the nation and decades, from remote sensing observations of forest canopy dynamics, geospatial data sets on disturbance and conversion, and statistical inventories, to evaluate relationships between canopy change observations and casual processes at multiple scales. Results show the variability of major change processes through regions across decades. Harvest affected more forest area than any other major change processes in the North East, North Central, Southeast, and South central regions. In the Pacific Coast and Intermountain West, more forest area was affected by harvest than forest fires. Canopy change rates at regional scales confounded the trends of individual forest change processes, showing the importance of landscape scale data. Local spikes in observed canopy change rates were attributed to wind and fire events, as well as volatile harvest regimes. This study improves the geographic model of forest change processes by updating regional trends for major disturbance and conversion processes and combining data on the dynamics of fire, wind, insects, harvest, and conversion into one integrated geodatabase for the CONUS.

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1. Introduction

[2] According to the US Forest Service (USFS), only a small fraction of forest stock undergoes abrupt structural changes each year due to natural disturbances (fire, insects, and storms), human-managed disturbances (harvest), and land-use conversion (forest land converted for suburban/urban development). The legacy of these processes is cumulative and persists for decades to centuries [*Turner*, 2010]. If 1% of forest canopy cover was lost per year over the last 25 years, 25% of the contiguous U.S. (CONUS) forest area (62.4 million ha of forest), an area equal to the size of West Virginia, would have been lost. However, not all canopy loss is permanent and assuming a 100% mortality rate in disturbed forests is unrealistic for natural disturbance events and a portion of human-managed disturbance events. Interpreting observations of the dynamics and end state of forest canopy changes requires an understanding of the underlying processes [*Reams et al.*, 2010].

[3] There is demand for a better geographic model of the many causal processes underlying forest canopy change in the CONUS. For example, patterns of forest change and their underlying causal processes are necessary to better characterize source and sinks and reduce error in carbon budget estimates [*Birdsey et al.*, 2009; *Pacala et al.*, 2001; *Turner et al.*, 1995] and may be useful for place-based mitigation in carbon management and policy [*Murray et al.*, 2000]. Changes in the location, frequency, and severity of each forest change process may alter historical patterns of forest carbon sequestration and release [*Kurz et al.*, 2008a] as the amount of carbon released from disturbances is highly dependent on the type of process and local site factors [*Amiro et al.*, 2010]. Studies on how carbon budgets are

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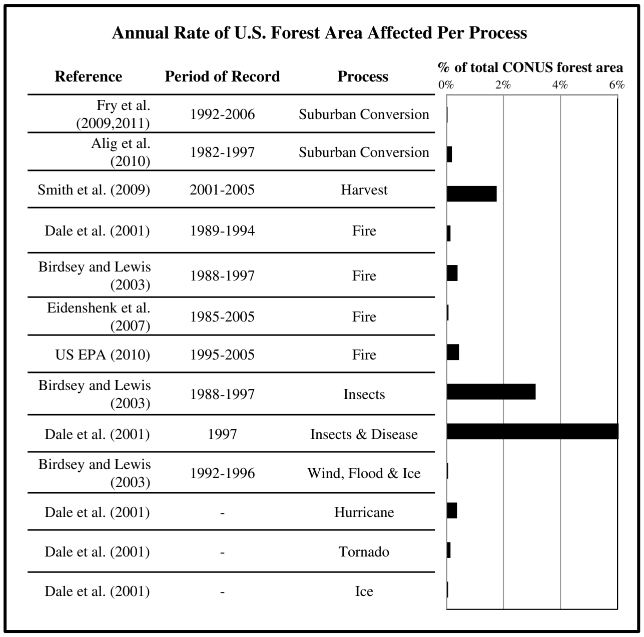

Figure 1. Estimated annual rates of national forest land area affected by disturbance and conversion process vary greatly.

affected by individual canopy change processes across the nation such as fire [*Houghton et al.*, 2000; *Wiedinmyer and Neff*, 2007], hurricanes [*Zeng et al.*, 2009], forest land conversion [*Houghton and Hackler*, 2000], forestry [*Masek et al.*, 2011; *Plantinga and Birdsey*, 1993], insects [*Hicke et al.*, 2012; *Kurz et al.*, 2008b], development to residential uses [*Nowak and Walton*, 2005; *Zheng et al.*, 2011], and broad reviews of the impacts of forest disturbance on carbon cycling are available [*Goetz et al.*, 2012; *Liu et al.*, 2011].

[4] A recent synthesis of the trends in forest area affected by major change process across the CONUS, at regional or finer scales, including severity measures is lacking. National estimates of forest area affected per causal processes vary widely (Figure 1). *Birdsey and Lewis* [2003] provide historical estimates of regional forest area affected by fire, harvest, insects and disease, conversion (among others) at decadal time steps up to and including 1997. At national scales, *Kasischke et al.* [2013] collected trends on the forest area disturbed by harvest, fire, and insects. Estimates of forest area affected by individual forest change processes across the nation are derived from empirical remote sensing observations [*Eidenschenk et al.*, 2007; *Fry et al.*, 2009; *Fry et al.*, 2011], model simulations [*Hurtt et al.*, 2002; *Kurz et al.*, 2009; *Seidl et al.*, 2011], ground inventories [*U.S. Department of Agriculture (USDA)*, 2001, USDA, U.S. Department of Agriculture 2003, U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis. (Available at www.fia.fs.fed.us/, retrieved Septemeber 2010)], and combined approaches [*Vanderwel et al.*, 2013]. Terms, such as "forest disturbance," "forest land conversion," "forest change," "forest cover loss" and "forest canopy loss," and permanent vs. temporary canopy loss are sometimes confounded [*Kurz*, 2010; *Pickett and White*, 1985; *Reams et al.*, 2010]. Here, "forest change" describes changes in stand level forest canopy including temporary losses due to disturbance and long-term losses (greater than two decades) due to conversion of forest to suburban/urban cover. We consider natural and human-managed disturbance events to be with-in state changes, meaning they are temporary disruptions to canopy cover which regrows with time. Silviculture encapsulates a suite of forest management activities, but only harvest of merchantable timber is used here to represent human-managed disturbances. Natural disturbances are limited to temporally abrupt events that cause stand level mortality and are climatically driven including, wind storms, fire, and insect outbreaks. Fire is considered a natural disturbance because one of the primary drivers is weather, regardless of the ignition source [*Thomas*, 1954]. In this paper, the term "conversion" is limited to forest canopy loss due to suburban/urban development. Many other processes affecting forest canopy dynamics such as afforestation, reforestation, conversion to agriculture, fertilization, floods, avalanche, ice storms, disease, drought, etc., are outside the scope of this paper.

[5] Each data set used in this paper has inherent strengths and weaknesses. FIA data offer more than five decades of ground measured estimates, but methods have changed through time and across regional data collection centers [*Gillespie*, 1999], and the resolution of observations may not be adequate to make inferences on clustered or rare forest events [*Bradford et al.*, 2010; *Fisher et al.*, 2008]. The North American Forest Dynamics (NAFD) project provides 20 plus years of landscape level data on the geography and timing of forest change events, from Landsat observations [*Goward et al.*, 2008]. NAFD forest history maps offer consistent methods through time and space, using repeat measurements at relevant spatial and temporal resolution, but are only available for a small set of sample areas and do not have causal processes associated with patches of canopy change [*Masek et al.*, 2013]. Monitoring Trends in Burn Scar (MTBS) data describe fire history with severity, but do not discriminate forest fires from those in other land covers [MTBS, 2010,

Montinoring Trends in Burn Severity. (Available at http://mtbs.gov/data/search.html)]. National Land Cover Data (NLCD) data offer spatial data on land cover and use changes, but at poorly resolved time steps and only for years between 1992 and 2005. Also, the NLCD is more effective at measuring long-term conversion than rapid cyclical forest disturbance and regrowth, which can be mislabeled as conversion to agriculture [*Drummond and Loveland*, 2010; *Fry et al*., 2009]. The only data on harvest area across the CONUS are provided by the USFS; however, methods of estimation may vary through time, and the spatial and temporal resolution is coarse [*Smith et al*., 2009]. USFS Aerial Detection Surveys (ADS) provide the most complete data on forest area affected by insect and disease, but use an opportunistic sampling scheme, methods that vary across regions, and area "affected" may be much larger than the actual crown area killed [*USDA*, 2000]. Historical tornado and hurricane paths for the US are available, but do not discriminate underlying land cover or related forest mortality. All data used were publicly available.

[6] The first goal of this study is to evaluate current trends in forest area affected by fire, insects, wind, harvest, and suburbanization across six CONUS regions. The second goal is to evaluate relationships between these coarse-scale trends, finer geospatial data on causal processes, and satellite-based observations of forest area canopy changes from regional through local scales. Since no one data set fully describes forest disturbance and land use, and reference data is scarce, we integrate multiple lines of evidence into a multiscale geodatabase for the CONUS. Together, these data offer unique perspectives on different aspects of the dynamics of forest canopy change and the underlying processes. The integrated geodatabase of underlying causal processes created for this study will be publically available through the ORNL DAAC (http://daac.ornl.gov/).

2. Data and Approach

2.1. Forest Area and Canopy Change

[7] Multiple data products depicting forest area and change are available, and estimates vary [*Masek et al*., 2013]. For decades, statistics from FIA national ground measured inventory provided the only information available on forest land trends across the nation. FIA data offer the longest recorded estimates on the extent, composition and structural characteristics of the country's forest. A strength of the US forest inventory approach is that quantitative data have been collected repeatedly from a large number of samples (~125,000, roughly 1 per 2428 ha) every 5–15 years [*Smith et al*., 2009]. Also, measurement errors are documented [*Pollard et al*., 2006], as are sampling errors for aggregated county, state, and regional reporting scales [*Smith et al*., 2001]. Recently remeasured FIA data have been used to simulate changes in aboveground biomass in the eastern US for eight forest disturbance processes [*Vanderwel et al*., 2013]. However, the FIA did not sample nontimberland forest or did not sample and remeasure these forest with the same intensity as on timberland forest for many years [*Birdsey*, 2004].

[8] The human or landscape scale is the salient resolution where forest canopy change processes occur and accumulate [*Miller*, 1978]. Remote sensing observations, consistently gathered and processed over large scales, offer a bridge between local studies and coarse national inventories yielding empirical data at the scales where forest change processes operate [*Fry et al*., 2009; *Huang et al*., 2010; *Masek et al*., 2008]. Forest land dynamics do not scale linearly, implying that when sampled measurements are aggregated to coarser-scale biases, uncertainty and error increase in unpredictable ways [*Goward and Williams*, 1997; *Hurtt et al*., 2010; *Williams et al*., 2012]. Without fine temporal resolution observations, temporary loss of forest cover and changes in forest stand age structures can be confounded with deforestation or omitted due to fast regrowth rates [*Frolking et al*., 2009; *Masek et al*., 2008]. Equally, without fine spatial resolutions, localized forest change in highly heterogeneous areas would not be observed leading to under estimation of change rates [*Jin and Sader*, 2005; *Masek et al*., 2008; *Tucker and Townshend*, 2000]. Landsat satellite data can provide the level of spatial-temporal detail needed, at 1 ha or less with seasonal updates, to detect individual forest disturbance events and their severity as well as monitor recovery or land changes that follow these events [*Cohen et al*., 2002; *Goward and Williams*, 1997].

[9] Many remote sensing-based US wide forest change studies exist [*Fry et al*., 2009; *Goward et al*., 2008; *Loveland et al*., 1999; *Masek et al*., 2008; *Mildrexler et al*., 2007; *Potapov et al*., 2009]; however, the fine resolution and depth of the NAFD project data are unique. The NAFD project provides the first comprehensive look at forest disturbance rates, with sample and measurement error estimates, for contiguous U.S. forests using the Landsat fine spatial and temporal observations recorded from 1985 to 2006 [*Goward et al*., 2008]. The NAFD methodology including sampling scheme [*Kennedy et al*., 2006], image selection [*Huang et al*., 2009], preprocessing [*Masek et al*., 2006], algorithm processing [*Huang et al*., 2010], measurement error assessment [*Thomas et al*., 2011], and sampling error [*Masek et al*., 2013] are available.

[10] NAFD forest history maps used in this paper record the location, year, and extent of canopy change from 1985 to 2005. NAFD maps were available on a sample of 54 nonoverlapping sample polygons, each with an area of roughly 2.2 million ha (150 km by 150 km) (Figure 2). NAFD uses a canopy cover-based spectral definition to define change events, with a minimum spatial minimum mapping unit (mmu) of 0.4 ha (0.9 acres). The data have a temporal mmu of two time steps meaning that canopy changes that do not persist for more than two time steps, such as intraseasonal insect defoliation, will not be flagged as disturbed. For each sample location, 12–14 nominal biennial image dates were used, depending on image availability and in an effort to avoid cloud cover. Therefore, time between individual dates can vary from 1 to 3 years. Change detection from nominal biennial dates was interpolated where necessary to report annual rates of change. Using biennial images with NAFDs temporal mmu can lead to the under representation of low to moderate severity/density disturbance events, such as partial harvest and insect and storm damage, particularly in locations with high forest site productivity that regrow quickly [*Thomas et al*., 2011].

2.2. Forest Change Processes

[11] *Harvest*: The first harvest data set is USFS Timber Products Output (TPO) surveys [*USDA*, 2010] which

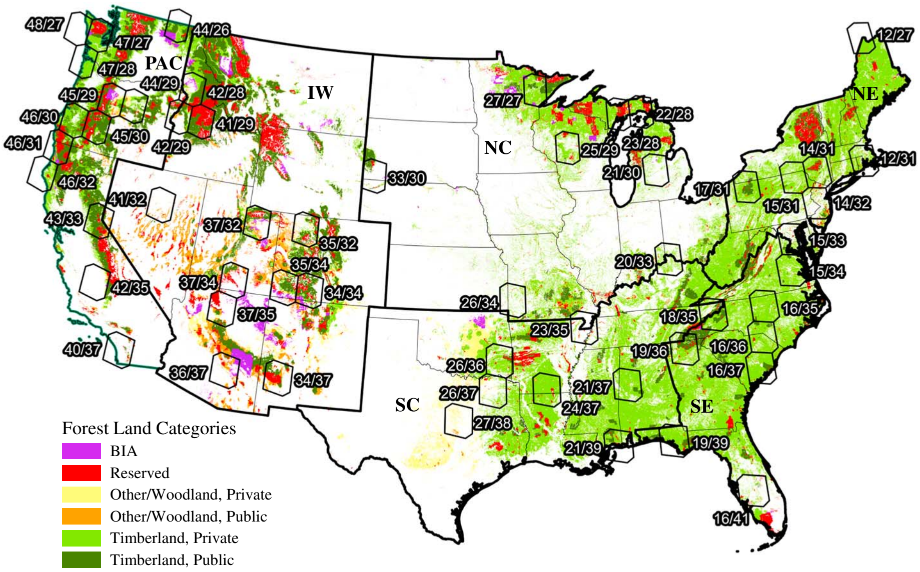

Figure 2. The locations of NAFD LTSS sample polygons (n = 54) are marked and labeled by WRS-2 path/row. Forest type categories were derived according to methods and data described in *Nelson and Vissage* [2007]. The six FIA regional subsets are also outlined (NE = North East, NC = North Central, SE = Southeast, SC = South Central, IW = Intermountain West, PAC = Pacific Coast).

estimate, at county or super county levels, the volume of timber harvest processed at the mill. It is assumed that the full population of timber mills responds to the voluntary survey, so there is no sampling error. Measurement uncertainty is not quantified. The USFS cautions data users on the spatial accuracy of the TPO data as lumber may pass county and state boundaries before it reaches the mill destination. It is important to note that the timber product volume is only a small proportion of total harvested volume and therefore not equal to FIA statistical estimates of the volume of timber harvest removals derived from field visits.

[12] The second harvest data set used is USFS harvest area estimates. It could not be confirmed that methods used by the USFS to calculate harvest area for the 1980–1990 period reported in *Birdsey and Lewis* [2003] are the same as those used for the 2001–2005 period reported in *Smith et al.* [2009]. Estimates in *Smith et al*. [2009] are modeled using the TPO survey and FIA ground observations. Clear-cut harvest is estimated to have greater than or equal to 80% of the tree basal area in a site removed. Partial cuts represent a spectrum of removals ranging from less than 80% of basal area down to cutting small gaps into forest stands to encourage establishment of pioneer species (B. Smith, personal communication, 2010). No error estimates are given.

[13] *Suburban/Urban development*: Three on conversion to suburban/urban development data products were used. First are the NLCD set change products 1992–2001and 2001–2006, which are derived from image differencing of Landsat imagery [*Fry et al*., 2009; *Fry et al*., 2011]. NLCD measures land cover changes, at three snapshots in time over 15 years. Change class error assessments are not available [*Wickham et al*., 2010]. Second, is the National Resource Inventory (NRI), a ground-based inventory providing decades of statistical estimates of forest land conversion with error estimates that vary by county and sampling unit details [*Nusser and Goebel*, 1997; *USDA*, 2009b]. We use the 1987–1997 NRI estimates of forest land converted to suburban/urban/developed land in *Birdsey and Lewis* [2003]. Neither the 2002 nor the 2007 NRI land cover data were available at the time of this analysis. Finally, for pre-1992 conversions, we use data from *Theobald* [2005], a spatial record of increasing housing density assembled from census data and other ancillary layers. Increasing housing densities are considered a better proxy for suburbanization than changes in population [*Radeloff et al*., 2005]. The Theobald housing density increase data does not discriminate among land covers.

[14] *Insects*: USFS Forest Health Protection (FHP) program collects data on forest mortality and damage from insect, disease, and abiotic processes from ADS, providing historical and current areal measure of forest land affected collected from *Johnson and Wittwer* [2008]. ADS data should be interpreted cautiously, as the reported forest area “affected” by insects may be much larger than the actual crown area killed [*USDA*, 2000]. The severity of forest damage by different insects depends on factors such as the type and life cycle of insects and the characteristics of forest stands in the affected landscape. For example, there is a 100% chance of mortality when a host tree is infected by a boring insect, such as one of the bark beetles species. Defoliators, such as Gypsy moths, cause temporary decreases in productivity of the host trees with small rate of mortality, normally. However, when trees are stressed from drought or over stocking the mortality rates of host tree species can become severe [*Campbell and Sloan*, 1977; *Raffa et al*., 2008]. Locations of ADS samples are not derived from a statistical sampling scheme. Data users are warned that the technique has uncharacterized spatial and thematic inaccuracies [*Johnson and Ross*, 2008]. FHP printed reports were used for regional statistics, and digital geospatial ADS data were used in the geodatabase.

[15] *Fire*: The USFS has collected wildland fire data for over a century. From USFS records, *Birdsey and Lewis* [2003] give estimates of the area of forest fires at decadal intervals, unaccompanied by a description of methods or estimated error. The finest grain (highest resolution) national breadth remotely sensed fire data come from the Monitoring Trends in Burns Severity (MTBS) project. MTBS provides annual geospatial data, from Landsat imagery, for individual fires that are >1000 acres in the West and >500 acres in the East. Severity is categorized along a gradient related to damage to vegetation and validated by analysts manually [*Eidenschenk et al*., 2007]. MTBS fire location rasters were used for fine-scale geospatial analysis and statistical tables of fire severity per lifeform from the MTBS website were used for regional statistics. MTBS data does not record land cover types, is still under production and has many data gaps in time and space, especially in states east of the Mississippi river [*MTBS*, 2010].

[16] *Wind Storms*: Forest mortality rates and forest area damage extent reports are limited and where reported, vary widely across storms [*Canham et al*., 2001; *Everham and Brokaw*, 1996; *Zeng et al*., 2009]. The quality and quantity of records on wind events generally decrease with their physical size from hurricanes, to tornadoes then down to *Derecho*s and other downburst events [*Peterson*, 2000]. For the latter storms, there is no systematic data record. Data on hurricane and tornado locations, timing, and intensity are collected and archived by the National Atmospheric and Oceans Administration (NOAA). The land covers affected are not recorded.

2.3. Regional Statistics

[17] We subset the CONUS into North East (NE), North Central (NC), Southeast (SE), South Central (SC), Pacific (PAC), and Intermountain West (IW) regions (see inset Figure 2). These boundaries are consistent with historical USFS regional boundaries and are relevant to current carbon stock summaries [*Smith and Heath*, 2008]. The regional divisions represent a post hoc selection of NAFD sample locations, so estimators of variance and probability used in the national sampling scheme were not applicable. Instead, we derived regional rates by averaging the change rates, weighted by forest area per sample, of all samples in a region; errors and bias cannot be calculated. However, the proportion of forest group types [*Ruefenacht et al*., 2008] and forest land types (Figure 2) in NAFD sampled locations were found to be reasonable representations of the proportion of forest group and land type found in the full FIA regional populations [*Schleeweis*, 2012].

[18] Regional historical data on forest area affected by insects (1987–1997), forest fire (1988–1989), and harvest (1980–1990) area were taken from *Birdsey and Lewis* [2003]. For recent rates, state level tables of area statistics for insect (1997–2005), harvest (2001–2005), and forest fires (1984–2008) were aggregated to historic regions [*MTBS*, 2010; *Smith et al*., 2009; *USDA*, 2000, 2005, 2009a]. Two time periods of the rate of forest converted to developed land (1992–2001 and 2001–2006) were calculated from NLCD data by subsetting the national maps to historic regional boundaries, dividing the area of "forest changed to developed" by the sum of the area of persisting forest and the area of forest changed to other land covers, then multiplying by 100 [*Fry et al*., 2009; *Fry et al*., 2011]. In regional statistics, we separate area affected by defoliating and boring insects, as a proxy for severity (see section 2.2).

[19] For comparison across data sets and regions covering different size forest areas, change rates were calculated and reported in terms of the percentage of total forest area per region. FIA regional forest area estimates in *Smith et al*. [2009] were used in the denominator to calculate the ratio of regional forest area affected by individual processes. Rates were averaged to an annual mean to allow comparisons across data sets with differing time steps. No method was used to fill "no data" gaps in space or time for change process data sets.

2.4. Integrated Geodatabase

[20] A geospatial database was built in ARCGIS 9.3 to facilitate geographic analysis of forest change processes and canopy change observations through space and time. National breadth, consistent recording methods through time, and the finest available spatial and temporal resolution were criteria used to choose data sets included in the geodatabase. Table 1 summarizes the data source, type, resolution, and extent of data for each data set used in the geodatabase. The geodatabase will be archived at the ORNL DAAC (http://webmap.ornl.gov/) and will be available for public download.

[21] The method of import, filtering, and manipulation varied for each data set used in the geodatabase. Data were standardized where necessary, filtered, and used to calculate value added layers, such as frequency layers. The Census Bureau's definition of suburban (1 unit per 0.1 – 0.68 ha; 0.24 – 1.68 acres) and urban (1 unit per <0.1 ha; 0.24 acres) areas were used to threshold the housing intensity data from *Theobald* [2005]. NLCD retrofit change data set (92-01) and '06 change layer (01-06) were filtered to include only classes related to forest land cover and suburban/urban development. MTBS regional mosaics were downloaded, imported, and mosaicked into a national map for each year.

[22] Storms listed in the National Hurricane Centers North Atlantic Hurricane Database (HURDAT) [*Jarvinen et al*., 1984], which did not have wind speeds violent enough to cause significant forest damage (category 3 or greater on the Saffir-Simpson Hurricane and Fujita Tornado wind scales) or which did not occur between 1984 and 2008, were filtered out. Hurricanes widths are not recorded in HURDAT, so hurricane tracks were buffered by 50 km (19 miles) to identify areas potentially exposed to severe hurricane winds. This buffer is more conservative than that used by *Costanza et al*., 2008 who estimated swath widths of 200 km when analyzing hurricane affected areas. Buffered storm polygons were converted to 30 m grids.

[23] ADS data for each region were downloaded, imported into ARCGIS, converted to shapefiles, and reprojected to the USA Contiguous Albers Equal Area Conic projection where necessary. Polygons with damage agents not related to insects and disease such as fires, wild animals, domestic animals, abiotic damage, competition, and human activities were filtered out. Using custom python code, each remaining ADS polygon was ranked according to a severity-confidence (S-C) rank of high, moderate, and low based on data exploration of the values in the attribute fields for "damage type," "damage agent," "pattern of the host species," and "severity" fields [*Schleeweis*, 2012]. The cumulative frequency map of moderate to high severity-confidence insect disturbances

Table 1. Ancillary Geospatial Data for Forest Change Processes

Change Process	Measurement Method	Data Source	Spatial		Temporal	
			Grain	Extent	Grain	Extent
Fires	Landsat, NDVI change	MTBS http://MTBS.gov	30 m grid	national	annual	1984–2007
Hurricanes and Tornadoes	Ground measurements-wind speed	U.S. National Hurricane Center http://www.nhc.noaa.gov/pastall.html	lines	national	annual	1851–2007
Suburbanization/ Urbanization	Decadal Census - # new housing units	[*Theobald*, 2005]	100 m grid	national	decadal	1940–2030
Suburbanization/ Urbanization	Landsat, Land Use Change	NLCD Retrofit Change Datahttp://www.mrlc.gov/changeproduct.php	30 m grid	national	Decadal	1992–2001
Suburbanization/ Urbanization	Landsat, Land Use Change	NLCD 2001/2006 Land cover Chang ehttp://www.mrlc.gov/nlcd2006_downloads.php	30 m grid	national	5 years	2001–2006
Harvests	Timber Product Output Surveys	USFS FIA http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int2.php	County polygons or >	sampled - national	5–10 year cycles	1997–2007
Insects and Pathogens	Digitized Aerial sketches of insect damage	US Forest Health Program http://www.fs.fed.us/r3/resources/health/fid_surveys.shtml	polygon <1 ha	sampled - national	annual	WA and OR: 1984–2005; CA: 1994–2008; AZ: 2000–2009; NM: 1998–2009; states in the NC and NE regions: 1997–2009; NV,UT and southern ID: 1991–2008; Northern ID, MT ND: 2000–2008; most of Wyoming, CO,SD, NE, KS: 1994–2009
Southern Pine Beetle	Aerial Spot Detection Surveys	[*Williams and Birdsey*, 2003]	County polygons	SE and SC states (except OK)	Annual	1987–2004

was created by weighting the severity-confidence ranks, then summing the annual data layers.

[24] To create a spatial layer for the intensity of harvest activities, TPO county removal volume (from logging activities only) for the 1997–2002, 2002–2007, and 1997–2007 periods was normalized by the amount of nonreserved county forest land listed in the 1997 FIA forest inventory. If there was not a 1997 inventory, data from the most recent prior inventory were used [*USDA*, 2010]. Tabulated harvest intensity for across periods was summed, categorized by natural breaks, and mapped to county boundaries.

3. Results/Discussion

3.1. Across Regions

3.1.1. Process Trends

[25] The vast majority of canopy change was due to disturbance (harvest, insects, fire, and wind) processes, not conversion (to suburban/urban land use). Harvest was the most abundant forest canopy change process in the NE, NC, SE, and SC. Rates for each process vary by region and decade (Figures 3a–3d), though the forest region most affected by a particular process did not. Across both time periods, conversion affected the largest percentage of regional forest area in the SE region, fire affected the largest percentage of regional forest area in the IW, and both harvest and insects both affected the largest percentage of forests in the SC region. Wind affected the SE and SC regions the most. Across all regions through the periods of observation, the rate of forest conversion decreased, the total rate of insect infestation decreased, and the forest fire rate increased except in the NC.

[26] When comparing estimated rates of the same process from different sources, we found conspicuous differences. For example, over the same time period in the IW, forest fire area estimates varied by as much as two orders of magnitude between *Birdsey and Lewis* [2003] and MTBS (which use the 2001 NLCD land cover data to help discriminate burn severity by life forms) (Figure 4a). No large-scale historical fire data set explicitly records the land cover of burned areas, and methods for estimating the cover type of fires [*Brewer et al.*, 2005] vary as do ways to calculate the area affected [*Cocke et al.*, 2005] vary. For example, estimates of area based on counting perimeter-based fire are larger than estimates where unburned islands within perimeter are not counted [*Shapiro-Miller et al.*, 2007]. Also, the USFS fire area estimates include prescribed forests which are not well characterized by MTBS or other studies using optical satellite images during full leaf canopy maturity [*Eidenschenk et al.*, 2007; *Schroeder et al.*, 2011].

[27] The location and amount of forest in different forest maps are known to vary [*Nelson et al.*, 2003]. We found estimates varied widely for calculations of the amount of forest area affected by a process depending on which forest mask was used for calculations when the data set did not inherently discriminate the land cover affected, such as MTBS fires and hurricanes/tornadoes. When the NLCD forest mask (30 m) was used to estimate the amount of forest area exposed to wind storms, with wind speeds sufficient to cause widespread forest mortality, the result was 3.58 million ha of forest. The estimate was almost twice as large when the *Ruefenacht et al.* [2008] FIA forest mask (250 m) was used. The area of MTBS forest fires is 63% higher when the FIA forest mask was used to calculate CONUS forest fire area compared to when the NLCD forest mask was used in the same calculation.

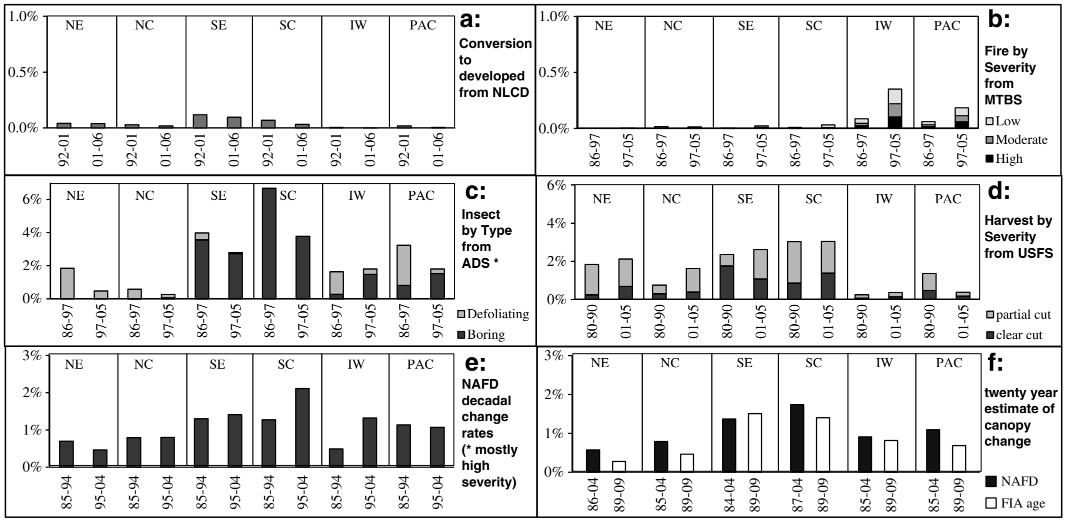

Figure 3. Annual rates of forest area affected by (a) conversion, (b) fire, (c) insect infestations, (d) harvest, (e) NAFD disturbance and conversion, and (f) FIA disturbance. Averaged annual rates are given as a percentage of the total regional forest area from *Smith et al*. [2009]. Figure 3a shows conversion data from NLCD [*Fry et al*., 2009; *Fry et al*., 2011] Figure 3b shows fire data from *MTBS* [2010]. Figure 3c shows insect Insect affected area 1986–1997 data from *Birdsey and Lewis* [2003], 1997–2005 data from FHP reports [*USDA*, 2000, 2005]. * FHP reporting methods for the SC and SE vary drastically from other areas of the country and may lead to inflation of reported numbers. Figure 3d shows harvest area and severity 1980–1990 data from *Birdsey and Lewis* [2003], 2001–2005 data from *Smith et al*. [2009]. Figure 3e shows disturbance and conversion rates (not differentiated) from NAFD results. Figure 3f shows averaged annual change rates from NAFD results and FIA forest stand age estimates [FIDO tool].

[28] There are numerous flaws in the regional estimates of forest area affected by each change process. First, the six FIA administrative boundaries used in this work are helpful for historical comparisons, but confound different disturbance regimes across local and anthropogenic and environmental gradients. Second, none of the data used have estimates of error or uncertainty. Third, there are large gaps in the data record. For example, for the most widespread and perhaps severe forest disturbance process in the country, harvest, there are no explicit harvest area estimates between 1990 and 2000. NLCD conversion data are only available post-1992. At the time of print, 2002 and 2007 NRI land cover change data, below national summary statistics, were not available. Finally, some of the variability in per process rates estimated through time may be an artifact of inconsistent methods. For example, the pair of estimates for harvest area, given for the1980–1990 and 2001–2005 periods, are both published by the USFS, but are estimated with methodologies that are not fully documented and may differ (B. Smith, personal communication). The volatility in estimates of forest area "affected" by insects might be due to the interannual variations in the opportunistic sampling scheme, and not solely to insect activity levels [*Johnson and Wittwer*, 2008]. Though a national protocol exists, western, southern, and northern regions have different styles for recording severity.

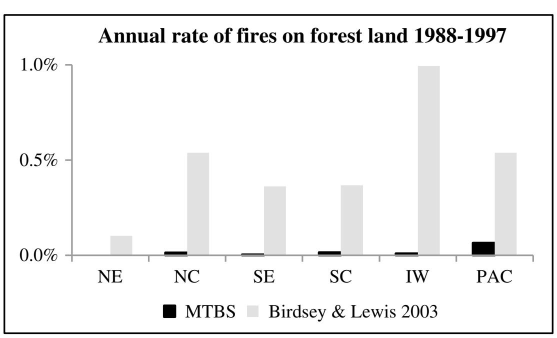

Figure 4. Annual estimates of the regional percentage of forest fires vary widely depending on the data source.

3.1.2. Overlapping Processes and Observations

[29] Double counting in aerial estimates of forest change, due to multiple canopy change events or processes on the same forest land, is recognized but remains largely unquantified [*Birdsey and Lewis*, 2003; *Dale et al*., 2001; *Smith et al*., 2009]. For example, increases in fire occurrence can follow hurricane and insect damage [*McNulty*, 2002; *Myers and van Lear*, 1998]. Mortality from insect epidemics can cause extreme fuel loads increasing the risk of catastrophic fires [*Jenkins et al*., 2012]. Reports on the frequency and extent of salvage and sanitation harvests, important forest management tools to control outbreaks, and severity of insect damage and fires are limited [*Fettig et al*., 2007; *Radeloff et al*., 2000; *Samman and Logan*, 2000]. *McNulty* [2002] estimates that 13% of damaged trees are salvage logged after catastrophic wind storms, but the rate of salvage logging varies depending on access and timing of events [*Robinson and Zappieri*, 1999].

[30] Integrating geospatial data into a single geodatabase provided a better geographic model providing insights into the frequency and overlap of multiple forest change processes across the CONUS (Figure 5). Though not the

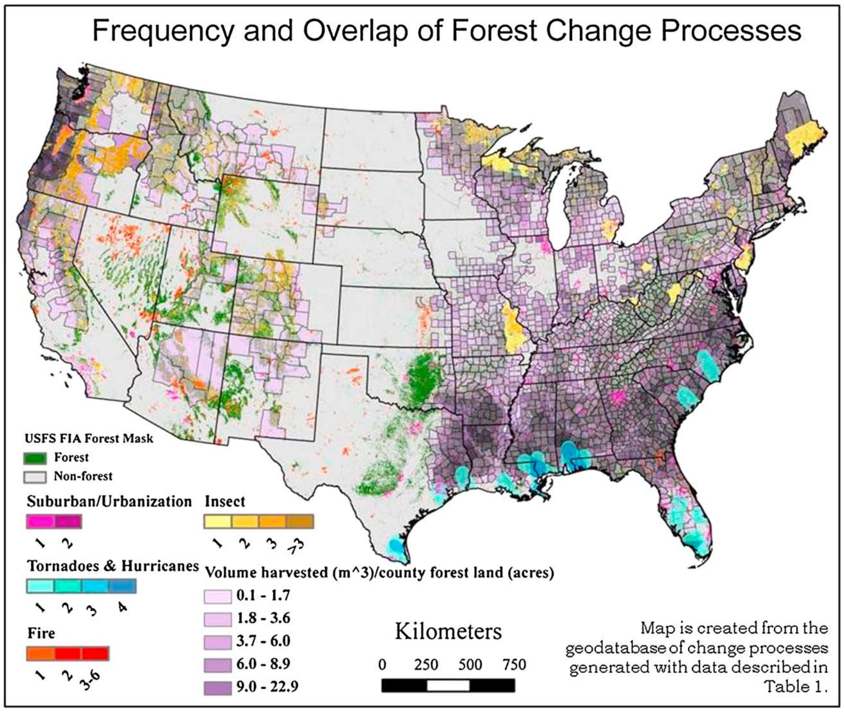

Figure 5. The spatial and temporal overlap of fire, insects, wind storms, suburbanization/urbanization, harvest, and forest area in the CONUS. Frequency was calculated as number of events through time and calculated for each processes separately. Volume harvested is a cumulative measure. Layers are partially transparent to help visualize how some forest areas have been subject to many change processes over the last two decades (see Table 1 for spatial and temporal grain and extent of each data set).

focus of this paper, questions of timing and synergy between multiple processes can be examined with the geodatabase. For example, a spatial query to the geodatabase using MTBS fire locations, hurricane paths, and NLCD forest land returned few forest fires within the four years after Hugo. A similar analysis, using the buffered path of hurricane Katrina, showed that the forest area burned in the 12 years prior to Katrina was only 4000 ha less the forest area burnt in just one third that time (4 years) after the storm. Overlaying insect ADS and MTBS fire data revealed where fire and insect forest disturbance observations overlap in space, and their order in time (areal estimates of insect-fire overlap would not be meaningful, due to the opportunistic sampling scheme of ADS data).

[31] The geodatabase helped elucidate underlying causal processes and canopy change events mapped by NAFD that were often conflated at the regional-decadal scale. Many spikes in NAFD disturbance rates coincided in time and space with disturbance events in the fire and wind layers. Evidence of volatile harvest regimes was captured in some NAFD samples, but widespread verification is difficult with the scales of existing national geospatial harvest data. Though insect damage is prevalent in forests across the CONUS, spikes in NAFD canopy change rates did not converge in location or timing with insect outbreaks. The proportion of the canopy change rate associated with each disturbance type could not be calculated due to the course resolution, and numerous spatial and temporal gaps of some geospatial change process data. Details vary regionally and are articulated in more depth in the regional case studies (see section 3.2).

3.1.3. Canopy Change Trends

[32] Forest canopy change estimates derived from remote sensing, even when sampling and measurement errors are provided, are not always adequate [*Reams et al.*, 2010]. For context, we compared NAFD regional forest change rates to rates estimated from FIA ground measurements of forest age classes, an often used proxy for disturbance history [*Pan et al.*, 2010; *Williams et al.*, 2012]. FIA and NAFD data show similar magnitude patterns across regions, with the SE and SC regions having the highest amount of young forests (Figure 3f). NAFD rates were higher than FIA rates for all regions except the SE. Higher NAFD rates are in part due differences in the sampling scheme of the two approaches and to the finer spatial and temporal resolution observation of the NAFD data which can resolve more partial and clustered disturbances (see section 2.1). The NAFD methodology is also able to record multiple change events on the same parcel of forest land area [*Huang et al.*, 2010]. Both data sets may underestimate total area of forest disturbances. NAFD's use of biennial imagery can lead to underestimation of partial and repeat disturbances (see section 2.1). There are also limitations to using forest age from ground inventories as an indicator for time since the last disturbance, especially for uneven-age stands, where partial disturbances did not reset the forest age class to zero [*Bradford et al.*, 2008; *Lorimer*, 1985].

[33] When the rates of change from individual sample locations of the NAFD forest history maps are graphed at annual time steps, two contrasting temporal patterns emerge (Figures 6a–6f). The first is a consistent or "background" change rate. This signal could be due to a single dominant,

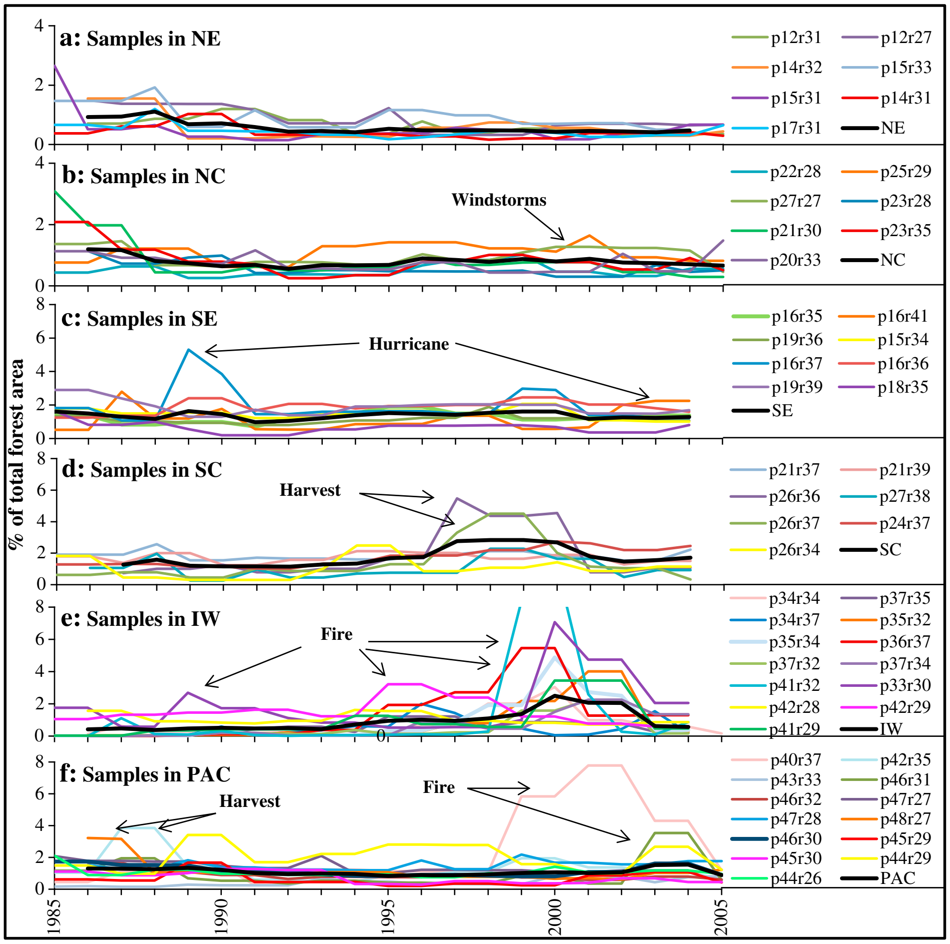

Figure 6. (a–f) Annual NAFD disturbance rates for sample and regional subsets are given as a percentage of forest area in the region. Regional averages were weighted by the amount of forest area in each NAFD sample, but were not drawn from an equal probability sample.

fairly stable rate process across the region or the combined signatures of multiple processes. The second is a sudden, brief "spike" in the canopy change rate of the region and or sample. Large infrequent natural disturbances are known to cause occasional peaks in mortality [*Foster et al*., 1998; *Turner et al*., 1998].

[34] There is large interannual variability in the NAFD change rates within and between regions. Anomalies, defined here as a period where the change rate is ± 3 standard deviations outside of the 20 + year mean change for the sample, existed in the time series of change rates for many of the NAFD samples. When plotted, the frequency distribution of the magnitude of the annual disturbance rate (in terms of its z score) shows empirical evidence that the occurrence and severity of observed forest change phenomenon are not normally distributed, and that the distribution of each regional subset is skewed by infrequent large events (Figure 7).

3.2. Within Regions

3.2.1. North East

[35] While the USFS inventories suggest the amount of forest land in the NE has been nearly constant since the 1970s [*Smith et al*., 2009], changes in forest age distributions and species composition from forest inventories suggest decreasing disturbance rates [*Lorimer and White*, 2003]. The NE rate of forest canopy change derived from FIA forest age classes, 0.28% of total forest area per year (0.095 million ha yr^{-1}), and NAFD forest history maps was the lowest of any CONUS region (Figure 3f). Averaged annual NAFD change rates decrease from 0.70% yr^{-1} to 0.54% yr^{-1} between the 1986–1994 and 1995–2004 periods, respectively. The area and average severity of harvest and fires increased, while insect infestations and conversion rates decreased over time (Figures 3a–3d). Harvest was the dominant forest change process in the region through time both by area and severity.

[36] NAFD samples individually and as a group in the NE have low interannual variability around their median change rate. The constant rates, we assume are mostly driven by harvest, as it was the most pervasive change process in the region through time. However, harvests are not evenly dispersed across the forested landscape, and the random locations of the NAFD samples may not reflect overall disturbance trends from harvests in the region. For example, there is an inverse relationship between the location of large population centers and the magnitude of commercial forestry operations [*Polyakov et al*., 2008; *Wear et al*., 1999]. Four

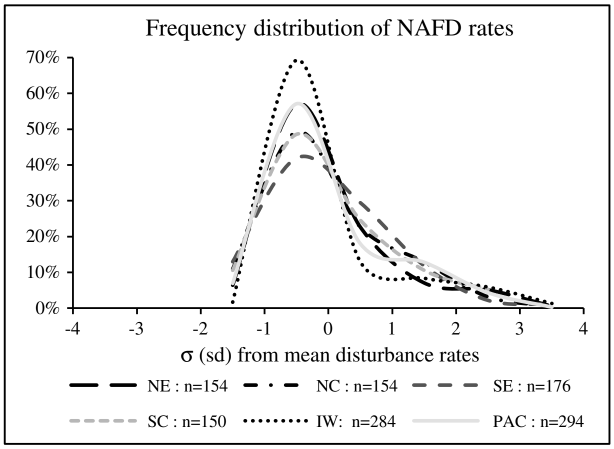

Figure 7. Magnitude, measured as the distance of the annual change rate from the 20 year mean (the z-score), is calculated individually for each NAFD sample and grouped by region. The number of image years available in each sample location and the number of samples in each regional subset varies. Frequency is given in percentages of the total number of image years (n) per region (summed across samples within a region). Because the LTSS regional subsets are an adhoc selection from the national sampling scheme, sampling error and uncertainty cannot be calculated.

of the seven NAFD samples are located on the densely populated coastal corridor. Data limitations for harvest and insect events, which also affect large areas of NE forest, preclude time and site-specific comparisons with NAFD results.

[37] More forest land was affected by harvest than any other process in the NE region, and the rate of area harvested increased through time (Figures 3a–3d). Harvests increased from 1.8% yr^{-1} to 2.1% yr^{-1} (0.728 million ha yr^{-1}) of total forest area and the clear-cut harvest rate rose 189% from 0.24% yr^{-1} to 0.70% yr^{-1} between 1980–1990 and 2001–2005 (Figure 3d). Volume of harvest removals reported in TPO data also increased (1997–2007). Increases in harvest area and severity reported by the USFS are contrary to the decline in NAFD regional estimates of canopy change. Mapping TPO data along with NAFD forest history maps revealed that of the counties with the highest increase in removals from harvests between 1992 and 2007 (in NH, WV, and ME), only one was covered by NAFD data. If counties where the TPO volume of removals increased are near to locations of increased clear-cut harvesting, then the disturbances would not have been captured by the NE NAFD sample locations.

[38] The rate of NE forest conversion suggests low quantities of forest land affected, though estimates vary by an order of magnitude by source. NRI conversion rates are 0.31% yr^{-1} (0.106 million ha yr^{-1}) between 1987 and 1997 [*Birdsey and Lewis*, 2003]. NLCD conversion rates are 0.042% yr^{-1} and 0.040% between 1992 – 2001 and 2001–2006, respectively. The relatively small forest area affected by conversion, it is unlikely that a large proportion of the change rates for NE NAFD samples are due to conversion, even in the four sample locations that overly heavily growing urban population centers. Historical census housing density data set from *Theobald* [2005], proved useful for visually confirming forest conversion events in NAFD canopy change maps prior to 1992 (the first year the NLCD conversion data is available).

[39] The rate of regional forest area affected annually by insects, was exclusively due to defoliators, and decreased from 1.9% yr^{-1} (0.64 million ha yr^{-1}) to 0.5% yr^{-1} between 1986–1997 and 1997–2005 (Figure 3c). Starting in 1989, the second worst outbreak of gypsy moths, since the 1940s, was recorded in the NE region. PA was the hardest hit state, reporting 2.83 million ha defoliated over a three year period [*USDA*, 1995]. In general, intraannual disturbance events, such as defoliation by insects, that do not lead to high mortality rates in affected forest areas are not mapped by NAFD and will not contribute to calculated disturbance rates (see section 2.1). Repeat heavy gypsy moth defoliation events can cause substantial tree mortality [*Campbell and Sloan*, 1977]. Three of the NAFD samples overlap parts of PA, but fine geospatial data on gypsy moth damage locations is not available pre-1997 for comparison with NAFD forest history maps.

[40] MTBS forest fire rates increased from 0.0001% yr^{-1} to 0.001% yr^{-1} (1302 ha yr^{-1}) of NE forest area burned annually between the 1986–1997 and 1997–2005 periods (Figures 3a–3d). MTBS does not record a single fire records in the NE between 1988 and 2001. *Birdsey and Lewis* [2003] report 0.1% yr^{-1} of NE forest burned between 1998 and 1997.

[41] Between 1984 and 2006, the average annual forest area *exposed* to major hurricane and tornado winds was 0.01% yr^{-1} of NE forest land (4628 ha yr^{-1}) (calculated using the 2001 NLCD forest mask and hurricane and tornado layers). Using the wind event layers in the geodatabase, we counted 30 moderate to severe tornadoes in the NE region. Eight of these tornado polygons overlapped with NAFD sample p17r31 in western PA. Tornado polygons were found in close spatial proximity to linear swaths of forest mortality mapped by NAFD, but did not overlay directly (Figure 8). In this case, storm-related mortality "tracks" in the NAFD map were so localized they blended into the overall "background" change rate for the sample, rather than creating interannual spikes. *Derecho* storms are also responsible for localized wind mortality events in the region [*Bentley and Mote*, 1998], but are not included in the above estimate of forest area exposed to major storms. The 1995 *Derecho*, which resulted in 15,300 ha of forest in Adirondack Park in New York, was classified as having 60–100% of timber blown down and was not covered by an NAFD sample location [*Robinson and Zappieri*, 1999].

3.2.2. North Central

[42] The amount of forestland and the volume of timber have been slowly increasing for decades in the NC region [*Smith et al.*, 2009]. While, poplar and birch, short-lived pioneer tree species that sprout after natural disturbances, are aging and dying in the NC region, signaling changes in local disturbance regimes and shifts in forest composition [*Lorimer and White*, 2003]. Over the last two decades, the regional FIA annual forest disturbance rate was 0.48% yr^{-1} of total forest land (0.182 million ha yr^{-1}). The annual NAFD rate, 0.80% $yr^{-1}$of total forest land, was 70% higher than the FIA rate and stable at decadal time steps (Figure 3e). Regionally, the annual rates of forest area affected per change processes were mixed in magnitude and direction. Forest conversion, fire and insect infestations

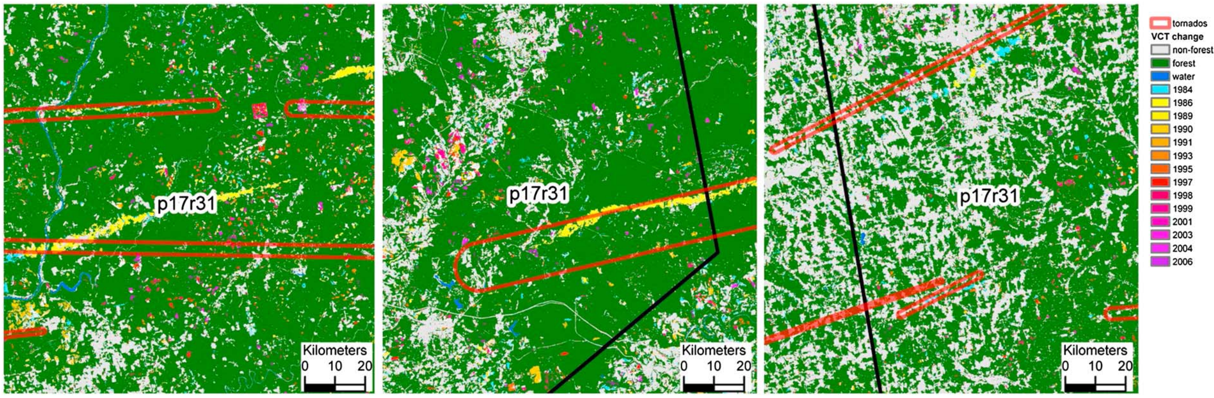

Figure 8. In 1985, a cell of severe tornadoes touched down in western PA, near Alleghany state forest. The area falls within NAFD sample p17r31. Tornado tracks polygon outlines, from the NOAA storm track data set, are shown in red, overlaid on the NAFD forest history map which maps the year and location of mortality events.

rates decreased, while harvest area and average severity both increased (Figures 3a–3d).

[43] In general, the NC NAFD samples individually and as a group show low interannual variability around the median forest change rate. Regional statistics suggest harvest was the dominant change process in the region, by area and severity, and was responsible for the “background” disturbance rates of forest change in NAFD results. Localized spikes in change rates were partially attributable to severe localized wind storm events. However, not all NAFD mapped forest mortality events and related spikes in the samples disturbance rate, intersected with specific events in the causal process layers in geodatabase, and remain unattributed or explained.

[44] Harvest was the dominant canopy change process in NC forests, by area and severity (Figures 3a–3d). The rate of forest land harvested annually went up between 1980–1990 and 2001–2005, attributable to the increase in the rate of partial harvests from 0.45% yr^{-1} to 1.23% yr^{-1} (0.42 million ha yr^{-1}) of all NC forest land, respectively. The rate of clear-cut harvest remained almost stable. NAFD forest history maps do not capture partial harvest as well as clear-cuts, when biennial image stacks are used (see section 2.2), which may account for the stagnant regional NAFD change rates, in spite of the large increase in total harvested area seen in USFS data. Mapped TPO data of cumulative removals (1997–2007) show harvest were more concentrated across the northern forests in the region (Figure 5). TPO county level timber volume removal trends suggest NAFD samples capture more counties with decreases in their removal for the 1997–2002 period. There was no clear trend in the 2002–2007 TPO data record for counties within NC NAFD samples.

[45] The NRI and NLCD rates of forest conversion in the NC region vary by more than an order of magnitude. According to NRI data, the NC had the highest forest conversion rate of any CONUS region, 0.43% yr^{-1} (0.146 million ha yr^{-1}) of forest per year, between 1988 and 1997 [*Birdsey and Lewis*, 2003]. The NLCD NC forest conversion rate was 0.029% yr^{-1} (9024 ha yr^{-1}) of total forest area between 1992 and 2001 and 0.018% yr^{-1} between 2001 and 2006. Conversion likely contributed nominal amounts to the “background” canopy change rates of NAFD NC samples, due to the low rate of conversion and that the NAFD samples did not overlay many NC population centers or their suburbs.

[46] Regional statistics for NC forest insect infestation rates dropped across inventory periods to 0.27% yr^{-1} (0.098 million ha yr^{-1}) of total NC forest area (Figure 3c). Defoliators accounted for 76% of the infestations between 1997 and 2005. Repeat forest damage events by beech bark disease (BBD), Emerald Ash Borer (EAB), Spruce budworm, and tent caterpillar affected large areas across the region [*USDA*, 2005]. When mapped, the area affected by EAB appears as a conspicuous blob across southeastern MI (Figure 5). On average, Ash trees have low stem counts across the forest landscape, so the density of dead trees related to EAB can be very low, though widespread. A similar pattern appears in the upper peninsula of MI with BDD. Mapped NAFD canopy losses do not match spatially or temporally in p21r30 with EAB damage nor in p22r28 with BBD damage.

[47] Fire suppression has changed the forested landscape in the NC region during recent times [*Schulte and Mladenoff*, 2005]. MTBS averaged annual forest fire rates declined from 0.02% yr^{-1} to 0.01% yr^{-1} (4280 ha yr^{-1}) of total forest area across decadal time periods. Low severity fires accounted for 80% and 70% of fire area, respectively (Figures 3b–3c). Forest fire estimates in *Birdsey and Lewis* [2003] suggest 0.53% of NC forest land burned annually between 1988 and 1997.

[48] Although wind is acknowledged as the dominant natural disturbance process of northern forests [*Lorimer*, 2001], no formal estimate exists for the total regional forest area affected by windstorms (of any type) through time. Using the geodatabase, we calculated an annual average of 0.06% yr^{-1} (19,822 ha yr^{-1}) of NC forests was *exposed* to major tornado/hurricane winds between 1984 and 2006. *Derecho* windstorms, for which no comprehensive geospatial data exists, also cause forest mortality in the region. For example, an intense *Derecho*, with winds the strength of a category three to four hurricanes, caused widespread forest blowdown across 193,000 ha of the Superior National Forest in MN in 1999 [*Nelson et al.*, 2009]. In the same year, NAFD change rates spiked for samples p27r27 (northern MN) and p25r29 (central WI). The best match

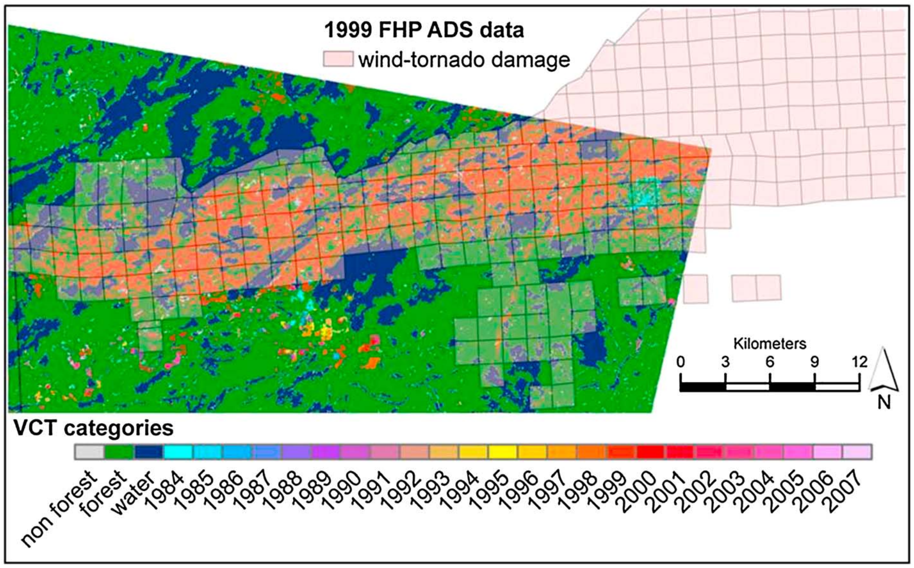

Figure 9. A large swath of forest area in upper MN was labeled as disturbed in 2001 by the VCT algorithm, shown here in the NAFD forest history map for p27r27. Reference data, in this case, the 1999 ADS data and published literature, suggest that the mapped forest canopy loss was caused by wind damage.

spatially and temporally between NAFD mapped canopy loss in these locations and the events layers in the geodatabase was with ADS data. ADS polygons can record forest damage by abiotic agents in addition to insects and diseases. ADS data for 1999 and 2004 contain polygons with abiotic damage labeled as "wind-tornado," which converge with NAFD canopy change in p27r27 (Figure 9). Attributing NAFD canopy change solely to the *Derecho* is not certain as there are also records of damage from defoliating insects in the same location between 2001 and 2002. NAFD data for p25r29 (central WI) also recorded canopy damage in vicinity of *Derecho* events in 1998 and 2001.

3.2.3. Southeast

[49] The coastal plain has some of the most productive land in the southern U.S. and is on its "fourth" forest since the large-scale clearings of the 1800s [*Trani et al*., 2001]. The averaged SE NAFD change rate translates to a forest replacement rate of 73 years (1986–2005). NAFD rates are 9% less than the FIA annual disturbance rate of 1.5% yr^{-1} of all SE forests (0.546 million ha yr^{-1}). Decadal NAFD canopy change rates were stable at 1.3% yr^{-1} and 1.4% yr^{-1} of total forest area (Figure 3e). However, regional trends show the rate of boring insect infestations, clear-cut harvesting, and conversion dropped (Figures 3a–3d).

[50] Within the SE group of NAFD samples, there was substantial interannual variability in observed NAFD change rates (Figure 4c). Hurricane timing and location corresponded to large mortality events mapped in NAFD forest history maps and "spikes" in NAFD change rates at individual sample and regional scales. Insect damage and harvest affected the most SE forest area. We have to assume the temporary canopy loss associated with these processes comprises the majority of the "background" NAFD rates, but cannot confirm due to data gaps and coarse scale of available reference data.

[51] The SE rate of harvest was nearly flat between 1980–1990 and 2000–2005, at 2.4% yr^{-1} and 2.6% yr^{-1} (0.93 million ha yr^{-1}) of total forest area, respectively (Figure 3d). Over the same periods, the average harvest severity decreased as the proportion of clear-cut harvests dropped from 75% to 41% of total harvested area (Figure 3d). The highest TPO cumulative logging removals were in counties sandwiched between the coast and the Appalachian ridge (Figure 5), where five of the eight SE NAFD samples fall. At five year time steps, there were no clear trends in TPO harvest volumes for counties within the NAFD sample boundaries. Repeat harvest on the same forest plot area is a common practice in industrial logging operations. The SE, where forestry rotations and tree growth are quick, had the second highest rate of multiple disturbances in NAFD results. In the SE 4.6% of the NAFD observed, forest area in the region experienced more than one disturbance event during the period of observation (SC = 5.9%, NC = 1.6%, NE = 1.4%, PAC = 1.1%, IW = 0.6%). Further work is necessary to determine how many of the repeat disturbance events were due to multiple harvests.

[52] The heavily forested SE region has some of the most sprawling suburbs in the nation [*Miller*, 2012; *Schneider and Woodcock*, 2008]. According to the NLCD data, the SE region had the highest forest conversion rate across the CONUS. SE NLCD conversion rates were 0.12% yr^{-1} and 0.097% yr^{-1} (24,828 ha yr^{-1}) of total forest land, between 1992–2001 and 2001–2006, respectively. The NRI rate of forest land converted annually was 0.37% between 1988 and 1997, the second highest across the CONUS [*Birdsey and Lewis*, 2003]. Differences between the two approaches to estimating forest area converted may in part be due to the NRI's ability to record more conversion in rural land [*Schleeweis*, 2012]. NAFD samples overlay many of the growing urban areas in the region including Atlanta, Raleigh, Norfolk, Richmond, and Tampa and may have captured a proportion of forest conversion not representative for all regional forest land.

[53] The rate of SE forest area affected by insect infestations dropped from 3.98% yr^{-1} to 2.8% yr^{-1} (1.01 million ha yr^{-1}) between 1986–1997 and 1997–2005, respectively (Figure 3c). Infestations of Southern Pine Beetle (SPB) account for 94% of the 1997–2005 insect infestations. SPB

endemic to the native pines in the southern region, with a 100% mortality rate in infected host trees. In 1995, epidemic levels of SPB infested 4.16 million ha of forest in the SE region [*USDA*, 2000]. In the southern region, an SPB "outbreak" is defined as the number of hectares of a host tree species having *one or more* locations with multiple trees infected per 405 ha (1000 acres). If the lowest density of infestation is assumed, then in 1995, across the affected 4.16 million ha of forest infected, there may have been only 10,271 locations with multiple trees that died, or an average of 0.24 trees per ha that died per outbreak spot (assuming 100 trees per "spot"). The regional rate of forest area affected by insects in ADS data spike in 2000–2002, due to intense SPB outbreaks in northern GA and north west SC [*USDA*, 2005]. Overlay analysis found no coincidence between timing and location of spikes in NAFD canopy change rates and counties with hotspots of SPB outbreaks.

[54] An average of 0.54% yr^{-1} of SE forest land burned (0.13 million ha yr^{-1}) between 1988 and 1997 according to USFS data [*Birdsey and Lewis*, 2003]. The MTBS annual forest fire rate is 0.004% yr^{-1} to 0.006% yr^{-1} between 1986–1997 and 1997–2005 (Figure 3b). Differences in accounting for prescribed burns may account for some of the differences between MTBS and USFS forest fire estimates in the region (see section3.1.1).

[55] Eleven major hurricanes made landfall in the SE region between 1984 and 2008 (Figure 5). Using overlay analysis in the geodatabase of change processes and the 2001 NLCD land cover data for a forest mask, we calculated an annual average of 0.13% of SE forest area (45,484 ha forest yr^{-1}) was *exposed* to major tornadoes/hurricanes between 1984 and 2008. Seventeen percent of the forest area exposed to major wind storms suffered more than one storm event during the period. In 1989, hurricane Hugo made landfall on South Carolina's coast and the center of NAFD sample p16r37. The total forest area affected by hurricane Hugo, 1.8 million ha of South Carolina's forest, is six time times larger than the forest area affected by Mt. St. Helens and the Yellowstone fires combined [*Saveland and Wade*, 1991]. The NAFD change rate in p16r37 increased nearly 400% between 1989 and 1991, equal to 118,130 ha of forest disturbance. NAFD sample p16r36 to the north also shows anomalous rates in the year of and after Hugo (Figure 6c). Between 2001 and 2004, four hurricanes crossed the boundaries of NAFD sample p16r41, which had elevated NAFD disturbance rates for those years. However, more ground reference data are needed to fully attribute areas of NAFD mapped canopy change to wind-related mortality in areas of wind storm events.

3.2.4. SC

[56] NAFD change rates for the SC region were the highest across the nation, equal to a median forest replacement rate of 60 years, and 24% greater than the FIA annual disturbance rate of 0.717 million ha of forest per year (Figure 3f). The decadal NAFD forest change rate increased 80% to 2.18% yr^{-1} of total SC forest area between the1985–1994 and 1995–2004 periods (Figure 3e). Trends in the magnitude and direction of change rates for individual change processes were mixed (Figures 3a–3d). Conversion and insect infestations rates, mostly from boring insects, decreased. The rate of forest fires increased slightly. The dominant share of canopy change according to regional statistics is due to harvest, which increased in average severity over time, though total area remained flat. The impact of rare catastrophic localized events, such as hurricane Katrina in 1999 which potentially damaged 2.03 million ha of Gulf timberland, also has dramatic effects on regional forests [*Forest Inventory and Analysis (FIA)*, 2005].

[57] NAFD samples within the SC region are notable for their high temporal and spatial variability (Figure 6d). Overlaying change process layers and NAFD change maps in the geodatabase suggest that fire, wind, and insect dynamics in the region may not be captured well due to NAFD sample locations. The ubiquity of harvest activity suggests that the NAFD "background" change rates were due to harvest disturbances. Also, large spikes in the disturbance rates were attributable to changes in local harvest regimes.

[58] Across the six CONUS regions, SC forests had the highest rate of total harvest, 3.0% yr^{-1} (1.5 million ha yr^{-1}) and of clear-cut harvests 1.3% yr^{-1} (0.71 million ha yr^{-1}) between 2000 and 2005 (Figure 3d). Between 1980–1990 and 2000–2005, the proportion of clear-cut harvests increased from 28% to 45% of all harvest activity (Figure 3d). Counties in the center and south center of Alabama and Mississippi had the highest intensity TPO cumulative rates of harvest volume removals (Figure 5). NAFD sample p24r37, which had the highest median and maximum annual change rates, lays directly over this area in Alabama. No clear trend emerged across counties when TPO surveys were mapped at their nominal 5 year intervals.

[59] The change rates in two NAFD samples, p26r36, in southeast Oklahoma and its southern p26r37, stand out (Figure 6d). From 1997 to 2000, the annual disturbance rates in p26r36 and p26r37 spiked to 5.4% and 4.5% of total forest area in the scene, 300% above their respective 20 year means. These rates translate to 0.274 million ha and 0.115 million ha of disturbed forest land in p26r36 and p26r37, respectively, over the three year period. Only TPO records were coincident in space and time with NAFD mapped canopy disturbances in counties with the highest increase in NAFD rates (Pushmatah, Le Flore, and McCurtain counties in southeast OK). For these counties, TPO harvest removal volumes changed (−) 7%, (+) 114%, and (+) 39%, respectively, between the 1997–2002 and 2002–2007 surveys. The USFS alerts TPO data users that mills may be reporting receipts and processing of timber that was logged across county and state lines. We visually inspected the Landsat time series imagery of p26r36 and p26r37 using methods similar to those in *Cohen et al*. [2010]. The high severity and regular geometrically shaped patterns in NAFD mapped patches of canopy loss were consistent with harvest events. To further investigate, we contacted Kurt Atkinson, the assistant Oklahoma state forester at the time. His office had also noted large increases in harvested forest area and suggested rising regional timber prices, local increases in demand and capacity due to the opening of new chip and stud mills, and real estate exchanges by Weyerhaeuser as reasons for the increase in local harvest activities (K. Atkinson, personal communication).

[60] NLCD forest conversion rate declined across the 1992–2001 and 2001–2006 observations, from 0.07% yr^{-1} (31,070 ha yr^{-1}) to 0.034% yr^{-1} of total forest, respectively. The NRI 1987–1997 forest conversion rate was much higher, 0.17% yr^{-1} of SC forest land per year [*Birdsey and Lewis*,

2003]. Spatially clustered locations of large population centers and areas of increased housing density generally do not fall within NAFD sample boundaries.

[61] There was a decrease in the rate of forest annually affected by insect infestations between 1986–1997 and 1997–2005, respectively 6.67% yr^{-1} (3.3 million ha yr^{-1}) to 3.77% yr^{-1} of SC forest land (Figure 3c). All infestations are attributed to SPB. SC counties reporting high numbers of SPB spots between 1991 and 2004 do not fall within the boundaries of NAFD samples [*Williams and Birdsey*, 2003].

[62] MTBS forest fire rates increased from an annual average of 0.01% to 0.03% (15, 000 ha yr^{-1}) over the 1986–1997 and 1997–2005 periods (Figure 3b). *Birdsey and Lewis* [2003] report annual forest fire rates of 0.36% of total SC forest area (1988–1997) (Figure 4a). Prescribed burns are used widely across the south in silviculture management [*Haines et al.*, 2001], but MTBS may not record as many prescribed burns as the USFS data (see section 3.1.1). The mismatch of locations of moderate to severe MTBS fires in the SC region and NAFD sample locations suggests fire did not contribute largely to NAFD disturbance rates across the region. Selecting from the geodatabase for MTBS fires of moderate to severe intensity, which occurred on NLCD forest cover, and within the spatial and temporal boundaries of NAFD samples, yielded few results. One match was an unnamed fire in southeast OK that occurred in March 2004, but the timing of NAFD disturbance in the same location differed by 9 years. In the second match, the HEE MTN II fire of August 1998, NAFD disturbance had 100% spatial agreement with MTBS data, but were labeled as occurring in 1999.

[63] Seven major (H3–H5) hurricanes hit the SC coast between 1984 and 2006, including hurricane Katrina (Figure 5). If the area of timberland potentially damaged by hurricane Katrina is annualized over the 1984–2006 period, the result is 84,791 ha yr^{-1}; however, the timberland area affected covers a wide spectrum of severity from 3 to 67% of over story trees being uprooted or otherwise damaged enough to die within one year [*FIA*, 2005]. Using the buffered hurricane and tornado layers and the 2001 NLCD retrofit data as a forest mask, we calculated that an annual average of 0.19% of SC forest land (93,008 ha yr^{-1}) was *exposed* to extreme wind storms. NAFD site p21r37 in southern MS overlaps spatially with the severe hurricanes Helen (1985), Ivan (2004), and Katrina (2006). However, the time window of imagery used for the NAFD sample (1985–2004) excluded the possibility that NAFD captured wind-related forest mortality from the latter two storms.

3.2.5. IW

[64] The IW has the largest area of forest land of all regions (58.6 million ha), and it has the least timberland (highly productive forests), the most publically owned forest land, and the most forestland reserved from harvest activities across the CONUS regions [*Smith et al.*, 2009]. FIA and NAFD estimate similar amounts of forest land disturbed annually, 0.82% yr^{-1} (0.482 million ha yr^{-1}) and 0.91% yr^{-1} of IW forest land, respectively (Figure 3f). Across decades, NAFD forest history maps can also resolve an increase of 170%, from 0.49% yr^{-1} to 1.33% yr^{-1}, in the average annual disturbance rate (Figure 3e). The disturbance profile, or proportion of IW forest area affected by each change process, is noticeably different from other CONUS regions. The rate of the three major change processes, fire, harvest, and insects increased through time, as did the average severity of the processes (Figures 3a–3d). Overstocking, related to fire suppression and selective harvesting, combined with prolonged droughts in the IW region have contributed to epidemic insect and fire levels that are among the highest in recorded history [*Raffa et al.*, 2008].

[65] Large spikes in the NAFD disturbance rates, for 10 of the 13 NAFD IW samples, fall between 1999 and 2002, suggesting that a region-wide disturbance process was occurring at that time (Figure 6e). Fire reference data converge in space and time with NAFD mapped canopy mortality events and corresponding spikes in disturbance rates. The "background" NAFD disturbance rate in the region is minimal. Forest blow down occurs in montane and subalpine forests throughout the west, but no systematic geospatial data exist for these wind events or related windthrow (uprooting of trees) [*Peet*, 1981].

[66] Less forest area was harvested in the IW then any other CONUS region (Figure 3d.) Harvest rates increased from 0.24% yr^{-1} to 0.37% yr^{-1} (0.22 million ha yr^{-1}) between the 1980s and 2000s epochs. The rate of clear-cut harvest increased also, from 0.08% yr^{-1} to 0.14% yr^{-1} of total IW forest land. Mapped TPO cumulative harvest removals (1997–2005) show more harvest activity in the densely stocked and productive forest lands in the northwest of the region (Figure 5). The disturbance rates in NAFD samples that overlay these productive forests, p42r29 and p42r28, have a higher median and lower coefficient of variance than rates from NAFD samples in other parts of the region. These statistics, suggesting continuous high disturbance, do not hold for NAFD sample p41r29 whose boundaries overlay highly productive forests, but which has the highest amount of forest land reserved from harvest of all NAFD samples.

[67] Forest conversion affected IW forests the least of any the CONUS regions. NLCD forest conversion estimates of 0.005% yr^{-1} between 1992 and 2001 dropped to 0.001% yr^{-1} between 2001 and 2006 (Figure 3a). The NRI 1987–1997 forest conversion rate is 0.17% yr^{-1} (7284 ha yr^{-1}) of SC forestland per year [*Birdsey and Lewis*, 2003]. Spatially clustered locations of large population centers and areas of increased housing density generally did not fall within NAFD sample boundaries.

[68] Overall, there was an increase from 1.64% yr^{-1} to 1.81% yr^{-1} (1.01 million ha yr^{-1}) of IW forest land affected by insects (Figure 3c). The abundance, location, and type of insect activity varied widely through time across the region. Epidemic outbreaks of Western Spruce Budworm (WSB), a defoliating insect, peaked in NM in 2001, in ID by 2003, and in MT by 2005 [*USDA*, 2009a]. The total forest area affected annually by WSB was down 300% between the 1986–1997 and 1997–2005 periods [*USDA*, 2009a]. Piñon Ips Bark Beetle, a boring insect that kills pines across the southern IW region, reached epidemic levels for the first time in 2001 and has since been causing unprecedented levels of mortality [*USDA*, 2009a]. Mountain pine beetle (MPB) is a boring insect that primarily kills pines in the northern part of the IW region. Forest area affected by MPB peaked in 1980–1981, dropped to levels common with endemic population counts through the 1990s, and was increasing to record high levels again, with 2.3 million ha affected in 2005 alone [*USDA*, 2009a]. In general, NAFD biennial results do not pick up

low to moderate severity/density or slow onset disturbances, so it is unlikely that insect damage contributed to the NAFD disturbance rates regardless of the overlap between NAFD sample locations and insect activity (see section 3.1.2).

[69] The MTBS annual rate of forest fire increased substantially from 0.09% yr^{-1} to 0.32% yr^{-1} (0.174 million ha^{-1}) between the 1986–1997 and 1997–2005 periods, respectively (Figure 3b). The area of high and moderate severity forest fires increased 260% and 330% above the area between the 1986–1997 and 1997–2005 periods, respectively. MTBS estimates of burned forest area are two orders of magnitude less than those reported in *Birdsey and Lewis*, 2003 between 1998–1997 (Figure 4a). Sharp spikes in NAFD annual disturbance rates match well with the location and timing of moderate to severe MTBS fires. For example, the Galena fire (1988), and the Corral Creek-Blackwell Fires (1995) occurred in the same location and time as spikes in the NAFD disturbance rates for p33r30 and p42r29, respectively. Spatial and temporal overlay suggest the Eureka and Sadler fires in 1999 spiked the disturbance rate in p41r32 to 11% of the total forest area (equal to 3540 ha) for that year. In 2000 and 2001, the high severity Diamond Peak, Flossie, Clear Creek, Salmon Challis, and Snowshoe fires occurred within the boundaries of NAFD sample p41r29. NAFD disturbance rates spike to 33,220 ha, or 3.4% of the total forest area in the sample, disturbed in both 2000 and 2001.

3.2.6. PAC

[70] The PAC NAFD change rate, 1.09% yr^{-1} of total forest land, was 59% higher than the FIA disturbance rate, 0.64% yr^{-1} (0.220 million ha yr^{-1}) (Figure 3e). At decadal steps, NAFD average rates of forest change were nearly stable between 1985–1994 and 1995–2004 at 1.14% yr^{-1} of PAC forest land and 1.07% yr^{-1}, respectively (Figure 3e). Processes that increase or decrease in frequency and/or intensity through time can cancel over aggregated regional or decadal scales [*Harmon*, 2001; *Zheng et al*., 2011]. For example, a steep decline in harvest rates occurred in wet productive forests along the west coast during the 1990s, and severe insect and fire affected area in the dryer inland forests increased during the latter part of the time series. Historical inventories suggest the prevailing forest change processes in the region have been harvest, fire, and insect disturbance, though the quantities and average severity of each have changed through time (Figures 3a–3d). Blowdowns also affect PAC forests, but little geospatial data exist on wind storms in the region [*Franklin et al*., 1987].

[71] High spatial variability of forest land ownership, type, and location affect the forest dynamics in the PAC region (Figure 2). At landscape scales, the amount of forest land between the PAC NAFD samples and annual disturbance rates within the samples varied widely (Figure 6f). Large shifts in land management goals, beginning in the late 80s, affected harvest regimes on private lands [*Wear and Murray*, 2004], dramatically decreased harvest quotas on federal lands (60% of all PAC forest land) [*Williams et al*., 2007] and timber processing capacity [*Collins et al*., 2008], and culminating in the 1994 Northwest Forest Plan (NFP). The overall effect of these changes on harvest regimes was evident in coarse-scale inventories, but not the finer geographic patterns. NAFD forest history maps capture localized examples of changes in harvest and fire frequency. Disturbance rate spikes in individual NAFD samples were most attributable to fire events.

[72] The PAC is the only region to show a decrease in the total area harvested through time. The 1997 FIA inventory showed a 40% decrease in harvest removal volumes compared to a decade earlier. The annual rate of forest harvest dropped from 1.4% yr^{-1} (513,951 ha yr^{-1}) to 0.38% yr^{-1} of total PAC forest land between the 1980s and 2000s (Figure 3d). The percentage of clear-cut harvest area rose from 35% to 46%. In NAFD sample p48r27, which includes the forests in and around the Olympic National Park, NAFD forest history map resolved increases in the canopy change rates on private forest lands and decreases in the disturbance rate on public forest lands after the NFP [*Huang et al*., 2011; *Pierce et al*., 2005]. In Oregon and Washington, mapped county level TPO data had decreasing harvest removals in counties bordering the coast and increasing harvest removals in counties further inland between the 1997 and 2002 reports. PAC TPO data are only post NFP.

[73] There were nominal amounts of forest land conversion to suburban/urban use in the PAC region. According to NLCD, the conversion rate between 1992 and 2001, was 0.018% yr^{-1} of total PAC forest land dropping to 0.005% yr^{-1} (1448 ha yr^{-1}) between 2001 and 2006 (Figure 3a). Hotspots of forest conversion in the region did not fall within the boundaries of NAFD samples. The NRI estimated rate of conversion was an order of magnitude higher at 0.06% of PAC forest land per year between 1987 and 1997.

[74] The ADS annual rate of forest area affected by insects decreased from 3.24% to 1.81% (0.66 million ha yr^{-1}) of PAC forest (Figure 3c). Infestations of insects with lower mortality rates, such as WSB (defoliator), dropped while epidemics of boring Bark Beetles increased between the 1986–1997 and 1997–2004 periods [*USDA*, 2005]. Although NAFD sample locations overlay patches of spruce budworm epidemic, the NAFD forest history maps do not systematically catch related insect damage to tree canopies.

[75] The MTBS forest fire rate increased from 0.10% yr^{-1} to 0.18% yr^{-1} (67,163 ha yr^{-1}) of total forest area between the 1984–1996 and 1997–2005 periods (Figure 3b). The area of high severity fires more than doubled between the two periods. The USFS rate reported in *Birdsey and Lewis* [2003] for the 1988–1997 period is 0.54% yr^{-1} of forest land in the PAC region (Figure 4a). Large severe fires occurred within the boundaries of 10 of the 13 PAC NAFD samples. Spikes in NAFD forest change rates correspond to the timing and location of many of these severe fire events, such as the Pines fire in sample p40r37, the Biscuit fire in sample p46r31, and HashRock, Flagtail, and Tamarack Creek Fires in p44r29 (Figure 6f). Many other fires fall outside NAFD sampling scheme.

4. Conclusions and Next Steps

[76] Information of the location, timing, type, severity, and regrowth rates of forest disturbances over time cycles that are longer than cyclical climate, political, and economic cycles are necessary [*Birdsey et al*., 2009; *Kurz*, 2010; *Pacala et al*., 2007]. This paper establishes recent regional trends for major forest change processes including fires, insect infestations, harvests, wind storms, and conversion to

suburban/urban, with severity measures, through time across the CONUS. We present a better geographic model of forest disturbance and conversion history across the CONUS with an integrated geodatabase of canopy change processes. Together, this suite of data tells a more complete narrative of local through regional forest disturbance and conversion. Combining empirical observations from NAFD forest canopy change, historical inventories and geospatial data on change processes is a first step to linking the spatial-temporal dynamics of forest disturbance and their underlying processes.

[77] The regional rates of forest area affected by major change processes varied greatly between processes and for each process through time. Harvest was the most widespread canopy change process in the CONUS, with rates that increased through time in all regions except the PAC. However, harvest data had the poorest spatial and temporal resolution limiting quantitative analysis. Improved geospatial characterization of all harvest activities including repeat harvests and sanitation and salvage logging events (before and after natural disturbances) is necessary to better interpret observations and the end state of remote sensing canopy cover changes products. Rates per process varied greatly by source in the case of fire with possible implications for downstream applications.

[78] Overlapping time and location specific change events and coarse-scale statistics for multiple forest change processes and canopy observations revealed strengths and weaknesses of each data set. The dynamics of the multiple processes affecting forests in a region were confounded by regional estimates of canopy change, highlighting the need for landscape level interpretation and observation of forest canopy change. More work is needed to estimate the area of overlap of individual forest change processes through time such as wind storms, fire, and insects.

[79] Integrating data on multiple causal processes and NAFD forest history maps, helped in some cases to expose the underlying forest change processes that caused sharp "spikes" and consistent "base" NAFD disturbance rates. Natural disturbances, such as hurricane Hugo, *Derechos* in northern Minnesota, and fires across the IW and PAC regions, as well as anthropogenic disturbances, such as volatile harvest regimes in SE Oklahoma and western Washington, caused dramatic increases in mortality rates. In some cases, the area of mortality related to frequent small disturbance events, which contribute to the background or "base" NAFD disturbance rate, dwarfed that of large infrequent disturbances. For example, between 2001 and 2006, the area of timberland harvest was almost four times (370%) larger than the area of timberland damaged by hurricane Katrina in 2005 [*FIA*, 2005; *Smith et al.*, 2009]. In the IW and PAC regions, the annual rate of forest affected by harvest was higher than by forest fires. Not all spikes in NAFD change rates could be attributed to a causal process, and better data are needed to characterize the dynamics of forest change processes captured within NAFD "base" rates.

[80] This geodatabase is only a first step and can be improved through updating as new data become available, inclusion of empirical observations of change events from regional and local studies, and improved measures of uncertainty and severity [*Kasischke et al.*, 2013]. For example, tree level estimates of forest mortality from wind storms [*Negron-Juarez et al.*, 2010] and bark beetles [*Meddens et al.*, 2013] would be improvements over the simple calculations used in this study. VCT disturbance magnitude products, which were not used in this study, could help address the need for continuous measurements of mortality in disturbed areas.

[81] Due to small sample sizes, small and the high spatial heterogeneity of underlying causal processes, the dynamics of some key regional processes, such as increasing harvest in the NE region, and large catastrophic events, such as hurricane Katrina and the Yellowstone fires were not captured in NAFD estimated disturbance rates. NAFD, as a core project part of the North American Carbon Program, is currently conducting a wall-to-wall annual analysis of forest disturbance across the CONUS (1985–2010). Wall-to-wall monitoring would ensure that stochastic events, which can greatly affect carbon fluxes at the national and regional levels, are captured and eliminate biases due to the underlying spatial heterogeneity of causal processes [*Masek et al.*, 2013].

[82] Data gaps, mismatched definitions, and coarse resolutions of available ancillary geospatial data for individual forest change processes prohibited robust attribution of underlying causal processes to NAFD observed canopy change events. An active area of research for NAFD is using an empirical modeling approach to attribute causal process to NAFD mapped canopy change. Rather than using extant process data as declarations of "truth," the process data, along with temporal, geometric, magnitude, and topological metrics, will be used as predictor variables in empirical models. The layers in the disturbance and conversion geodatabase will be used to construct spatial and temporal proximity metrics for the major canopy change processes. Attributing causal process to national NAFD forest history maps has the potential to advance nationwide estimates of the area wind damage and harvest across US forests, and estimates of the variability through space and time among major forest canopy change processes.

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