ABSTRACT

Title of Document: TOWARDS A BETTTER UNDERSTANDING OF FOREST CHANGE PROCESSES IN THE CONTIGUOUS U.S.

Karen Schleeweis, Ph.D. 2012

Directed By: Dr. Samuel N. Goward, Department of Geography

Estimates of forest canopy areal extent, configuration and change have been developed from satellite based imagery and ground based inventories to improve understanding of forest dynamics and how they interact with other earth systems across many scales. The number of these types of studies has grown in recent years. Yet, few have assessed the multiple change processes underlying observed forest canopy dynamics across large spatio-temporal extents. To support these types of assessments, a more detailed and integrated understanding of the geographic patterns of the multiple forest change processes across the contiguous US (CONUS) is needed.

This study examined a novel data set from the North American Forest dynamics (NAFD) project that provides a dense temporal record (1984-2005) of forest canopy history across the U.S., United States Forest Service (USFS) ground inventory data, and ancillary geospatial data sets on forest change processes (wind, insect, fire, harvest and conversion to suburban/urban land uses) across the CONUS to develop a more robust understanding of the implications of the shifting dynamics of forest change processes and our ability to measure their effect on forest canopy dynamics. A geodatabase of forest change processes was created to support synoptic and specific quantitative analysis of change processes support through space and time. Using the geodatabase, patterns of forest canopy losses from NAFD and USFS data and the underlying causal process were analyzed across multiple scales.

This research has shown that the overlap of multiple disturbance processes leads to complex patterns across the nation's forested landscape that can only be fully understood in relation to forest canopy losses at fine scales. Regional statistics confounded the direction and magnitude of forest canopy loss from multiple change processes operating on the landscape. Data gaps and uncertainty associated with process data prevent a full quantitative analysis of the proportion of forest area affected by each forest change process considered here. Fine scale data were critical for interpreting the highly variable NAFD canopy change observations and their ability to capture the continuously changing spatial and temporal characteristics of forest change processes across the CONUS.

TOWARDS A BETTER UNDERSTANDING OF FOREST CHANGE PROCESSES IN THE CONTIGUOUS US

By

Karen Schleeweis

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
Of the requirements for the degree of
Doctorate of Philosophy
2012

Advisory Committee:
Dr. Samuel N. Goward, Chair
Dr. Chengquan Huang
Dr. Ralph Dubayah
Dr. Jeffrey G. Masek
Dr. Bill Fagan

Dedication

To my grandmom, Grace Marini DiPietro, who helped instill in me a deep love and appreciation for craft and creating, and always provided an example of what can be accomplished through hard work, determination, pig-headed tenacity, and the support of a loving family. (1914-2012)

Acknowledgements

Without my lovely family and friends, I'm not sure if I would have gotten to the end of this thesis, but I am absolutely sure that life wouldn't have been so great along the way. To Enrique, thank you for reminding me along this journey, even on days that I was not receptive, about the importance of laughter and perspective. You add an anchor of reality and a balloon of surreal absurdity to my life that I treasure. Milena, our baby girl, maybe you were the spark that shifted me into sixth gear? You've been growing inside me through the writing of the dissertation, losing Grace, the defense, the wedding, and maybe (?) the graduation. Thank you for constantly reminding me to keep my eye on the finish line and making the last 8 ½ months so special. I hope I can be for you what my Mom has been for me. Many thanks to my Mom and Dad, who instilled a work ethic in me that has helped me through all of my 'career' choices and taught me many lessons on acceptance and tolerance.

I'm not sure I can acknowledge all the contributions from my advisor, Dr. Sam Goward. Like a good story that you keep drawing from long after you've read it the first time, his mentorship is of the sort that will continue to give and guide throughout the rest of my career. I hope one day that I have such good conversations with my own students and that the deep currents of curiosity and wonder for Earths' systems continues to lead us both on paths that we enjoy so much. I would also like to thank the rest of my committee, Dr. Chengquan Huang, Dr. Ralph Dubayah, Dr. Jeff Masek and Dr. Bill Fagan for your patience and for generously sharing your time, experience and expertise.

I am extremely grateful for the opportunity that I have had to grow professionally and personally within the North American Forest Dynamics (NAFD) project. This research was supported under NAFD project grants from the North American Carbon Project. The unique scope, vision and duration of the NAFD project have been a source of constant learning. Technical conversations and thoughtful feedback with NAFD colleagues was invaluable. I am particularly grateful to Dr. Gretchen Moisen, Dr. Warren Cohen, Dr. Robert Kennedy, Dr. Jeff Masek, Dr. Chengquan Huang, Khaldoun Rishmawi and Nancy Thomas for their support and inspiration. Many thanks also to those who shared their data and expertise on US Forests including Brad Smith, Tony Johnson, Micah Thorning and Mark Nelson.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Forests are an integral element of land surfaces affecting earth systems across many scales. Covering about 30% of the planet, forests modulate water, energy, and nutrient fluxes between the biosphere, hydrosphere and atmosphere [*(FAO)*, 2001]. Change is a central element of forest systems. Succession, disturbance, mortality and growth, are natural parts of forest land dynamics. These dynamic processes are reflected in the structural components of forests. Anthropogenic disturbances and conversion also strongly affect forest distribution and structure. To understand the influence of forests on earth systems, local forest change dynamics, as well as the underlying causes of these changes, must be better described [*Burnett and Blaschke*, 2003].

Explanations of the role of forest land dynamics in Earth systems are complex because coincident processes, at multiple levels of organization with cross-scale interactions and feedbacks, are driving both abrupt and extended trends within the landscape [*Allen and Star*, 1982; *Wu and Loucks*, 1995]. Simultaneously, many forest processes are changing forest structure at different scales (Figure 1-1). For example, forest ecosystem composition and distribution are constrained by slow continuous geomorphic processes and climate at regional scales (up to 1000's km^2). At small scales (<1 ha), individual tree growth and mortality are constrained by microclimatic and environmental gradients and genetics. In between, at local landscape scales involving stands of trees, changes in structure and age distribution have been coupled for millennia with natural disturbance processes such as episodic storms and lightning-ignited fires and cyclical pest and disease outbreaks [*Barnes et al.*, 1998]. Where human populations are present, volatile markets, policy, and culture impose additional changes on forest stands, through forestry management and conversion to other land uses [*Drummond and Loveland*, 2010]. There is increasing evidence that landscape level forest change is more strongly related to disturbance processes than to changes of local environmental conditions [*Ohmann et al.*, 2007].

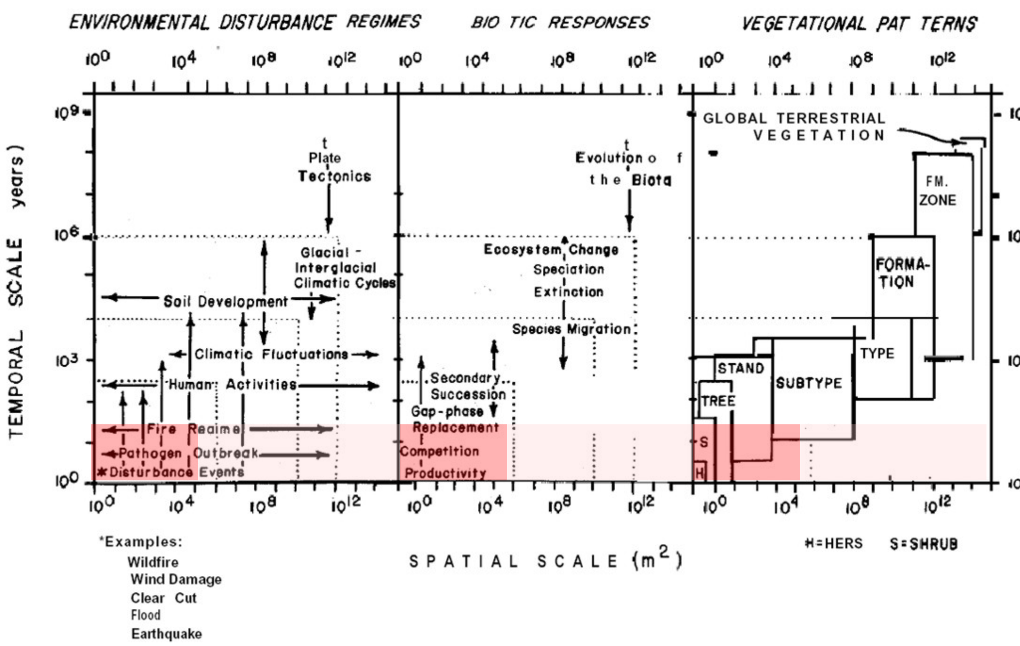


Figure 1-1 The resolution of forest change processes from Delcourt and Delcourt ([1988] overlaid with red boxes showing the lower and upper bounds Landsat class observations. With the free release of the Landsat imagery archive there has been a dramatic increase (overlaid with light pink boxes) in the spatial extent of what is feasible to observe with Landsat imagery [*Woodcock et al.*, 2008].

1.1. Observations and Understanding of Forest Dynamics

Understanding of the patterns of forest distribution, composition, arrangement, and how they change through time, are reliant on our capacity to observe and analyze these phenomenon. Observations of pattern are inherently scale-dependent, so the scale of the observation must be commensurate with the scale of the process [*Levin*, 1992] [*Wu and Loucks*, 1995] . Forest change processes can be abrupt and discrete (i.e. suburbanization, wind storms) or subtle and continuous (i.e. drought, desertification, growth) through time. Fine scale data at broad temporal and spatial extents are necessary to draw generalizable trends from localized forest change events.

As our ability to observe *and* analyze evolve, so does our understanding of forest land dynamics. Until the late 20^{th} century, forest disturbances events were only observable through ground observations and field studies based in local space and time. Early studies of forest systems were primarily concerned with forest succession processes of equilibrium communities [*Clements*, 1916]. However, attention on the heterogeneity or variability of disturbance and related legacies within the forest landscapes grew which led to new understanding of the significance of the role of disturbance processes [*Pickett and White*, 1985; *Sousa*, 1984; *Watt*, 1947]. New theories such as intermediate disturbance theory [*Sousa*, 1979] and island biogeography [*MacArthur and Wilson*, 1967] ushered in a new wave of thinking for land based studies [*Wu and Loucks*, 1995]. Broad scale national inventories recently revealed the nationwide extent of young forest [*Lorimer*, 2001; *Masek et al.*, 2008; *Pan et al.*, 2010; *Trani et al.*, 2001]. These observations have fueled initiatives to better understand the spatial and temporal dynamics of localized forest change using moderate resolution remote sensing products and newly developed algorithms to detect forest change [*Goward et al.*, 2008].

1.1.1. Field Studies

Field based studies, because of their ability to focus at the fine scales where the most dynamic forest change processes are occurring, are excellent for exploring the spatio-temporal context of canopy change and the underlying causes and the effects on local species, hydrology, nutrient cycling and biodiversity [*Amiro et al.*, 2010; *Busing and White*, 1997; *Clinton*, 2003; *Laiho et al.*, 2003; *Papaik and Canham*, 2006; *Peterson and Pickett*, 2000; *Sun et al.*, 2001; *Tarrega et al.*, 2006]. Observations from many individual change events can be aggregated to construct characteristic 'regimes' for a single process based on the frequency, extent, severity of events, and the related predictability and exposure to future damage [*Pickett and White*, 1985]. The synthesis of local observations of change from multiple studies has been done for many individual forest change processes, such as fire [*Oliver and Larson*, 1990; *Schoennagel et al.*, 2004a; *Stanturf et al.*, 2002; *Stephens*, 2005], windstorms [*Everham and Brokaw*, 1996], pests/pathogens [*Gibbs and Wainhouse*, 1986; *Haack and Byler*, 1993], exurban growth [*Stein et al.*, 2005], forestry [*Whitney*, 1994], or processes specific to a region [*Lorimer*, 2001]. Disturbance regimes have been compared through space with other region regimes, or through time, using the idea of a historical range of variability (HRV) to indicate shifting trends and to relate the changes to fluctuations in climate, management, and/or ecological functions [*Nonaka and Spies*, 2005].

However, field studies, with their unique local scales and differing methodologies, are problematic to use for observations and analysis of wide-ranging trends. In the contiguous US, a few long-term projects, such as Harvard (1200 ha) and Hubbard Brook (3160 ha) Experimental Forests, have been in operation for over 50 years. These cases are the exception to the rule. In lieu of fine observations over broad time and space one vein of research focused on meta studies, or grouping of individual field studies, to look for aggregate trends. Varying methodologies, and the limited extent of observations of field studies render generalizations across studies largely descriptive and inference and prediction difficult [*White and Jentsch*, 2001].

1.1.2. Statistical Ground Inventories

In the US, the need to record and understand the broad temporal and spatial trends in forest dynamics was addressed with national ground based statistical inventories. The US Forest Service (USFS) Forest Inventory and Analysis (FIA) unit has collected data since the 1940's on forest structural changes, timber volume and forest land area [*(USDA)*, 2003]. FIA statistical ground inventories provide data on the distribution of young forest stands that result from recent stand-clearing disturbance processes and afforestation (Figure 1-2). Data on land use and the changing distributions of forest land also come from the Natural Resources Conservation Service (NRCS) National Resource Inventory (NRI) [*(USDA)*, 2001].

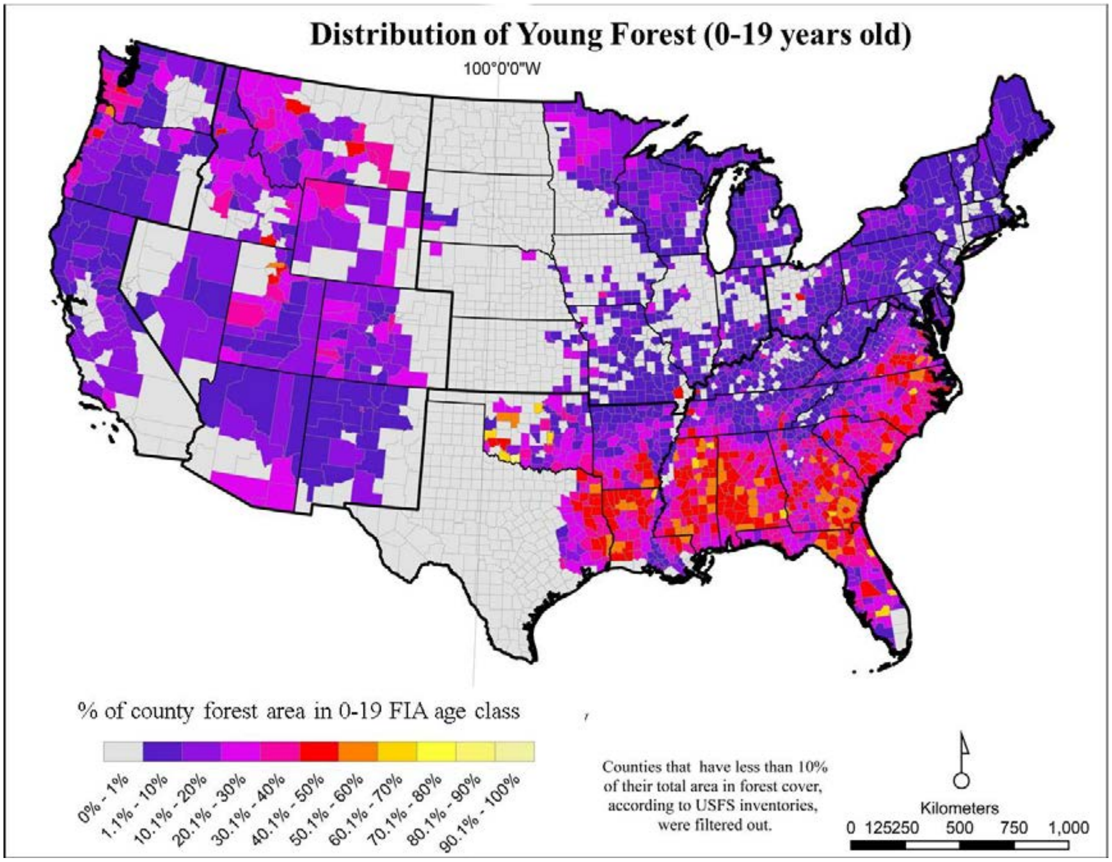


Figure 1-2 The spatial variability and large number of young forest stands across US counties, measured in FIA inventories, raises questions about the mechanisms and processes related to forest turnover. Tabular data was obtained from the FIDO FIA online tool [*(USDA), U S D o A*, 2010] and mapped in a GIS. Details on state specific inventories used are given in Appendix A.

Better characterization of the extent of young forest and changes in total forest land from national inventories has raised interest in better characterizing and quantifying the mechanisms and processes related to forest mortality and their implications. For example, the breadth and depth of the NRI and FIA decadal inventory data, have allowed for the first calculations of the impact of forest system dynamics from disturbance and land-use conversion on carbon flux at regional and national scales

[*Houghton and Hackler*, 2000; *Houghton et al.*, 1999; *Houghton et al.*, 2000; *Masek and Collatz*, 2006; *Pacala et al.*, 2007; *Song and Woodcock*, 2003; *Woodbury et al.*, 2007].

Some of the weaknesses of large-extent inventory data are that the observation methods have varied over time and between regional data collection centers and repeat measurements on the same tract of land are rare (before the beginning of annual surveys in 2000) [*Gillespie*, 1999; *USDA*, 2009]. These differences limit the use of inventory data for time analysis at local scales. Further, coarse resolution inventory methods are not designed to adequately capture spatially clustered or rare events, and therefore, have limited utility for analysis of processes with the spatial patterns characteristic of forest land disturbance and conversion [*Fisher et al.*, 2008].

1.1.3.Remote Sensing

The spatial resolution, temporal depth and extensive coverage of remotely sensed data offer a bridge between local studies and national inventories yielding landscape scale empirical data – needed to evaluate the processes and patterns of forest change [*Cohen and Goward*, 2004; *Fry et al.*, 2009; *Huang et al.*, 2010; *Masek et al.*, 2008]. The first images of earth from space literally changed people's perspective of Earth's land systems. The switch to digital data, which is easier to distribute, quantify and manipulate with computers, fortified the use of remote sensing for forestry applications. Remotely sensed observations, in the form of aerial photography, have been used by the US and other national forest services for nearly a half century, in support of their field inventory measurements [*Estes and Thorley*, 1983]. Now high to medium resolution sensors (aerial imagery, IKONOS, QUICKBIRD, Landsat, SPOT, LIDAR) are used to study forest structure, composition, and change [*Lefsky and Cohen*, 2003] . However, limited coverage and high data costs of high-resolution data have prohibited continental and national-scale analysis.

The advent of synoptic high temporal repeat digital coverage of the earth's surfaces from satellite imagery provided another avenue for estimating the extent and location of forest cover and forest type with products that improved in spatial resolution over time. For example, the first digital maps of global land cover were derived from the AVHRR sensor [*DeFries et al.*, 1995]. For the first time in history, near the end of the twentieth century, area estimates of all US forest land cover were available from data other than ground observations, at 30m resolution for the nominal year of 1991 from Landsat observations [*Vogelmann et al.*, 2001]. Information on forest characteristics from satellite data were enriched when the US forest group types were mapped from AVHRR data at a 1km spatial resolution in the early 90's[*Zhu and Evans*, 1994]. Ten years later the spatial resolution of the US forest type map was refined four fold using USFS inventory and MODIS imagery [*Ruefenacht et al.*, 2008].

Since remote sensing data has become widely available our awareness and capability to characterize the changes occurring on the earths land surfaces at salient scales has increased. Beginning with Landsat I in 1972 satellite observations have provided seasonal to yearly updates of land characteristics and conditions at spatial resolutions of 1 hectare or better [*Goward and Williams*, 1997]. This level of spatio-temporal detail supplies the information needed to detect individual forest disturbance events as well as monitor recovery or land changes that follows these events (figure 1-3) [*Aldrich*, 1975]. Without this temporal resolution, 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 these 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]. Due to different temporal and spatial measurement scales, definitions, and observation and analysis methods estimates of forest area and the rate of forest vary (Table 1-1). There currently is no systematic or operational methodology for observing or quantifying forest canopy changes across broad time-space regions.

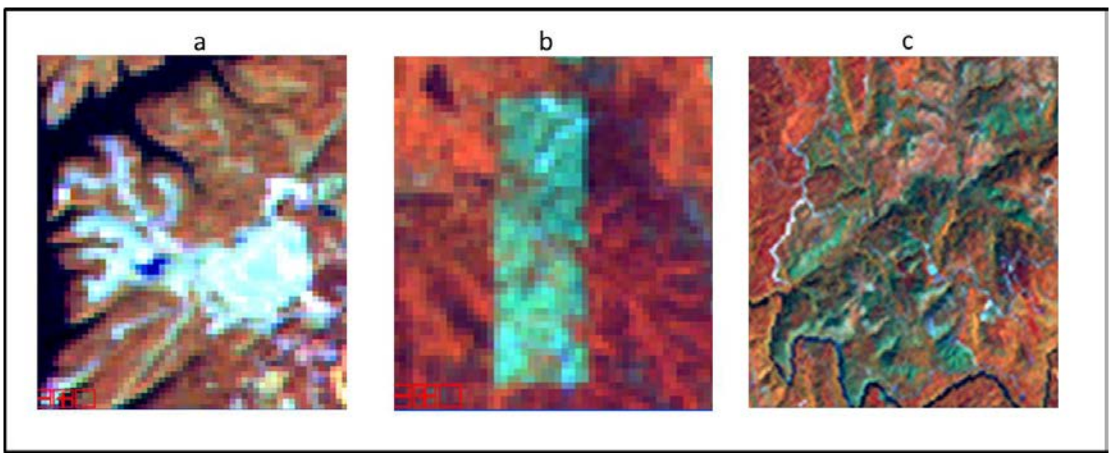


Figure 1-3: Data from the Landsat family of sensors are acquired at the scale of the forest change processes (Figure 1-1), permit detailed assessments of spatial and temporal patterns, and clearly show the evidence of disturbance processes. Patches of forest change caused by various types of forest change processes, including (a) clearing for housing developments (b) logging and

(c) fire are visible in these subsets of Landsat imagery.

Table 1-1: Variability in the estimated forest area and area changed stemming from different methodologies, scales and definitions. (* includes Hawaii and Alaska and Canada)

				Spatial		Temporal		Total Forest Land (millions ha)	National Change Rate
	Data Source	Forest Variable	Method of Collection	Grain	Extent	Grain	Extent		
Data Product	NAFD [Goward et al. 2008]	Discrete, forest canopy	Satellite	30m	sampled - national	biennial	1985-2004	255	1985-2004 East: 1.10% West : 1.05%
	MRLC Retrofit change data [Fry et al. 2009]	Discrete land use & land cover	Satellite	30 m	national	decadal	1992-2001	217.8	1992-2001 East: 5.4% West: 2.86%
	LEDAPS [Masek et al. 2008]	Continuous, forest canopy	Satellite	28.5 m	continental	decadal	1990-2000	X	1990-2000 East: 0.70% West: 0.22%
	USFS [Rufenbacht et al. 2008]	Discrete, forest type	Satellite and inventory	250m	national	annual	2001	259.1	X
	VCF [Popatov et al. 2009]	Continuous, forest canopy	Satellite	500m	global	annual	2001-2005	199.2*	2001-2005 East NA: 1 % West NA: 1.1%
	USFS [Smith et al. 2009]	Volume Harvested/ Processed	Modeling, Mill surveys & ground inventory	county	Sampled-national	decadal	2001-2005	249.8	West: 0.70% (Harvest only 2001-2005) East: 2.08%

However, remote sensing data alone cannot tell the full story of forest land use and disturbance history in the US [*Reams et al.*, 2010]. Optical sensors saturate and cannot distinguish between old growth forests and young forests with dense canopies [*Frolking et al.*, 2009]. Active sensors can tell us about the recent state of forests vertical structure [*Dubayah and Drake*, 2000; *Lefsky et al.*, 2002], but lack the coverage needed for regional or national assessments at fine scales. Climatic cycles that help drive many natural disturbance regimes (wind, fire and even insects and pests) and economic cycles that drive land use and harvest decisions can be longer than the Landsat data records [*Yu et al.*, 2010]. Finally, the ability to attribute the type of disturbance or conversion processes at work behind detected changes is still limited [*Kurz*, 2010; *Schroeder et al.*, 2011].

1.1.4. Process Specific Data

Although records of forest canopy changes have improved, records of the underlying processes and the ability to link the two together are still lacking. Reports on the annual amount of forest land with abrupt canopy structural changes caused by natural disturbances (fire, insects and storms), human-managed disturbances (harvest), and conversion processes (forest land converted for suburban/urban development) vary by reporting scales, definitions and methodologies (Figure 1-4). The vast majority of what we know about where and when wind, harvest, fire, and insect disturbances and conversions of land cover happen comes from ground observations on each of those processes. However, these observations often do not record important parameters for understanding the damage caused by each process to forest systems, such as the severity or land cover of the vegetation affected.

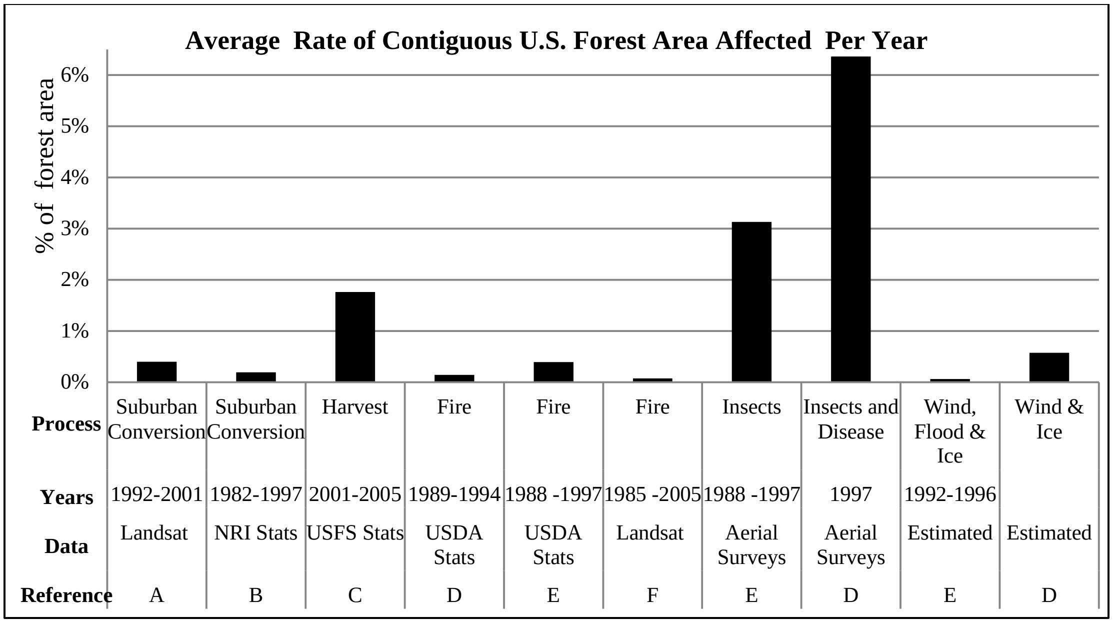


Figure 1-4: Estimates of annual rate of forest area affected by specific disturbance and conversion processes from previous studies. A=[*Fry et al.*, 2009], B= [*Alig et al.*, 2010], C=[*Smith et al.*, 2009], D= [*Dale et al.*, 2001], E= [*Birdsey and Lewis*, 2003], F= [*Eidenschenk et al.*, 2007].

1.2. Why understand Forest Dynamics

Where, when, how much forest canopy change occurs and the underlying causal processes is important for many applications in earth systems science and national/international bodies tasked with managing earth's resources [*Linke et al.*, 2007]. For example, carbon is not distributed evenly across the landscape, forest types or ages [*Turner et al.*, 1995], so changes in the Characterizing location, frequency, and severity of each forest change process may alter historical patterns of forest carbon sequestration and release [*Kurz et al.*, 2008; *Murray et al.*, 2000]. Furthermore, the carbon implications of different forest change processes vary greatly [*Frolking et al.*, 2009]. The spatial identification of carbon sources and sinks may be useful for place based mitigation in carbon management and policy [*Murray et al.*, 2000; *Zheng et al.*, 2011].

1.3. Research Goals

Debates in recent literature have highlighted the fact that no one data set can capture the full record of forest land use and disturbance history [Hansen et al., 2010; Potapov et al., 2009; Reams et al., 2010]. Due to the paucity of historic reference data on forest disturbance, there is no one dataset that can be referred to as the 'truth' regarding forest history [*Turner et al.*, 2001]. Combining multiple historic data sets and evaluating areas of convergence and divergence may be the only way to use imperfect and incomplete reference sources to interpret the results of current studies that reconstruct forest disturbance and conversion history. Currently, no previous study has attempted such an assessment across the contiguous US (CONUS).

This research synthesized forest inventory, remotely sensed, and geospatial data to reach a more unified understanding of how forest canopy dynamics and the underlying causal processes are changing through time and space. To accomplish this goal, the following specific research questions were addressed:

1. How has the amount of forest area affected by major disturbance and conversion processes changed through recent time across six US regions? (Chapter 2).

2. What are the geographic patterns of forest change processes (wind, fire, insects, harvest, and conversion to suburban urban lands) through time across the CONUS?

(Chapter 3)

3. Focusing within six US regions at local scales, can the causal processes responsible for observed canopy dynamics in forest history maps from the North American Forest Dynamics (NAFD) project be verified by synthesizing ancillary geospatial data sources? (Chapter 4)

Basic Approach:

1. Assemble statistics through time on forest land affected by major forest change processes for six CONUS regions.Examine the quality of the process statistics, specifically the strengths, limitations and assumptions of the different data sources.

2. Compare process statistics with observations of forest canopy change from the North American Forest Dynamics (NAFD) project and the USFS FIA.

3. Create a geospatial database of forest change processes including wind storms, insects, fire, and harvests, and suburbanization, for the contiguous United States.

4. Characterize the distribution of low, moderate and high severity forest change processes, and the overlap and uncertainty of these observations using the geodatabase.

5. Conduct a detailed within region analysis of the causes of forest change dynamics through space and time using NAFD forest history maps and inventory data (discussed in chapter 2) and the “process and uncertainty” geodatabase (created in chapter 3).

6. Identify areas where the convergence and divergence of multiple lines of evidence on forest change processes do and do not allow for ‘verification’ of causal processes underlying NAFD observations of canopy loss.

7. Investigate how the characteristics and quality of the data affect the ability to verify the relationship between observations of causal processes and forest change events in NAFD forest history maps.

Results of this thesis are summarized in the final chapter (chapter 5) along with the significance and future applications of this work. Parts of this thesis have been combined into a manuscript titled ‘Regional through Local Dynamics of Forest Canopy Change and their Underlying Causal Processes in the Conterminous US’, which was accepted to the Journal of Geophysical Research – Biogeosciences.

Chapter 2: Regional Rates of Forest Canopy Change and Underlying Processes

2.1. Introduction

The first trees evolved roughly 350 million years ago [*Barnes et al.*, 1998]. Since then, the composition and structure (spatial arrangement of parts) of forests have been changing. Dominant forest patterns visible today are related to processes of geological scales down to human scales and below. Change is a key element of forested systems because the processes that influence forest characteristics are themselves dynamic. Quantifying the rates (area affected over time) of change across large areas of forest land caused by different processes is important to support strategic national and regional level forest management decisions and to better understand forest land interactions with other earth systems.

The change processes that operate over human time and space scales, such as natural disturbances (wind and ice storms, fire and insects/disease), anthropogenic disturbances (logging) and land–use conversion (urban/suburbanization) can have beneficial and detrimental effects. Changes in forest structure and composition from disturbance and conversion have been related to biodiversity [*Hermy and Verheyen*, 2007], species distribution [*Hastings*, 2003; *Hermy and Verheyen*, 2007], evidence of past land-use [*Hermy and Verheyen*, 2007], forest health [*Raffa et al.*, 2008], carbon cycling [*Botkin et al.*, 1973; *Heath et al.*, 1996] , hydrology changes [*McNulty et al.*, 1996; *Sun et al.*, 2005; *Sun et al.*, 2001], nitrogen cycling [*Schoennagel et al.*, 2004b], air quality [*Weathers et al.*, 2001] and other ecosystem services [*(MEA)*, 2003].

Furthermore, each different type of change processes affects forest functioning, such as carbon sequestration, respiration, net primary production, in different ways [*Alberti*, 2005; *Foster et al.*, 1997; *Frelich and Lorimer*, 1991; *Frolking et al.*, 2009; *Sun et al.*, 2001; *Tarrega et al.*, 2006]. When the prominence of one or more local forest change processes varies through time it should be expected that the consequences on forest functions will also change. For example, the magnitude and distribution of forest carbon sinks and sources vary geographically depending on land use history and management, disturbance frequency and climate factors [*Amiro et al.*, 2010]. The lack of geographic data on related processes causes large uncertainty in national carbon flux estimates [*Pacala et al.*, 2007]. If the severity, frequency or extent of forest change processes vary over time, then the magnitude of sources and sinks of the North American carbon budget should also be expected to vary [*Murray et al.*, 2000].

The interest in forest land disturbance and conversion has increased with the realization that they are more widespread than first realized, thanks in part to the broad perspective that USFS statistical inventories provide [*Pan et al.*, 2010; *Trani et al.*, 2001]. However, the timing and amount of forest land affected by these processes is not well characterized. Estimates of forest area affected by different processes and are often dealt with as if the processes are static (figure 1-4). For example, the USFS estimates that an average 4 million ha ($9.9 * 10^6$ acres) forest land were harvested annually between 1952 and 1996, with 62 % of the total being partial harvests and

38% clear cut harvests [*Smith and Darr*, 2004].

There is a lack of integrative studies looking at data on the trends of forest change processes in conjunction with data on the trends of forest canopy changes. The most comprehensive study of the multiple processes affecting forest lands is from Birdsey and Lewis [2003] however, the data periods used in the paper end in 1997. The comprehensive nature of this paper was one of the inspirations for this work. Another was the impulse to understand how Landsat derived forest change history (1984-2004) could improve the understanding of recent forest canopy dynamics, that has largely come from USFS stand age estimates, and their causes.

The goal of this chapter is to explore both the dynamics of forest change - and the dynamics of multiple underlying causal processes through time and across 6 US regions. The six regions are derived from the historical boundaries used by the USFS to delineate forests of the Northeast (NE), North Central (NC), Southeast (SE), South Central (SC), Intermountain West (IW) and Pacific Coast (PAC) (Figure 2-1). Regional estimates of forest land affected by different processes through time are compiled from multiple sources. Forest canopy dynamics through time are compared, from USFS data and from forest history maps created by the NAFD project from Landsat observations. The dynamics of process specific forest canopy change are compiled from previous literature, various remote sensing products, USFS FIA ground inventories, mill surveys, and Forest Health Program (FHP) aerial detection surveys (ADS). Only publically available data on forest land area affected is used herein.

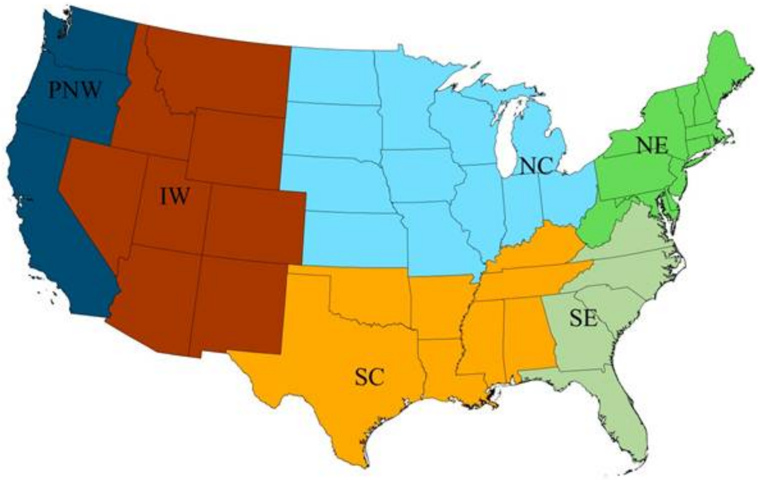


Figure 2-1: Outlines of the USFS historic regional boundaries used in this work and thestates they incorporate.

2.2. Terminology

There are many forest change processes that affect forest stands. Herein 'forest change' is used to only describe stand level forest canopy losses including temporary losses due to disturbance, and long-term losses (greater than two decades) due to conversion of forest to suburban/urban cover. A stand can be defined as a local sub-community of trees of sufficient uniformity of species composition, age, spatial arrangement or condition that it is distinguishable from adjacent stands [*Barnes et al.*, 1998]. The changes can be homogenous across the patch, implying that all trees were killed or removed and *if* the stand regrows it will be of even age trees, or a single age cohort. The changes can also be heterogeneous, as in the case of a partial disturbance where some older trees remain mixed with younger understory trees creating an uneven–aged distribution.

Disturbance events are considered with-in state changes, meaning they are temporary disruptions to canopy cover, but are assumed to recover. The USFS assumes that all harvested forest lands grow back, resulting in no net loss of forest land [*Smith et al.*, 2009]. Silviculture encapsulates a suite of forest management activities, including clear cut, partial and salvage harvesting, nutrient management, thinning, fire management, replanting of previously forested lands (*reforestation*), and planting of non-forest land (*afforestation*). Only reports of harvested merchantable timber are used as human-managed disturbance in this study.

Natural disturbances are herein limited to temporally abrupt events that cause stand level mortality and are climatically driven including, wind storms, fire, and insect outbreaks. Although fire is one of the primary mechanisms that man has used to dominate the landscape, in this paper, fire is considered a natural disturbance because one of the primary drivers is weather, regardless of the ignition source [*Thomas*, 1954].

Forest canopy land-use conversion processes can include *deforestation* and *afforestation* which, respectively, abruptly decrease and gradually increase the overall amount of forest land. Conversions between forest land, agriculture and grassland are often cyclical over multiple decades, and do not necessarily result in net forest loss over longer time scales [*Alig et al.*, 2010]. It is important to note the different time scales between short-term fluctuations in canopy cover from disturbance and reforestation and the long-term changes in forest land area from afforestation and deforestation. In this study, the term ‘conversion’ is limited to forest canopy loss due to suburban/urban development. Other types of deforestation, such as conversion of forest land to agriculture, pasture, or reservoirs do occur in the CONUS [*Alig et al.*, 2010]. Afforestation is not explicitly covered in this work.

2.3. Background and Data

2.3.1. Estimating forest area and area changed

Recently, stand age has been used to understand the legacy of disturbance regimes typical of an area, because of the lack of actual data on forest disturbance and land-use history [*Pan et al.*, 2010; *Song and Woodcock*, 2003]. Stand age (in addition to other factors) can be used to estimate the rates of characteristic functional processes of forest such as mineral weathering, cycling of water, air, nutrients and carbon, and biomass accumulation [*Barnes et al.*, 1998].

There are limitations to using forest age from forest inventories as an indicator for time since the last disturbance [*Bradford et al.*, 2008]. Even-aged stands are assumed to be the product of natural or human-managed disturbances, but the history of uneven age stands is less clear [*Lorimer*, 1985]. Most natural disturbances do not cause 100% mortality within the affected area. Natural regeneration can be a slow continuous process with new trees generating for decades after a disturbance. Stands that are largely unaffected by large disturbances still have individual tree mortality or small gaps that allow young trees to sprout, leading again to uneven aged stands.

Another method to estimate forest changes is monitoring of forest lands using direct observations to record the timing of the forest change events themselves. This approach requires more than one set of measurements through time, ideally with identical or similar methodologies. Comparing forest area from studies that recorded measurements only once through through time is problematic, but necessary when no other data is available. It can be difficult to trust variances between measurements, because noise from different methodologies is difficult to separate from the signal of actual changes in the variable of interest. Monitoring with more frequent temporal measurements can be done using ‘snap-shots’ through time, like a movie strip with decadal frames, or using dense time-series to derive metrics across the whole time period, not just the individual time steps.

Also important for measurements of forest area changed, from disturbance or conversion, are whether they record gross or net changes. Together, the areas of forest canopy gains and losses yield the net change in forest canopy cover area. Separately, gain or loss can be reported as gross changes in forest canopy over a period. Characterizing the gross changes from disturbance, reforestation, afforestation and deforestation, as well as the net changes is important for understanding forest land dynamics and how they affect other earth systems [*(IPCC)*, 2000; *Kurz et al.*, 2009; *Reams et al.*, 2010; *Zheng et al.*, 2011].

2.3.1.1. USFS FIA Data

The primary source for data on forest area and it’s changes, over large temporal and spatial extents has been the USFS FIA inventories [*(USDA)*, 2003]. FIA publicly provides area and volume measurements of forest characteristics through periodic reports [*Smith et al.*, 2009] and through the US Forest service Forest Inventory

Database Online (FIDO) (available at http://fiatools.fs.fed.us/fido/index.html).

The USFS FIA methodology has been modified over time. Forest land definitions varied by region until 2010, when definitions were standardized across the country. The definition of forest land applied to the majority of forest pre -2010, and now, all forests are defined as land that has 10% or more tree crown cover by trees of any size. Previously in the intermountain west region the definition had a 5% forest cover threshold. FIA data were collected on a periodic schedule until 2000 when the annual inventory started. States conducted surveys every 5 – 15 years on the periodic schedule. Decadal summaries are therefore influenced strongly by data gaps caused by the longer repeat periods of the periodic schedule and ultimately, the portion of the region with available data. Forest conditions are based on the measurements of 125,000 permanent 0.4 ha forest plots, with a density of 1 per 2427 ha, that are stratified by county and state. Larger area and population estimates are extrapolated from plot values using area expansion factors. National standards mandate each state survey meet sampling errors at the 67% confidence level, and have only a 3% per 404,700 ha allowable sampling error for timberland area estimates.

FIA inventories suggest that harvest has been the dominant forest change process for decades across all regions except the intermountain west where natural disturbance has dominated for the last two decades (Figure 2-2). The natural disturbance category includes removals from fire, wind, and insect events, but does not differentiate between them. Carbon modelers have used FIA volume measurements to model forest land carbon budgets and fluxes. Such studies often used estimates from only one decadal inventory and acknowledged that the results do not account for changes in disturbance regimes [*Turner et al.*, 1995].

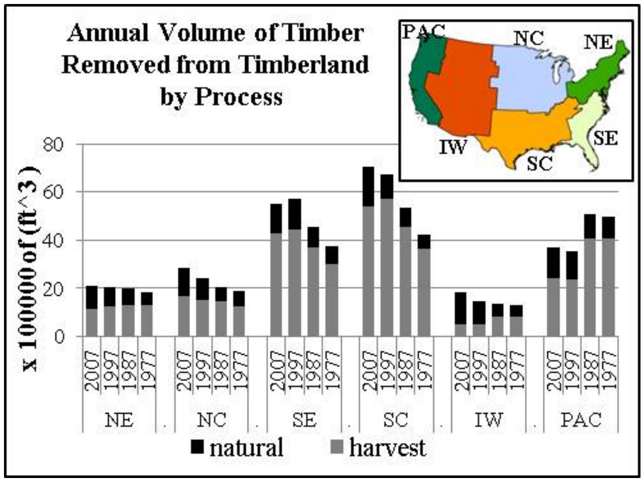


Figure 2-2: FIA measurements of volume of timber removed are assessed in the field during periodic surveys. Removal rate is shown as the average annual rate (cubic feet per year) for the historic forest service regions of Pacific Coast (PAC), Intermountain West (IW), North Central (NC), North East (NE), South Central (SC) and Southeast (SE). The Great Plains (GP) region has been aggregated into the NC region.

FIA area measurements of forest stand ages have their limitations as well. FIA ground measurements report the average age across the sample plot unless there is consistent age across the dominant tree species in the patch. Bradford *et al*. [2008] has shown that ground observations of tree age can be a poor indicator of time since last disturbance. FIA inventory data, cannot be easily integrated into high resolution spatial models of carbon cycling and dynamics [*Hurtt et al.*, 2004]. Finally, the inventory was not designed to capture episodic or clustered phenomenon such as disturbance [*Fisher et al.*, 2008].

2.3.1.2. National Resource Inventory (NRI)

The National Resource Conservation Service (NRCS) is a branch of the US Department of Agriculture (USDA) responsible for conducting long-term surveys of land use and natural resource conditions [*Nusser and Goebel*, 1997]. These NRI inventories are used to report land use changes into and out of forest use classes across the CONUS [*Alig et al.*, 2010; *Birdsey and Lewis*, 2003]. Data has been collected since the 1930s at irregular intervals. In 1977 the inventory changed to a 5 year interval with stratified sampling. The reliable minimum mapping unit of the 1977 through 1997 data, extrapolated from the 800, 000 NRI sample points, is a multi-county boundary with accuracies that vary spatially [*(USDA), U S D o A*, 2010]. In 2001, due to Congressional mandates, the NRI switched to an annual or continuous inventory to provide more timely information on a subset of its plots. The land use data for the post 1997 NRI data were still not available at the time of print.

2.3.1.3. Remote measurements

Satellite observations offer a different method of evaluating forest area and changes over large land areas and temporal periods [*Goward et al.*, 2008]. The forest service has been using remote sensing data for decades to help stratify plots for field inventories [*Estes and Thorley*, 1983] and there is evidence that forest service forest age maps can be improved by including remote sensing disturbance history products [*He et al.*, 2011].

The Advanced Very High Resolution Radiometer (AVHRR) data, with high temporal repeat (at least twice daily) and coarse spatial resolution (<1 km^2) was used for the first continental and global scale forest area maps [*DeFries et al.*, 1995; *Townshend et al.*, 1987; *Tucker et al.*, 1985] and change products [*Tucker and Townshend*, 2000]. Continental and global products have continued to improve in spatial resolution through refinements of spatial resolution in generations of the AVHRR sensor [*De Fries et al.*, 1998; *Loveland and Belward*, 1997], refinement of algorithms [*Hansen et al.*, 2000] and with the advent of higher spatial resolution data from the Moderate-resolution Imaging Spectroradiometer (MODIS) (500 m2) sensor launched in 1999 [*Hansen et al.*, 2005]. Tropical biomes have received the majority of attention in forest cover and change detection mapping with coarse spatial resolution sensors; however, United States forest have also been mapped with improving scales and algorithms [*Hansen et al.*, 2010a; *Ruefenacht et al.*, 2008; *Zhu and Evans*, 1994].

To create digital large area maps of forest land changes from remote sensing observations, two principal methods have evolved. The first method uses coarse spatial resolution and high temporal repeat data from the AVHRR and MODIS sensors, in a wall to wall comprehensive mapping analysis [*Hansen et al.*, 2010a; *Mildrexler et al.*, 2007]. The second method uses higher spatial resolution data from the Landsat or Spot sensors.

NASA's Humid Tropical Landsat Pathfinder project represents the first attempt at wall to wall mapping of regional land dynamics with high spatial resolution data [*Skole and Tucker*, 1993]. The first wall to wall US land cover dynamics product was created by the US Geological Survey [*Fry et al.*, 2009]. The advantage of wall to wall mapping with high spatial resolution data is that the method preserves information, that can be lost in coarser resolution products, on the spatial distribution of forests for geographical analysis [*Townshend and Justice*, 1988]. However, data costs, limited computing power and coarse temporal resolution (16-18 days) coupled with persistent cloud cover have prevented the adaptation of the approach by non-governmental institutions. The recent release of the Landsat archive [*Woodcock et al.*, 2008] and the exponential increase in computing power and storage are pushing wall to wall Landsat scale maps within reach.

The more common approach with Landsat data has been a sampling-based approach (either in time or space) using higher resolution data from Landsat such as in the operational Tropical Ecosystem Environment Observation by Satellite (TREES) [*Achard et al.*, 2002] or more recently efforts to characterize US forest dynamics [*Goward et al.*, 2008; *Masek et al.*, 2008]. The type of sampling scheme used determines how much loss of spatial contiguity occurs in the data. For example, fewer large samples will preserve more spatial detail than if many small samples are used. Sampling within a statistical framework provides reliable sampling accuracy estimates with error bars [*Czaplewski*, 2002].

There have been many improvements in the classification methods for localized ($< 100m^2$) change detection with satellite data forest change from satellite data [*Coppin et al.*, 2004; *Lu et al.*, 2004]. The norm in these studies of forest change detection has been bi-temporal analysis, or year to year change, regardless of whether a few image dates were analyzed [*Allen and Kupfer*, 2000; *Hall et al.*, 1991; *Lunetta et al.*, 2006] or a longer time series [*Cohen et al.*, 2002; *Eastman and Fulk*, 1993; *Healey et al.*, 2005; *Wilson and Sader*, 2002]. Temporal trajectory, or temporal profile, analysis uses high temporal frequency in data acquisitions to characterize spectral profiles through time [*Huang et al.*, in press; *Jin and Sader*, 2005; *Kennedy et al.*, 2007; *Lambin and Strahler*, 1994; *Lawrence and Ripple*, 1999; *Potter et al.*, 2005]. Recently, Kennedy et al. [2007] briefly categorized forest change remote sensing studies according to the type of temporal analysis employed.

The spatial and temporal resolution and extent of the multiple forest change products available for the contiguous US are outlined in Table 1-1. Experts suggest that to capture land dynamics the satellite needs to have a resolution of at the most $250m^2$, though this number was suggested not because it was more optimal than higher resolution data for observing changes, but rather because it was thought, at the time, that higher resolution data would create unmanageable data loads, for continental and global assessments [*Townshend and Justice*, 1988]. The TRENDS project used 6-8 year time steps between 1973 -2000 to evaluate fine scale land cover trends across the US [*Drummond and Loveland*, 2010; *Griffith et al.*, 2003a; *Loveland et al.*, 1999]. Lunetta et al. [2004] suggest that for land-cover change detection monitoring the least omission errors would be achieved with image acquisition of 1-2 year time intervals. The only product with the temporal breadth and depth and fine spatial resolution to meet these requirements is the North American Forest Dynamics (NAFD) forest history maps.

2.3.1.4. NAFD Data

The North American Forest Dynamics (NAFD) project provides the first comprehensive look at forest disturbance rates, with sample and measurement error estimates, for conterminous US forests using the Landsat fine spatial and temporal observations recorded from 1985-2010 [*Goward et al.*, 2008]. Funded by NASA as a core project within the framework of the North American Carbon Project (NACP), NAFD was designed to help the carbon community better understand US forest dynamics [*Wofsy and Harris*, 2002].

NAFD records changes that occur within 54 non-overlapping polygons, 3 for the prototype project, 23 for phase I, and 28 for phase II (Figure 2-3). Each sample area has an area of roughly 2.2 million ha (150 km^2) and is centered over a single unique Landsat scene area and identified in the World Reference System WRS-2 by a path and row frame [*Wu*, 2004] (Figure 2-2).

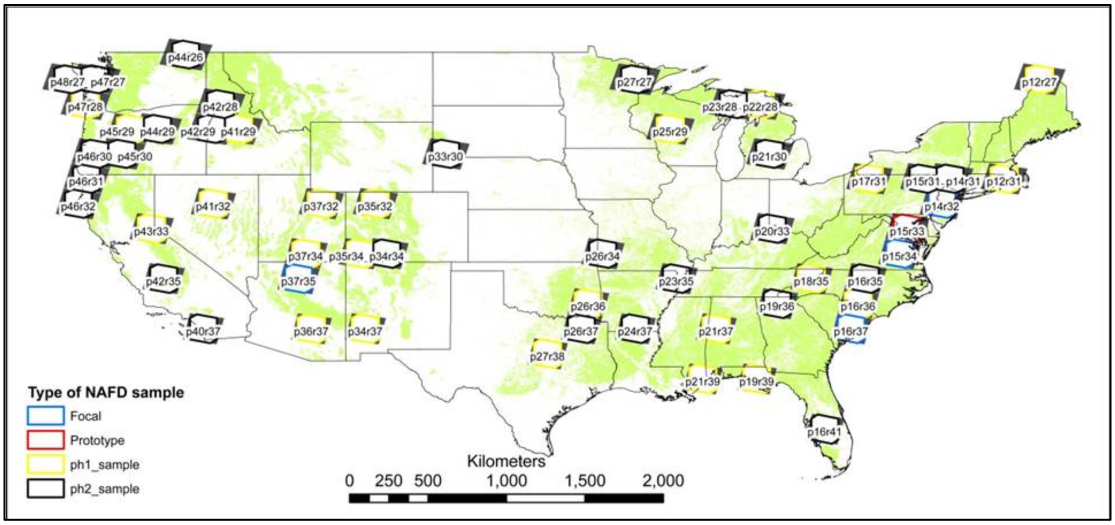


Figure 2-3: WRS-2 Landsat path row locations are shown in grey with their non-overlapping Thiessen polygons centered overtop.

When phase I of the NAFD project was started, in 2003, the high cost of Landsat imagery associated with doing a wall-to-wall biennial analysis (1984-2005) made a sampling scheme approach necessary (image dates used are in appendix B). The original NAFD sampling scheme used stratified (east and west) unequal probability sampling to provide a design-based estimate of national estimate of forest area and area changed [*Kennedy et al.*, 2006]. The unequal probabilities come from four inclusion classes (with different weights): diversity of forest types (40%), high total forest area (30%), scene dispersion (10%), and inclusion of existing Landsat stack locations that (30%) were developed for earlier NAFD focal and prototype studies. The USFS 250m forest group type map was used for forest type and area (Figure 2-4) [*Ruefenacht et al.*, 2008]. 10,000 random lists of WRS-1 path row locations were ranked by forest type and forest total area and the probability of a sample falling at the top of the list was used to make the unequal probability estimators. An advantage of the list system was that it was expandable, so when phase II of NAFD began in 2006, further sample sites were added, with known probabilities of inclusion for estimation, by moving down the ordered list.

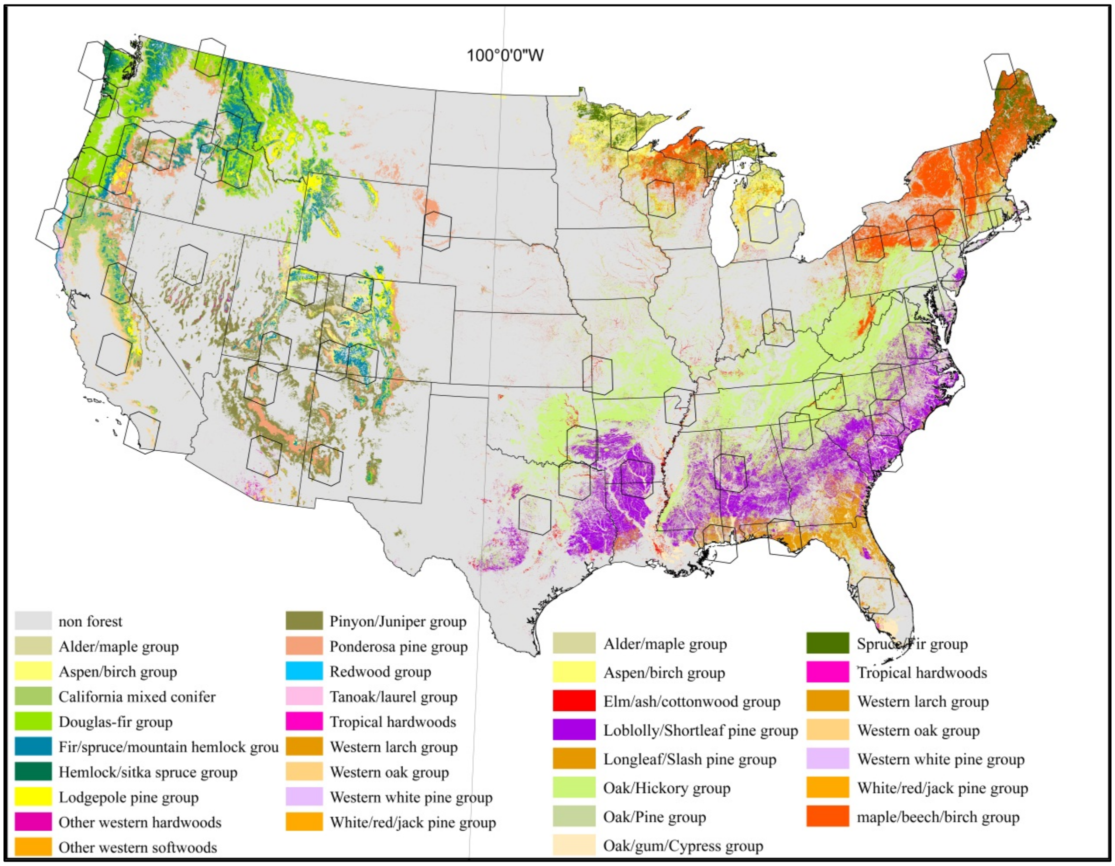


Figure 2-4 Forest Type groups [*Ruefenacht et al.*, 2008] are shown overlaid with NAFD sample locations. Forest group types with very minor areas not shown including exotic hardwoods and exotic softwoods.

The Vegetation Change Tracker (VCT) algorithm used by NAFD employs a temporal trajectory approach that takes advantage of dense time stacks of imagery. NAFD phase 1 and phase 2, because of image costs were limited to sampling through time creating biennial stacks of imagery. The biennial time interval of analysis 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 site productivity that regrow quickly [*Thomas et al.*, 2011]. Disturbances that do not persist for more than two time steps (i.e. 1991, 1993), such as seasonal insect defoliation, are not flagged as disturbed. In validated biennial NAFD sample sites, overall map accuracies ranged from 77% to 86%. Both measurement error and sampling error were variable from year to year [*Goward et al.*, 2012; *Thomas et al.*, 2011]. The NAFD methodology including image selection [*Huang et al.*, 2009], image pre-processing [*Masek et al.*, 2006], algorithm processing [*Huang et al.*, 2010] are available.

Products include maps of the location and extent of forest and change events, the magnitude of the event (in terms of vegetation indices), and the time until the forest signature (from vegetation indices) returns, at biennial time steps from 1985-2005. The 25 year time period was evaluated with nominal biennial dates, where the time between individual dates can vary from 1-3 years (in an effort to avoid cloud cover). Change detection from nominal biennial dates was interpolated to annual rates of change. NAFD detected changes include stand-level reductions of forest canopy cover on all forest land, including those that do not have a primary forest use, with a minimum spatial mapping unit of 0.4 ha (0.9 acres), and a minimum temporal unit of two time steps.

2.3.2. Estimating forest area changed by individual processes

A literature review revealed that estimates for the land area affected by different forest change processes varied as did reporting time scales (see Figure 1-4). In some cases the annual average estimates were based on very little data through time. For example, Dale et al. [2001], which has been cited by over 400 manuscripts, estimates the average annual forest area damaged by hurricanes in the US is 1.2 million ha (3.35% of total Southeast forest area or 0.48% of all CONUS forest area in 1997). The number was generated by multiplying the estimated forest area damaged by hurricane Hugo in 1989 (1.2 million ha), multiplied by the average frequency of major hurricanes per year that hit the contiguous US (1899-1989). In the twentieth century, only 20 hurricanes were category H4 at landfall. Only three of the twenty H4 storms, including Hurricane Hugo, made landfall in a heavily forested part of the coast. Therefore, using the frequency of all major hurricanes per year, not the frequency of those with characteristics similar to Hugo is unlikely to provide a representative estimate of averaged annual forest damage from hurricanes.

The most comprehensive study on multiple forest change processes through time is provided by Birdsey and Lewis [*Birdsey and Lewis*, 2003]. This paper reviews multiple forest change process for separate US regions since forest resources are region specific (Figure 2-5 and 2-6). Changes in land-use patterns across US lands from 1907-1997 are given in 6 time steps. Forest land affected by wildfire is given in decadal trends at 1,482,400 and 1,271,900 ha/yr between 1978-1987 and 1988-1997 respectively. Static estimates, insect affected forest areas (3,820,000 ha/yr between 1986-1997), harvest area (4,000,000 ha/yr between 1980-1990) and damage from weather (82,556 ha/yr between 1992-1996) are given. The latter two estimates are referenced from personal communications with no supporting data. Across the country (1988-1997) these selected disturbances affect 7,903,828 ha of forest annually, afforestation affects 1,060,000 ha/yr and deforestation 640,000 ha/yr (lost to developed, cropland, pasture, and rangeland) of forest. The paper notes that double counting of multiple processes on the same forest land is likely as they are not always mutually exclusive. The paper also looks at forest age classes across the region, noting that they are a different type of record of land-use and disturbance history.

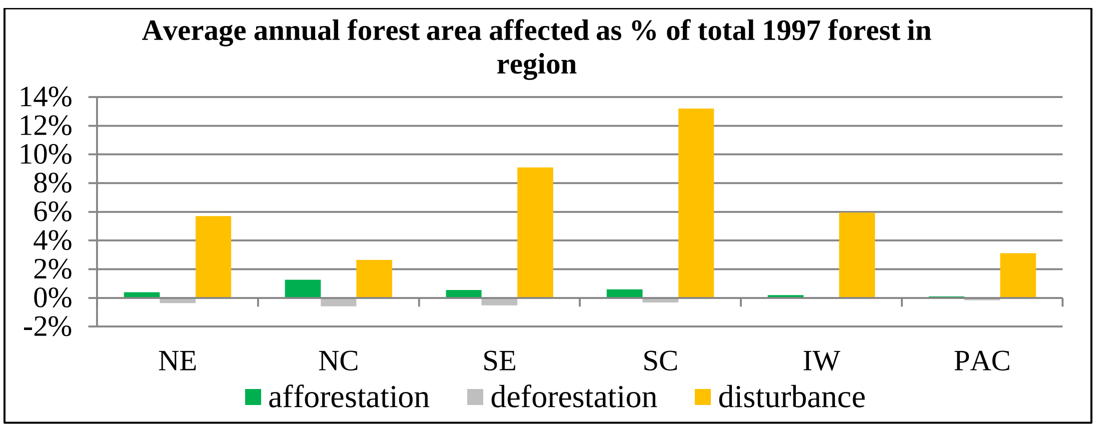


Figure 2-5: Afforestation and deforestation include changes between forest land, crop land, pasture, range land, and developed land, from NRI data. Disturbance includes wildfire, insects, partial and clear-cut harvests [*Birdsey and Lewis*, 2003].

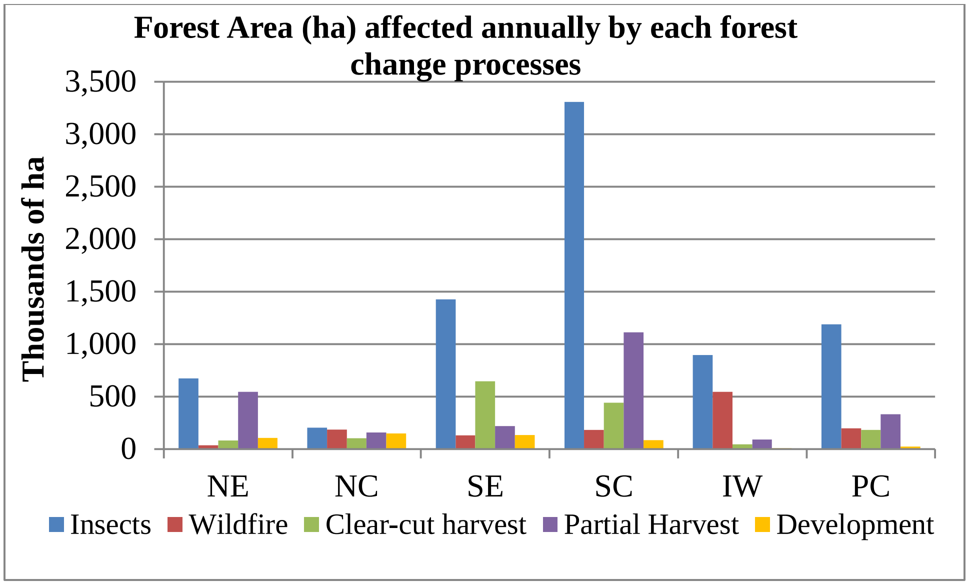


Figure 2-6: No distinction is made for severity of wildfire or insect damage in Birdsey and Lewis [*Birdsey and Lewis*, 2003]. Rates are given for a decadal average for the time period 1988-1997, with the exception of harvest data from 1980-1990.

2.3.2.1. Harvest Data

The methods to estimate harvest area and severity quoted in Birdsey and Lewis [2003] are not given. More recent estimates of forest area harvested across the CONUS for the 2001-2005 period are provided by Smith et al [2009]. Again, methods are not described and estimates are given at a regional level only. Clear-cut harvests remove >80 % of the tree basal area in a site, while partial-cuts range from removing 79% of basal area to creating small gaps in forest cover to encourage establishment of pioneer species (WB smith, personal communication, October, 2010).

2.3.2.2. Suburbanization/Urbanization

One of the leading provider of gross measurements for land use change has been the National Resources Conservation Service (NRCS) National Resource Inventory (NRI) [*(USDA)*, 2001]. The NRI definition of developed land includes urban areas, built-up areas and rural transportation, thus it is able to capture development in rural areas [*Alig et al.*, 2003]. The gross rate of forest conversion to suburbanization 1982-1997 was 400,000 ha/yr when averaged across the country [*Alig et al.*, 2003]. Nearly the same rate (394,505 ha/yr) as the NRI recorded for the shorter 1988-1997 period reported in Birdsey and Lewis [2003]. Data on land use dynamics from the 2001 nor the 2007 inventory has not yet been publically released. Estimates of per county sampling error are available [*(USDA)*, 2001].

The National Landcover Dataset (NLCD) is a suite of products created by the US Geological survey from Landsat and ancillary data sources (http://www.mrlc.gov/finddata.php). Among the 30 m spatial resolution products are the 1992-2001 retrofit land cover change product [*Fry et al.*, 2009] and the NLCD 2006 Land Cover Change Product (2001-2006) [*Xian et al.*, 2009]. No formal accuracy assessment has been conducted for these products. Change estimates from the Retrofit products are substantially higher the estimates from other remote sensing products of forest change (see Table 1-1). Because the NLCD change products use a land cover definition, many of the forest transitions to grassland, herbaceous or bare cover may actually be transitional states related to rotation harvests instead of permanent conversions.

To map forest to suburban/urban conversion the NLCD uses a combination of impervious surface and tree cover masked products to determine land use [*Homer et al.*, 2007]. The impervious surface layers are used to create hand edited masks of urban areas. These land cover masks are used to help model which forest changes are caused by conversions to developed urban/suburban land use.

2.3.2.3. Insect Data

USFS Forest Health Protection (FHP) collects data on forest insect and disease from aerial detection surveys (ADS) [*Johnson and Wittwer*, 2008]. The amount of forest area and severity of damage by insects depends on factors such as the type and life cycle of insects and the characteristics of forest stands in the 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 [*DNR)*, 2008]. When trees are stressed from drought or over stocking the mortality rates of host tree species from any damaging insect can become more severe [*Raffa et al.*, 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]. Locations of ADS samples are not derived from a statistical sampling scheme. Biases and uncertainties in the ADS data are unknown. Data users are warned that the technique has uncharacterized spatial and thematic inaccuracies [*Johnson and Ross*, 2008]. Birdsey and Lewis [2003] reference the ADS insect reports for 1988-1997.

This work uses the ADS reports directly to report insect activity from 1998 on.

2.3.2.4. Fire data

No large scale historic fire data set explicitly records whether or not the fire occurred on land covered with forest. Methods vary for estimating the cover type of fires [*Brewer et al.*, 2005] and for estimating area affected [*Cocke et al.*, 2005]. For example, counting perimeter-based fire areas yields larger numbers than if unburned islands within perimeter are left out [*Shapiro-Miller et al.*, 2007]. The USFS has collected wildland fire data for over a century. Birdsey and Lewis [2003] gives data for forest land wildfires only (1988-1997) with no mention how the subset of forest land was split out and no error estimates.

The finest grain (highest resolution) national 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 and severity is categorized along a gradient and validated manually by analysts [*Eidenschenk et al.*, 2007]. This data source is still under production and there are still many data gaps in time and space, especially in states east of the Mississippi river [*(MTBS)*, 2010].

2.4. <u>Approach</u>

2.4.1.1. Compiling data across regions

I subset the CONUS into North East (NE), North Central (NC), Southeast (SE), South Central (SC), Pacific (PAC) and Intermountain West (IW) regions (Figure 2-1).

These boundaries are consistent with historic USFS regional boundaries and boundaries used for the Congress mandated USDA Renewable Resources Planning Act (RPA) assessments.

To evaluate the increase or decrease of the region-wide influence of forest change processes through time, we compiled time-series of the rate of forest area affected per process were compiled. Area estimates used for region wide summaries were aggregated from tabular state level statistics for recent insect ADS (1997-2005), and USFS (2001-2005) harvest area, MTBS forest fires [*(MTBS)*, 2010; *(USDA)*, 2000; 2005; 2009; *Smith et al.*, 2009]. Harvest area data through, available for 1980-1990 and 2001-2005 are only available to the public at regional level [*Birdsey and Lewis*, 2003; *Smith et al.*, 2009]. The percentage of NLCD forest converted to developed land in each region per time step (1992-2001 and 2001-2006) was calculated by dividing all forest to developed change classes by the sum of the persisting forest and all change classes (from forest to other land covers) then multiplying by 100 (for each data set). For example, for the 1992-2001 retro fit data set classes class 42 (forest to developed land) was divided by the sum of all forest classes (map values of 4, 41, 42, 43, 45, 46, 47) multiplied by 100.

For comparison across data sets (and regions), with different base amounts of forest area, rates are normalized and given as a percentage of the total forest area. For data sets which do not include an estimate of total forest area FIA estimates given in Smith et al. [2009] were used. For comparison across data sets with differing time steps, rates are averaged to an annual mean. Data sets for disturbance processes that have gaps in space or time were not filled.

2.4.2. Representativeness

Because a statistical sampling scheme was not in place for the regional boundaries used here, the regional NAFD samples were checked for their "representativeness", or their ability to capture the dynamics full forest population of the region. Natural disturbance regimes are often associated with certain forest types in geographic space. The distribution of forest land type, a combination of forest ownership and forest land productivity, may also influence the forest dynamics of an area. It can be argued that if the samples for each of the six regions represent the total population of forest group types and ownership/productivity in the region, then the regional samples are adequate representatives for the whole region, just as the eastern and western NAFD samples were assumed representative of the forest dynamics of the whole stratum.

The relationship between forest group type and the forest land type for the regions as a whole and for the forest area captured in the regional samples were compared with weighted linear regressions. The population for forest group type comes from the 250m map product created from FIA inventory and MODIS data ([*Ruefenacht et al.*, 2008] (see Figure 2-4). Group type categories with less than 2% of total forest area per region were not included in the analysis.

A map of forest land type was constructed based on USFS forest land type definitions, which are land-use not just land cover based [*Smith et al.*, 2009]. Timberland is defined as land which can yield 20 cubic feet or greater volume of timber per acre per year and is not reserved from harvest by land use or protective measures. The other two categories of forest land defined by the USFS are “reserve” (forest land is spared harvest removals by local, state, national legislation and by ownership in land trusts) and ‘other’ (forest land neither meets these productivity nor protected criteria).

Multiple geospatial data sources were combined in a GIS to form the forest land category map. Data from the raster based USFS group type map was used to mask forest and non-forest areas. Polygons from the Protected Areas Database for the United States (PAD-US) , version 2.1, [*DellaSala et al.*, 2001] were used to filter forested pixels into ownership categories of 1)Bureau of Indian Affairs (BIA) 2) public lands (held by federal, state or local lands) and 3) private lands. The PAD-US database polygons were also used to filter forested pixels that were protected from extractive activities (IUCN categories I-V) and were held 1) publically or 2) privately, for example by land trusts [*Dudley and Phillips*, 2006]. Land productivity data was based on RPA plot data averaged over the hexagonal sampling scheme developed by the U.S. Environmental Protection Agency, Environmental Monitoring and Assessment Program [*Nelson and Vissage*, 2007]. Hexagons values were threshold to create two classes. The threshold was set at an average site productivity of 20 cubic feet/acre/year. The final map had nine categories including public and private timberland, public and private reserved forest land, public and private ‘other’ forest land, and BIA forest land. USFS ground based estimates of forest land are only for timberland, reserved and public categories so map classes were condensed for direct comparison. In some cases the ownership category may not represent a unique forest management system. For example, in the ownership category, BIA land was joined with private land. BIA forest land is not subject to the same rules as private US forest lands other work has shown that harvest patterns on timberland for both owners is very similar [*Huang et al.*, in press].

2.4.2.1. Regional estimates from NAFD samples

The regional divisions used here represent a post hoc selection of the NAFD locations. Therefore, the original inclusion probabilities that allowed for larger area inferences from sampled results could not be used here, because the six regions used in this paper are different than the two original stratums. Instead regional estimates were averaged from the NAFD sample, weighted by the amount of forest area in each sample (per region). Because the samples were not chosen within the framework of a regional statistical sampling scheme, NAFD derived regional amounts of area of forest land, persisting forest canopy and forest canopy cover changes have unknown errors and bias and may not be representative of the region. Weighted regional NAFD averages are still useful as a bridge to explore how local data on processes and forest canopy change relate to coarser FIA and process related datasets. Where NAFD samples spanned more than one region, the sample was assigned to one region or another based on similar forest type and local land use trends.

2.5. Results and Discussion

2.5.1. Representativeness

The forest area sampled by each NAFD sample varied as does the total forest area changed, but is suggestive of regional trends (Figure 2-7). To understand if the regions represent a useful boundary for aggregating the NAFD samples, the amount of forest, group type, and ownership and productivity for each region's forests were compared to the characteristics of the forest captured by the NAFD samples in each region. This work proceeds on the assumption that a tight relationships between the full population and the sampled population for those forested variables, would suggest that the NAFD samples also reasonably represent the full spectrum of forest dynamics for the region.

The forest area and location in the USFS group type map was used to calculate the regional amount of forest area and the amount captured in the regional NAFD samples. The total amount of CONUS forests sampled through NAFD is 21.78%. There is a substantial difference between the amount of forest area sampled in the PAC region and in the SC (Table 2-1). However, just because a smaller amount of forest area was sampled in the latter, does not mean that it does not represent the forests of the region well. Estimates drawn from smaller sample sizes can be more susceptible to higher variances caused by outliers.

Table 2-1: Amount of forest area per U.S. region

Region	Forest Area	
	%	ha
NE	15.95	56,530,312
NC	19.81	70,174,750
SC	12.88	75,197,312
IW	20.66	119,445,312
SE	27.92	121,068,812
PAC	39	134,584,562
All	21.78	577,001,060

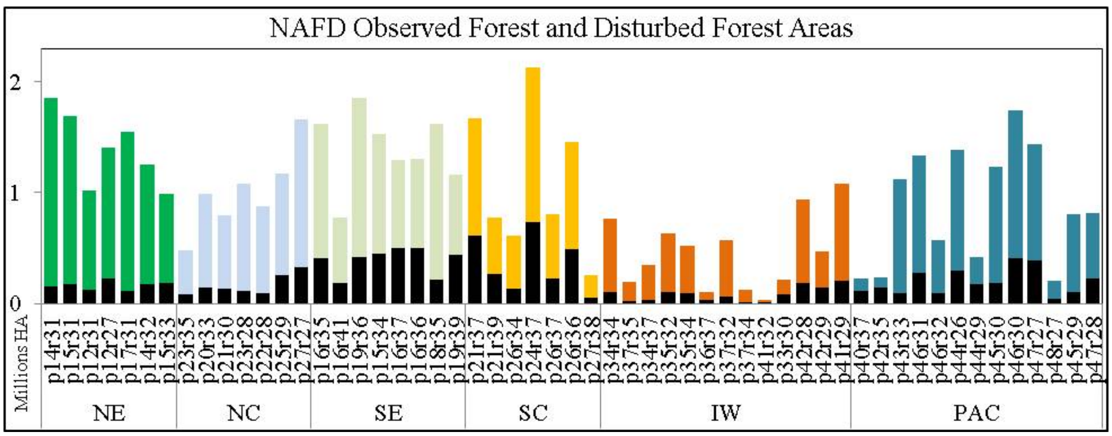


Figure 2-7: The overall length of the bar shows total NAFD derived forest land area for the sample location. The black portion of the bar is equal to the area of forest with canopy cover losses (1986-2004). The remainder of the bar represents the area with persisting forest cover (not interrupted) in the sample. Samples along the coastlines have low forest area due to the large proportion of water that falls within the samples footprint. The majority of the samples in the IW have the lowest forest area and area changed.

2.5.1.1. Forest type

The dominant forest type varies in each region by group type and by the proportion of forest area covered (Table 2-2). A regression between these variables gives an idea of the relationship between the full population of forest group types in the region and the amount of each group type captured in the NAFD samples of each region (Figure 2-8). The relationship is the tightest in the NE region where there are only four forest group types according to the FIA forest group type map. The NE NAFD samples captured the dominant Maple/Beech/Birch group well. In the SE, the dominant forest group type is Oak/Hickory, which the NAFD samples oversamples. The PAC region has the largest diversity with 10 forest group types. NAFD oversamples the dominant PAC region species group type, Douglas-fir group. Piñon/Juniper dominates the seven forest group types in the IW region and the group types captured in the NAFD IW samples.. The SC region is dominated by the Oak/Hickory group then the Loblolly/Shortleaf pine group type. NAFD locations in the region, captures the two forest types in reverse proportions, so Loblolly/Shortleaf dominates the NAFD forests area sampled. The weakest relationship between the full population of regional forest group types and the amount of each group type captured in NAFD samples was in the NC region. In the NC region, NAFD locations under sample by half the dominant group type, Oak/Hickory. However, the second and fourth most populous types, Aspen/Beech and Spruce/Fir respectively were largely over sampled.

Table 2-2: Forest group type per region calculated from the FIA forest group type map [Ruefenacht et al., 2008].

NE		
species group type	region	NAFD
maple/beech/birch group	50.7%	52.1%
Oak/Hickory group	33.7%	40.7%
Spruce/Fir group	8.5%	0.0%
White/red/jack pine group	3.0%	1.0%

SE		
species group type	region	NAFD
Oak/Hickory group	34.9%	45.5%
Loblolly/Shortleaf pine group	28.7%	27.1%
Longleaf/Slash pine group	14.5%	9.1%
Oak/gum/Cypress group	13.3%	11.1%
Oak/Pine group	7.6%	6.0%

PAC		
species group type	region	NAFD
Douglas-fir group	31.6%	40.1%
Ponderosa pine group	15.6%	14.6%
Fir/spruce/mountain her	13.2%	9.6%
California mixed conifer	13.2%	8.3%
Western oak group	7.8%	4.5%
Hemlock/sitka spruce grc	4.2%	6.2%
Pinyon/Juniper group	4.1%	4.5%
Lodgepole pine group	3.8%	4.4%
Alder/maple group	2.3%	2.0%
Tanoak/laurel group	2.2%	3.5%

NC		
species group type	region	NAFD
Oak/Hickory group	36.4%	17.2%
Aspen/birch group	26.3%	36.0%
maple/beech/birch group	15.4%	11.9%
Spruce/Fir group	9.6%	20.4%
White/red/jack pine group	5.0%	8.0%
Elm/ash/cottonwood group	4.2%	3.1%

SC		
species group type	region	NAFD
Oak/Hickory group	45.8%	31.9%
Loblolly/Shortleaf pine group	30.8%	40.5%
Oak/gum/Cypress group	9.4%	11.7%
Oak/Pine group	7.5%	8.0%
Elm/ash/cottonwood group	3.3%	3.0%
Longleaf/Slash pine group	2.4%	4.6%

IW		
species group type	region	NAFD
Pinyon/Juniper group	34.1%	29.0%
Douglas-fir group	16.5%	14.5%
Ponderosa pine group	10.6%	13.0%
Fir/spruce/mountain hemlock g	17.6%	24.2%
Lodgepole pine group	9.1%	5.2%
Aspen/birch group	5.3%	8.4%
Western oak group	3.5%	4.3%

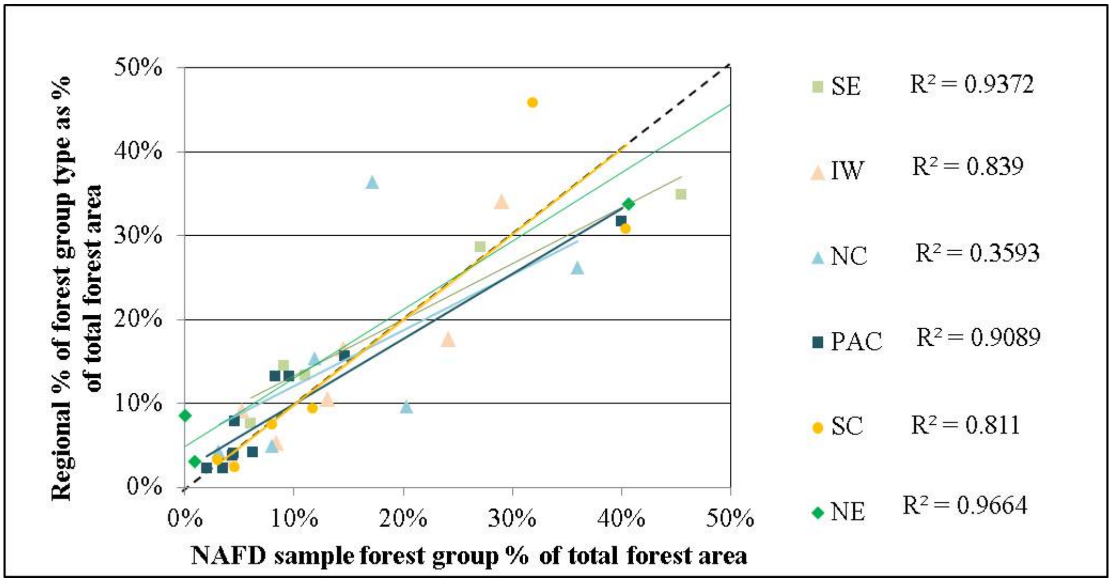


Figure 2-8: Forest group data come from the 250m FIA product generated from inventory ground data and MODIS imagery products [*Ruefenacht et al.*, 2008].

The importance of how well the NAFD locations sampled the regional distribution of forest group types depends on the dominance of the group type in the region and the different characteristic disturbance regimes of the group types. For example, Longleaf/Slash and Loblolly/Shortleaf pines grow under similar conditions, but are associated with different management concerns and thus different disturbance regimes. Longleaf pine is recognized as an endangered ecosystem in the South and home to endangered species which needs frequent low intensity burns to reach the age where it's a suitable nesting habitat for the endangered cockaded woodpecker [*Landers et al.*, 1995; *Mitchell et al.*, 2006]. However, the longleaf group type is a minority in the SE region (Table 2-1). Loblolly pine is often planted on rapid rotation commercial timber plantations throughout the south [*McNulty et al.*, 1996]. Over or under sampling loblolly/shortleaf pine, which is the second most common group type in the region, and suggestive of commercial harvesting, the leading disturbance type in the region, could have large implications for how accurately NAFD captured the disturbance dynamics and trends across the SE.

Another example comes from the NC region. The Aspen/Birch group is a pioneer species group that grows in small and large gaps created from fire, wind throw, insects and disease. Aspen forests will only persist longer than 50-70 years if the land is disturbed again. Past disturbance can be an indicator of future disturbance, especially for fire [*Peterson*, 2002]. While Aspen forests are an indicator of past disturbance history, disturbance regimes can change through time, and so are not predictive of future disturbances. The policy and management of fire suppression over the last in the NC region has changed dramatically in the last half decade [*Stephens and Ruth*, 2005; *Trani et al.*, 2001]. The fact that Aspen/Birch is the second most common forest (26% of the forest landscape) and NAFD locations oversampled it (36% of all forest sampled) implies only that 1/3rd of the NAFD locations overly areas that have undergone disturbance sometime since the last half century.

2.5.1.2. Ownership and productivity

The ownership map (Figure 2-9) was created to help evaluate the representativeness between the forest captured in the NAFD samples and the forest characteristics of the full forest population in each region. The scale of the ownership map is suitable only for national and regional estimates, because one of the layers is at a course resolution.

The mask to locate forest non-forest areas comes from the 250m FIA forest map and the PADUS polygons used to delineate reserved and BIA lands are of fine resolution; however, the EPA hexagons that were used to average site productivity, are roughly 65,000 ha each. Therefore, it would not be appropriate to use the map for local analysis that involved forest productivity.

The map was useful for calculating the regional forest land type and total forest land for comparison with FIA ground based measurements given in decadal RPA assessments [*Smith et al.*, 2004] (Table 2-3). The difference in land area estimates for 'other' woodland areas in the IW and PAC regions, as a function of different methodologies and definitions for minimum canopy cover has been acknowledged before [*Nelson and Vissage*, 2007]. The difference between total forest land area in the SE from the GIS constructed map, which uses data from a land cover approach, and the FIA inventories, which use a land use approach, may be attributable to the fact that the Southeast region has the highest percentage canopy cover in urban areas in the country [*Nowak and Crane*, 2002]. Discrepancies between estimates in the reserved forest land category in the NC and IW regions may be related to differences in the two protected area data sets including, the inclusion of private and BIA reserved lands and the higher resolution and spatial accuracy of the PADUS data.

The three types of forest land categories reported by the USFS, timberland, reserved and 'other' woodland, were used to model the relationship between the regional distribution of the categories and what was captured by the NAFD sampling scheme.

In general the modeled relationships were very strong as shown by the nearness of the data points to the 1:1 line (Figure 2-10). The data points for the IW ‘other’ and ‘reserved’ forestland are the farthest from the 1:1 line. The IW NAFD samples underrepresented ‘other’ forest land compared to the regional amount in the forest type map, and over sampled ‘reserved’ land (Table 2-3). The degree that over or under representing these categories has on understanding regional patterns of forest dynamics captured by the NAFD samples is unclear. The majority of harvest activities will occur on timberland, though some salvage clearing or preventative treatments can occur on reserved and low productivity woodlands [*Raffa et al.*, 2008]. It is unclear if fire and insects affect timberland, reserved forest land and low productivity wood land to the same degree. FIA inventories do not offer additional data on the subject. As mentioned earlier, it would be inappropriate to use the GIS forest type map in a fine scale disturbance analysis across forest land productivity categories.

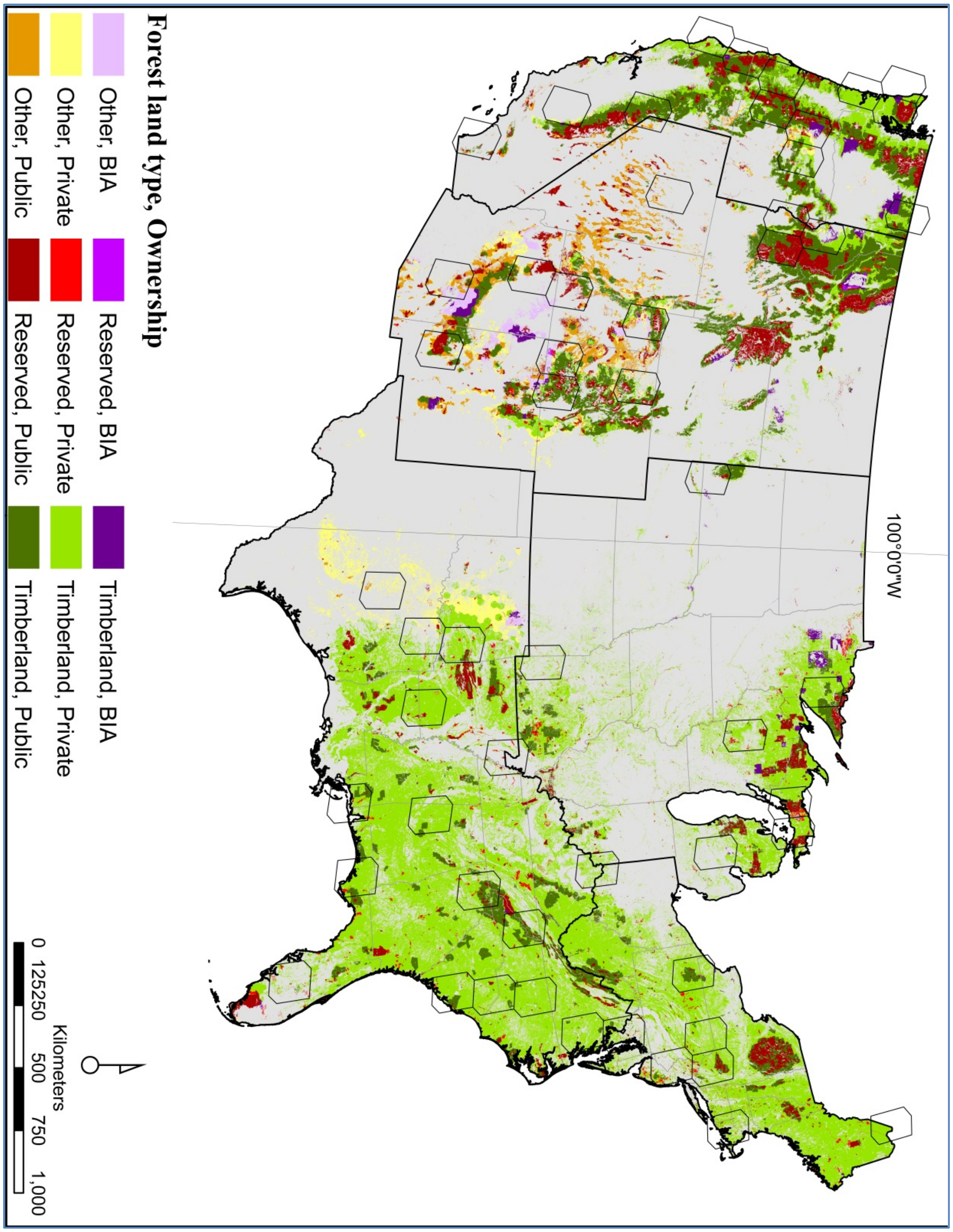


Figure 2-9: The forest land category map shows the greatest differences between the East, dominated by privately owned timberland, and the West, marked by high local spatial variability in both forest ownership and productivity.

Table 2-3 : Comparing estimates of forest land productivity from ground based USFS reports [*Smith et al.*, 2004] and GIS constructed maps [*Nelson and Vissage*, 2007].

REGION	all forest land (10^6 ha)		Timberland (% of all forest)		Reserved (% of all forest)		'Other' (% of all forest)	
	GIS map *	2002 USFS report	GIS map *	2002 USFS report	GIS map *	2002 USFS report	GIS map *	2002 USFS report
North East (NE)	38.0	34.4	93.2%	92.2%	6.7%	6.0%	0.0%	1.9%
North Central (NC)	32.0	36.2	88.0%	94.7%	11.9%	3.3%	0.1%	2.1%
South East (SE)	41.0	35.8	96.8%	95.7%	0.9%	3.6%	0.1%	0.7%
South Central (SC)	53.6	51.0	90.4%	93.5%	5.3%	1.0%	4.3%	5.4%
Intermountain West (IW)	57.5	56.5	51.3%	47.5%	21.4%	13.5%	27.3%	39.0%
Pacific Coast (PAC)	34.4	37.1	78.0%	64.3%	18.1%	13.5%	3.9%	22.1%
National	256.6	303.0	80.9%	67.2%	11.6%	10.3%	7.6%	22.5%

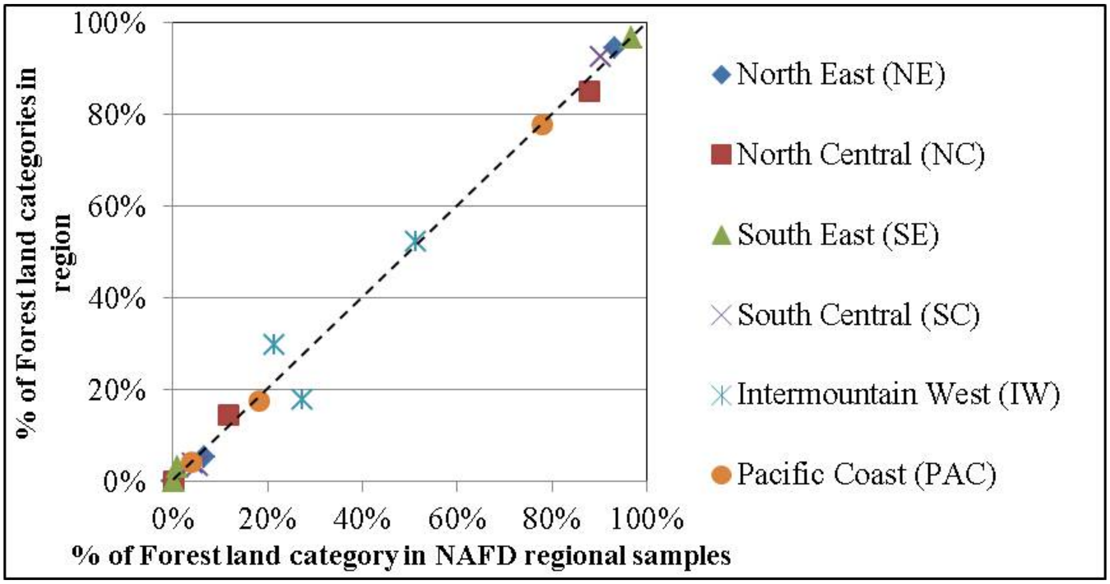


Figure 2-10: The relationships between the regional percentage of timberland, reserved, and 'other' forest land vs. the percentage captured in the NAFD regional samples closely follow the one to one line.

2.5.2. Regional rates through time

For decades, USFS ground inventories have been the gold standard of measurements across large areas on forest characteristics and their change. Volume measurements are great for translating changes to biomass; however, total area changed is also of interest [*Zheng et al.*, 2011]. Recently, the amount of young forest area has called attention to the high turnover rates of forest land in some parts of the country [*Pan et al.*, 2010; *Trani et al.*, 2001].

NAFD forest history maps offer one of the first alternatives to USFS forest age over large areas and multiple decades. Although the methods and sampling schemes are very different, the results both describe the legacy of forest land history over two decades (Figure 2-11). NAFD rates would include changes due to suburban/urban land-use conversion, while the USFS 0-19 year age category would not. USFS stand age rates would include regrowth after disturbances, areas of afforestation such as those from woodland encroachment or abandoned agriculture.

The general distribution across regions of the estimated rate of forest change were similar from NAFD data (year of disturbance) and USFS FIA data (stand age) were similar. For example, the NE had the lowest rates followed by the NC region and the SE and SC regions had the two highest rates of change in both NAFD and FIA estimates. Differences in the magnitude of the NAFD and FIA rates varied within regions. NAFD rates were higher by 107% in the NE, 70% in the NC, 24% in the SC, 12% in the IW and 59% in the PAC regions than rates calculated from USFS stand age data (given as a percentage of the USFS regional rates). In the SE NAFD rates were 9% lower than USFS forest age derived rates.

One likely reason for the difference in the rates from FIA and NAFD estimates is their ability to capture partial harvest. FIA age-class based estimates of forest area disturbed miss all partial harvests, because they would not reset the age of the stand to zero [*Lorimer*, 1985]. The NAFD rates, due in part to a biennial image acquisition approach, miss a lot, but not all partial or medium severity canopy loss events. Preliminary results have shown, that with an annual, cloud composited imagery the NAFD rates will capture more partial harvest and therefore, be higher [*Huang et al.*, in progress].

Because the sampling schemes, spatial and temporal resolution, and measurement methods of the two approaches are extremely different they are likely to sample each causal processes in different amounts. It is possible that in the NE and NC regions were the rates vary by the largest proportions the two approaches are capturing different underlying causal processes. This may be exacerbated where the processes are tightly clustered in space and time as the FIA sampling scheme was not designed to capture such events [*Fisher et al.*, 2008]. The temporal and geographic dynamics of the individual causal processes need to be characterized before relating the NAFD and USFS stand age change rates to causal processes.

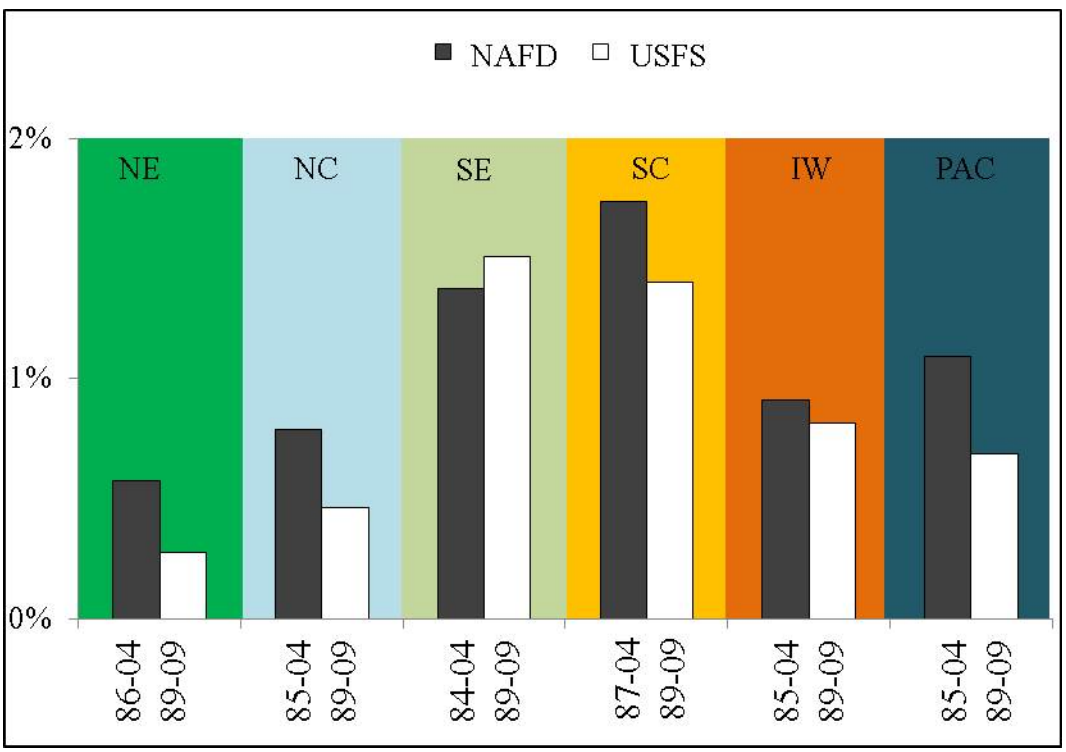


Figure 2-11 Annual forest change rates from USFS (based on FIA stand age) and NAFD forest

history maps varies in direction and magnitude across regions (observations are from slightly differing two decade periods).

Regional rates of forest change are caused by an amalgamation of many different forest change processes overlapping through time and space, but temporal data for the processes is not well synthesized. Therefore, this study assembled regional statistics of forest area affected through time by natural disturbance, human – managed disturbance and conversion processes to better understand how forest change process vary through space and time (Figure 2-12). Harvest and insect infestation rates were the most volatile through time, followed by fire then conversion. It is unclear if some of the volatility through time in harvest rates is due to different accounting methods from the two available sources. The region where each process was the most dominant did not change through time: conversion affected SC forests the most, fire affected PAC forests the most, harvest activities affected SC forests the most, and insects affected SC forests the most.

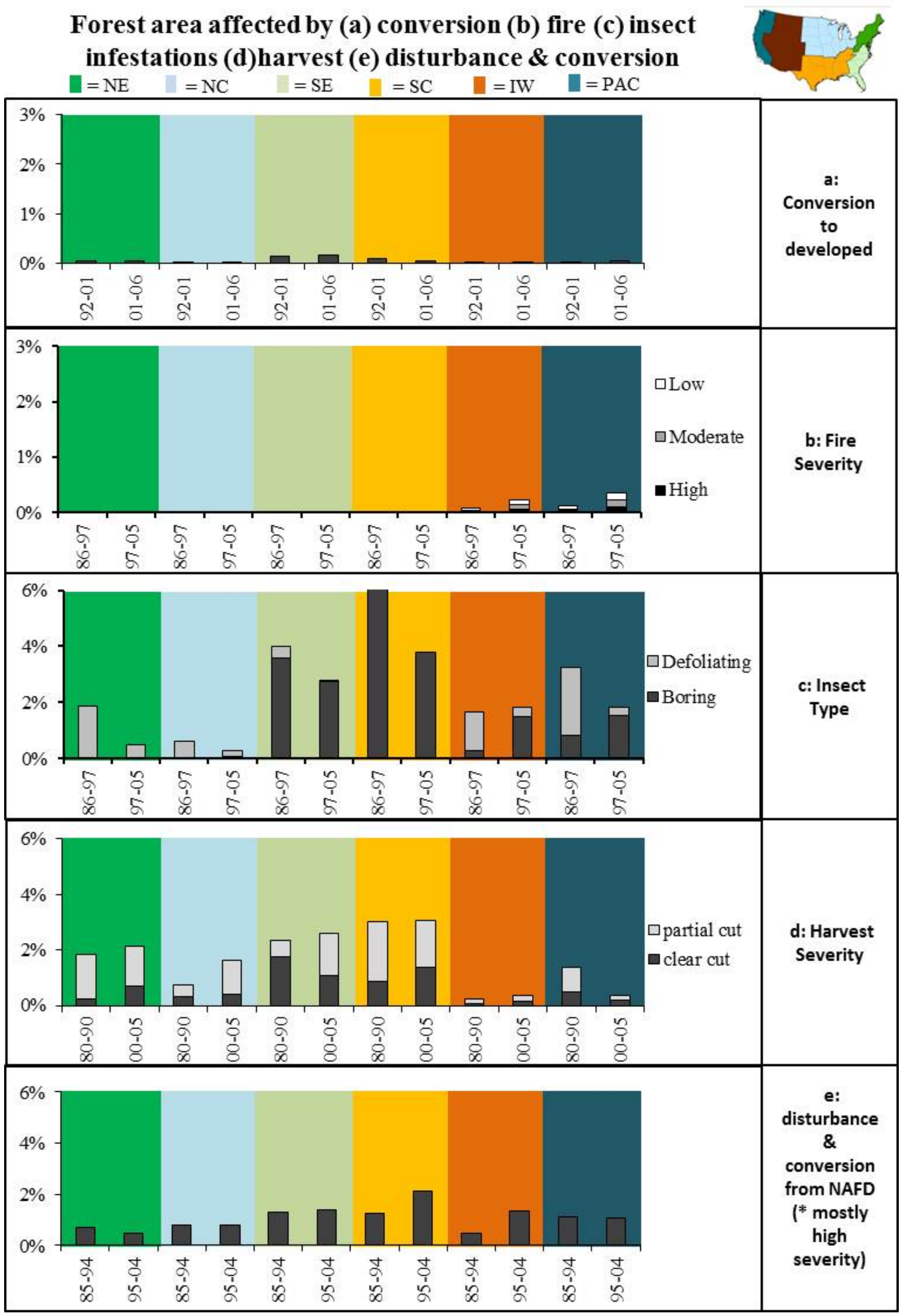


Figure 2-12: Averaged annual rates are calculated as a % of total forest area in the region using total forest area per region from Smith et al. [2009]. Reported areas for individual disturbance

processes are not mutually exclusive and lead to some double counting. *A*. Conversion data from NLCD [*Fry et al.*, 2009; *Xian et al.*, 2009] *B:* Fire data from MTBS [2010]. *C:* Insect affected area 1986-1997 data from Birdsey and Lewis [2003], 1997-2005 data from ADS [*(USDA)*, 2000; 2005]. * ADS reporting methods for the SC and SE vary drastically from other areas of the country and may lead to inflation of reported numbers *D:* Harvest area and severity 1980-1990 data from Birdsey and Lewis (2003). 2001-2005 data is from [*Smith et al.*, 2009]. *E*: Disturbance and conversion rates (not differentiated) from NAFD results [*Goward et al.*, 2008].

Assembling the rates for individual change processes through time provides new perspectives on the dynamics of these processes across time and space. However, the numbers must be interpreted with caution. The NLCD, MTBS, USFS harvest area, and ADS insect data, are *not* accompanied by national or regional estimates of accuracy. Another source of uncertainty for some of the data sources is that the methods vary across regions. For example, FIA inventory methods were not made consistent across regions until the institution of the annual sampling scheme in 2000. Also, the ADS data for the SE and SC regions varies dramatically from the collection methods in other regions. In the SE and SC, insect infestations are released only as county wide estimates compared to the small polygons reporting areas used by other regions. Finally, another source of uncertainty in the area estimates is related to the fact that natural disturbances rarely cause 100% mortality across the forest landscape. The ADS data records the area infested by different insects, not the forest area damaged or killed (Figure 2-12c).

Although the amount of forest area affected by conversion to suburban/urban land use is less than that affected by disturbances (Figure 2-12a), these changes can be very severe and have longer lasting implications for carbon cycling and other ecosystem services [*Stein et al.*, 2005; *Zheng et al.*, 2011]. Nowak and Walton [2005], using census definitions that capture mostly urban and some suburban boundaries, project that an amount of US forest land roughly equivalent to the size of Pennsylvania will be converted to these land uses between 2000 and 2050. However, different methods can yield different results. For example, the NRI conversion rates and NLCD change product rates differ across regions (Figure 2-13). It is difficult to make a direct comparison, since the reporting periods are different. Differences in the two methodologies ability to capture changes in more rural areas may be causing the discrepancies between the rates (see section.2.3.2.2). Both methods include infrastructure changes (transportation roads, etc.) in their definitions of forest change. It is notable, but not entirely explainable, that the magnitude of the difference between the rates from the two sources varies by region.

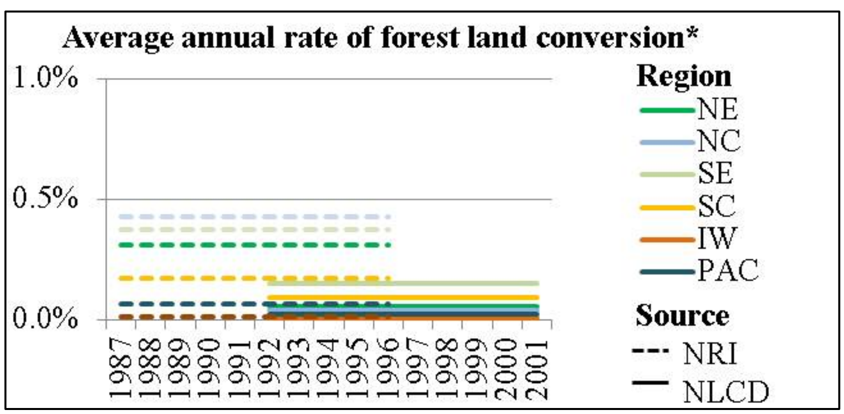


Figure 2-13: Forest land conversion in this context is specific to forest converted to suburban/urban developed land uses. The North Central (NC) region had the highest rates in the NRI data, but only the 4th highest rate in the NLCD data.

Disaggregating forest fire rates into different severities is a more meaningful way to evaluate the impact of this disturbance process in the landscape (Figure 2-12b). However, even if all MTBS fire severities are accounted for the estimated area varies substantially from estimates from Birdsey and Lewis [2003] (Figure 2-14). The same reporting periods are used for the comparison, so differences in rates are solely attributable to different recording methodologies (see section 2.3.2.4). As mentioned earlier, it is unreported how Birdsey and Lewis [2003] subset all wild land fires to just forest land area. MTBS data are masked to subset forest land fires, using a 2001 epoch forest layer with spatially varying accuracy estimates. The area inside of the entire MTBS fire perimeter was used in the comparison to the USFS data reported in Birdsey and Lewis [2003]. The MTBS data can also be used to measure only the areas inside of the fire perimeter that were assessed as high, medium, and low damage. When rates are calculated in this manner they are even smaller. The percentage drop in rates calculated using perimeters, vs. damaged areas only varies by region, 34% in the NC, 28% in the SE, 27% in the SC, 43% in the IW, 29% in the PAC (MTBS does not record any fires in the NE between 1988 and 1997).

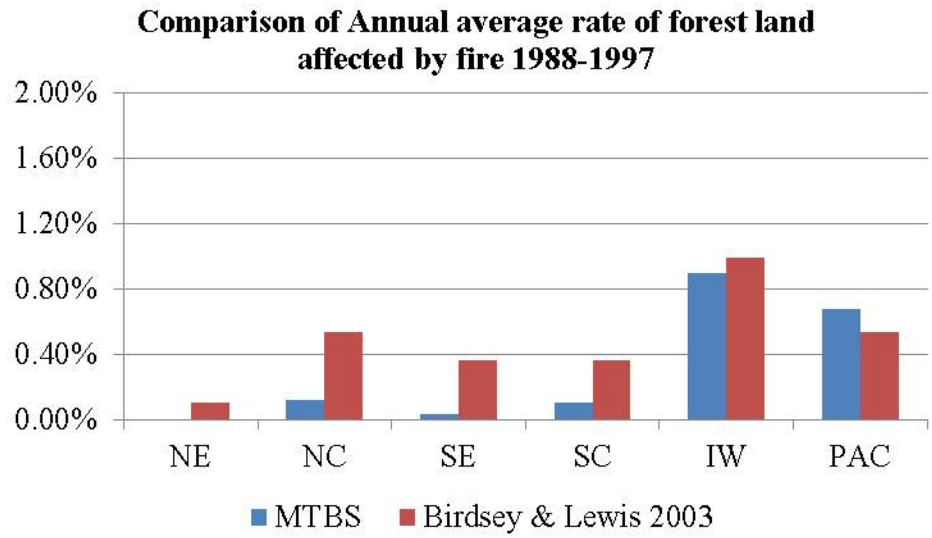


Figure 2-14: Differences between fire area recording methods, and the method of attributing fires to forest land cover are likely behind the different reported rates of forest area annually affected by fire across regions.

Harvest area estimates for the two time periods reported, 1980-1990 and 2001-2005, vary greatly through time and across regions (figure 2-12d). There is no documentation on how the earlier epoch data was generated [*Smith*, personal communication]. If low and high severity harvests are combined then harvest area estimates derived from volume (Figure 2-12d) and from stand age estimates (Figure 2-11) agree that the SC is the region with the largest percentage of its total forest area harvested. No explicit harvest area data is available between 1990 and 2001. Averaged estimates are published for longer time-periods [*Smith and Darr*, 2004], but no gap filling or averaging for missing data years was done for on process rates in this study. The missing data prevents conclusions or hypothesis being drawn on the relationship between harvest area estimates in the two short epochs of time (Figure 2-

12d) and the twenty year average rates from NAFD and USFS stand age (Figure 2-11).

Both USFS FIA stand age and NAFD (biennial) approaches are limited to capturing mostly severe canopy loss events. As such, the majority of the change observed by either method may be caused by clear-cut harvest, severe fires, conversion, and severe insect mortality (when it occurs across large contiguous canopies) or some combination of these processes. In all but the SE region the NAFD results are higher than the USFS rates. Since conversion is the highest in the SE, according to NLCD analysis, it is safe to rule out that conversion alone is responsible for the difference in rates. In light of both the USFS forest age and NAFD derived change rates, the rates for forest area affected by insect infestations is drastically higher than the rate of mortality from this causal process. In comparison with USFS estimates of forest harvest area, the USFS age categories and NAFD data both suggest much lower levels of forest area affected by harvest. The rate of moderate and high severity fires that are more likely to lead to mortality than low severity fires is almost non-existent in all but the IW and PAC regions. Since the largest difference between NAFD and USFS age derived rates is in the SC region it is unclear what role fire plays in the differences between the rates. It is likely that the true change rates from disturbances and conversion are higher than NAFD estimates, because NAFD's biennial approach under reports low density and low severity events such as partial harvests or sparse insect damage.

Ultimately, a better geographic model of forest change processes is necessary to understand how USFS forest age and NAFD methodological differences affect how the sampling methods capture various forest change processes and ultimately the estimated rates of forest canopy dynamics.

2.5.3. New perspectives from NAFD

Regional level analyses of forest dynamics can help support strategic natural resource planning and policy, but are relicts of the time when data and computing storage and processing capabilities were more limited resources. Ultimately, forest disturbance and conversion are happening over relatively short ranges of time and space. It is at these scales that vegetation changes on forest land are influencing the hydrologic, atmospheric and biotic systems of the earth. NAFD data offers a new perspective on the changes that are occurring at these scales.

Graphs of the temporal change trajectories for each NAFD path-row location show the temporal variability of rates varies between the regions and different categories of temporal patterns (Figure 2-15). One pattern is a “base rate” of change that are of stable magnitude over long periods, visible in many of the samples in the NE. Often the base rates are well matched to the twenty year mean for the sample and region. Base rates may be the result of a single type of change process that occurs consistently over an area through time, such as small frequent blow downs, or forest conversion to suburban lands on the fringe of a highly populated area. Base rates may also reflect a combination of multiple processes within the sample boundaries.

Sharp “staccato” peaks of short duration and high magnitude, are also evident in the

NAFD rates for some samples. For example, In the SE a large spike in p16r37 and a smaller one in its neighbor to the north, p16r36, are not echoed anywhere else in the region suggestive of a large isolated infrequent disturbance event (Figure 2-15c). In the IW there is a cluster of peaks around the year 2000 that suggest that the processes responsible for the sharp increase in forest canopy loss is operating over the entire region during those years (Figure 2-15e). Local staccato peaks in the disturbance rates of NAFD samples in PAC, IW and SC region were of sufficient magnitude that they skewed calculated regional and national level statistics in specific years. For natural disturbances such as wind storms and fire, there is an established inverse relationship between magnitude and frequency [*Turner et al.*, 1998]. Without a longer time-series of data it is impossible to know if the staccato peaks captured in NAFD results are a 'normal' parts of a cyclical disturbance regime or isolated extreme events.

Finally, a third temporal pattern is observable in NAFD results characterized by elevated change rates, above the mean, that persist for multiple years (3+). This type of pattern is observable in p26r36 and p27r27 in the SC region between 1997 to 2000 (Figure 2-15d). Ancillary data at germane spatial and temporal scales is necessary to interpret the NAFD results and attribute different temporal patterns to specific causal processes.

It is unclear how the nuances of the NAFD sampling pattern combined with the patterns of different local processes affect the capture of regional or sample-level disturbance rates. For example, the elevated signature of the disturbance rates in p26r36 and p27r27 are echoed in the regional SC average. The samples in the SC region capture the least percentage of the total forest area of all the regions sampled (12.9 %), under represent ‘other’ low productivity forest land, over sampled reserve forest land, and substantially over sampled the Fir/Spruce/Mountain hemlock forest group type. P26r37 and p26r36 weigh largely in the NAFD regional average as the samples with the third and fourth largest amount of forest area in the region. However, it is unlikely that the elevation in the regional rate is solely an artifact of the regional breakdown of sample locations, because the same elevated rate in the 1997 to 2000 time period is visible in the Eastern stratum of the national estimates, derived from the original statistical NAFD sampling scheme (Figure 2-16).

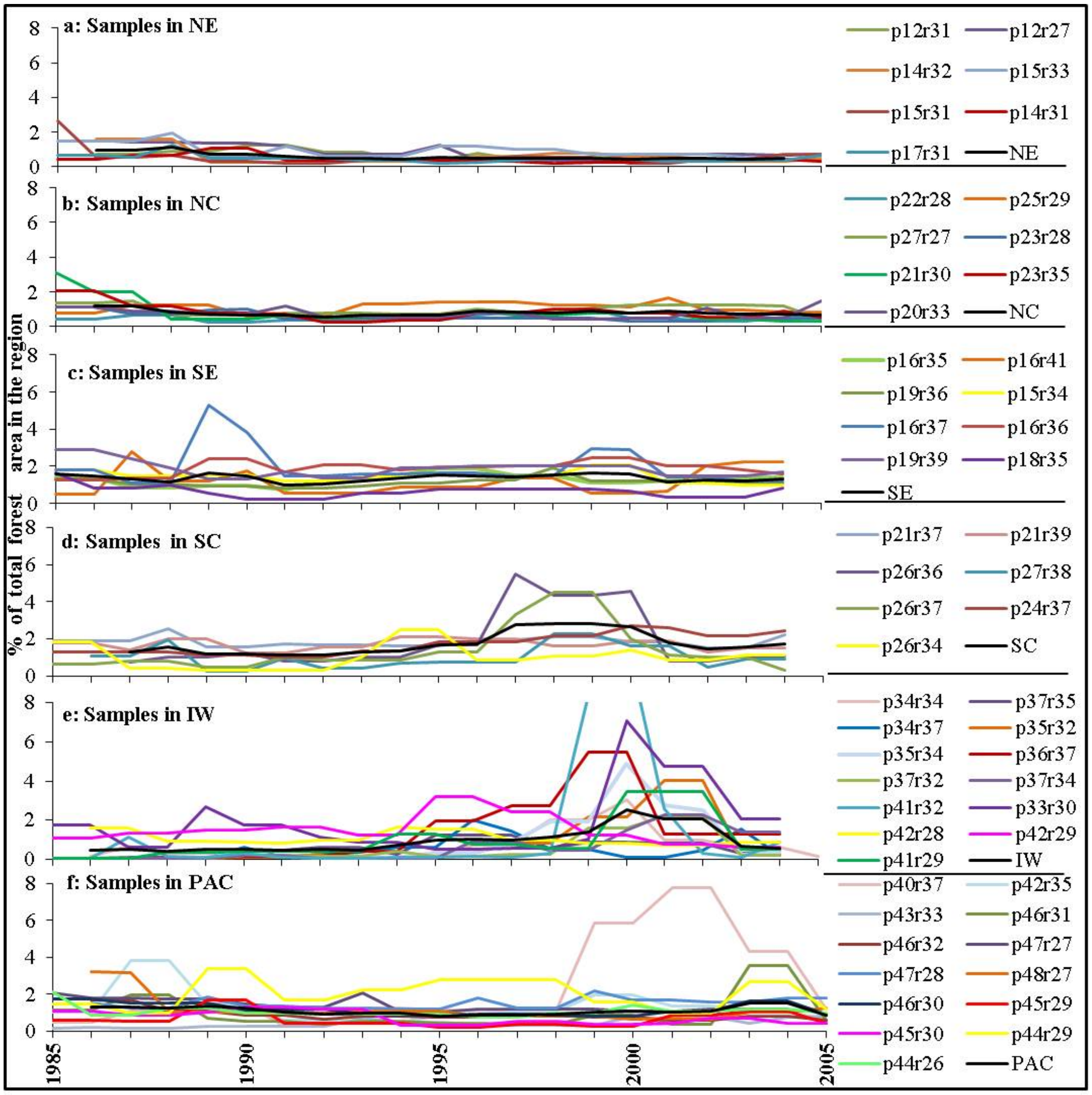


Figure 2-15: Graphs of the temporal change trajectories for each of the NAFD samples so different patterns of forest dynamics. The black line on each graph is averaged from yearly data from the samples in the region weighted by the amount of forest area in each location. So although some path rows have high rates of disturbance as percentage of the total forest area in that location (i.e. p40r37 in graph f) they may not affect the regional average much because they have little of the regions forest area within the sample boundaries (see figure 2-5 for the amount of forest area within each sample boundary). The regional samples do not have associated statistical probabilities. The forest area represented in graph c is not mutually exclusive of the

forest are in graph A or B.

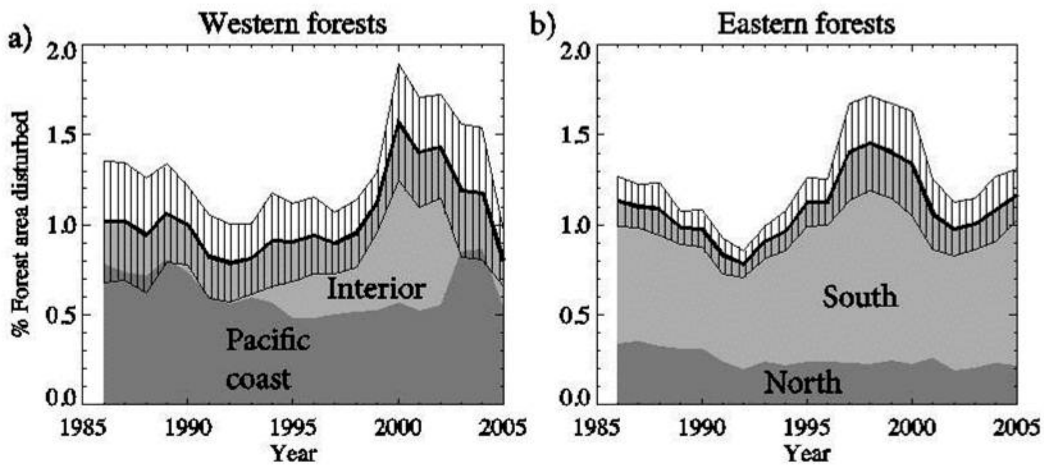


Figure 2-16: Eastern and Western Forest national estimates from the NAFD project show high inter annual variability in both forest change rates and uncertainty bounds. Uncertainty bounds include measurement error and sampling error (calculated as 1 σ uncertainty bounds using a conservative collapsed stratum variance method [*Cochran*, 1977] where each stratum consisted of another single NAFD sample that was geographically near) [*Goward et al.*, 2012]

Anomalies in the temporal record of NAFD forest change rates, 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 for many of the NAFD samples. When plotted together, the frequency distribution of magnitude vs. frequency of each regional subset shows empirical evidence that the occurrence and severity of observed forest change phenomenon are not normally distributed in space, and that they are positively skewed towards infrequent large events (Figure 2-17). Sampling different phenomenon with varying spatial and temporal heterogeneity can lead to biased estimates when aggregated to coarser scales and diagnosis and prediction of processes that have biases that shift over time are difficult to predict [*Bradford et al.*, 2010].

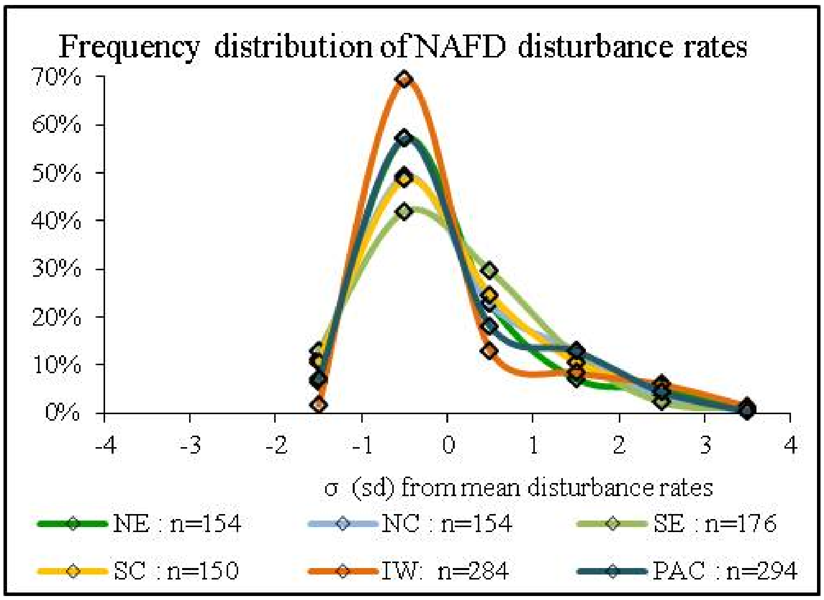


Figure 2-17: Magnitude, measured as the distance of the annual change rate from the 20 year mean (the z-score), is calculated individually for each NAFD sample and grouped by region. The number of image years available in each sample location and the number of samples in each regional subset varies. 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 were not selected with an equal probability of selection, the resulting distribution cannot be used for directly for inference to the regional populations.

NAFD forest history maps continuously monitor the same surface location through time with a consistent methodology. This represents a significant advance in the quality of data available on forest dynamics over the last thirty years. The USFS only began to implement a nationally consistent approach that allowed re-measurement of the same area (over a decadal period) in 2000. The first USFS re-measurement numbers are available and being analyzed now. Other remote sensing products from large area analysis cannot resolve the temporal trends visible in NAFD because of their coarser resolution or the use of time differencing methodology instead of a continuous temporal trajectory (see section 2.3.1.3.)

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]. The NAFD methodology, is able to record multiple change events on the same parcel of forest land area [*Huang et al.*, 2010]. For example, in the SC and SE, where forestry rotations are regrowth are quick, 5.9% and 4.6% of the NAFD observed forest area in the region experienced more than one disturbance during the period of observations, compared to 1.6% in the NC, 1.4% in the NE, 1.1% in the PAC and 0.6% in the IW regions (Figure 2-18a).

Abrupt disturbances and gradual continuous recovery of forest cover can occur on the same patch of land confounding area measurements reported for forest cover loss [*Kurz*, 2010]. These gradual processes are an important element of disturbance and land use history. Many land cover products set a base level of forest area for the first year of data that is not placed in a context of continual forest change. NAFD tracks how much forest land had little to no canopy cover at the beginning of the time–

series, was classified as forest land by the end, and had no disturbances in between. Calculated rates are 5.1% in the NE samples, 4.8% in the NC samples, 7.8% in the SE samples, 9.5% in the SC samples, 1.8% in the IW samples, and 7.9% in the PAC (Figure 2-18b). NAFD includes these areas of gross canopy regrowth in its calculations of total forest area when estimating the rate of canopy loss per year (as a % of total forest area). If only the static measure of area that was forested at the beginning of the time series was used, the rates of canopy loss would be much higher. Ancillary data or a longer time series will be needed to determine if these events are due to afforestation or reforestation, a current area of research for NAFD.

The USFS and international bodies interested in forest carbon dynamics assume that forest land that has been harvested will grow back into forests given enough time [*(FAO)*, 2001; *Smith et al.*, 2009; *UNFCCC*, 1997]. Optical image data such as Landsat observations saturates during forest growth or regrowth [*Frolking et al.*, 2009]. Landsat observations are good at picking up the short signals of forest canopy removal and recording when they do not grow back, as long as the time series is long enough to have registered a consecutive forest signal for multiple years. NAFD can show the patterns of where there was forest canopy cover loss that did not return to the forest signal after a decade, 5.7% in the PAC, 4.8% in the SE, 2.9% in the IW, 2.4% in the NC and SC, and 2.0% in the NE (Figure 2-18c). Possible explanations for these results vary by region. On the highly productive SE forest lands it is arguable that these results are due to conversion rather than disturbance processes. NLCD data suggest a SE decadal forest to suburban-urban land use rate of 6.2 %. The large forest areas in the IW and PAC captured in this time-series statistic are more likely due to severe disturbances on low-productivity lands. Without high spatial resolution ancillary data and/or a much longer time series it is impossible to resolve underlying cause with any certainty.

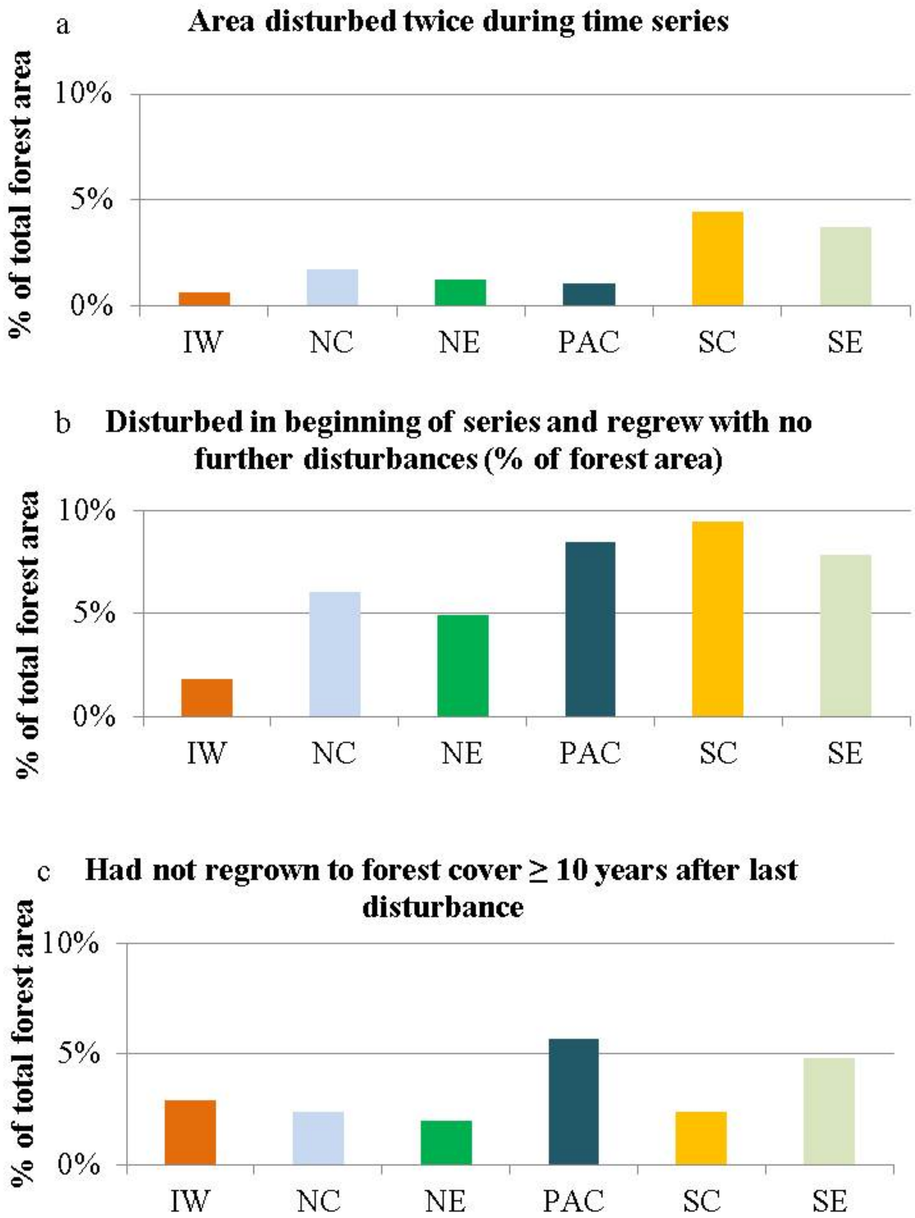


Figure 2-18 : NAFD tracks the same surface area continuously through time. This novel approach allows for metrics that take advantage of the 20+ year time series such as the rate of double disturbances on the same land area (graph a). Ancillary data is still needed to fully interpret these patterns in the context of forest change processes.

2.6. Conclusions

The goal of this chapter was to explore both the dynamics of forest change observations and the dynamics of multiple underlying causal processes through time and across six US regions. Comparisons were limited to the six USFS regional boundaries, due to the use of historical published data that is only available for these geographic boundaries. The compiled temporal statistics on regional rates of forests area affected by individual processes offer new information on the trends of causal processes of forest canopy loss. However, the regional-scale of the process data prevents attempts to disaggregate and quantify the proportion of each process captured by the empirical USFS stand age or the NAFD forest history observations. To address the overlap between multiple processes, a better geographic model of forest change processes is necessary.

The first question examined in this chapter was whether it was reasonable to use the NAFD sample locations to explore regional patterns of forest dynamics. Comparison of forest group type and of forest land categories for the forest area in each region and the forest area captured in NAFD samples suggest that the NAFD samples are reasonable representations of the regional forests. It is unclear how over or under representation of specific forest group types, ownership or productivity forest groups would affect estimated canopy loss rates for the region. Research on decadal disturbance and conversion rates in relation to forest type, ownership or productivity across the nation or in the USFS regions would be useful, but have not been published to date.

This study offers a new perspective on the temporal dynamics of the underlying causal processes of fire, insects, conversion to suburban/urban land-use, and harvest over the CONUS. Harvest has been suggested as the dominant process across all regions through time [*Smith et al.*, 2009]; however, this study shows the forest area affected by each process and related severity increase and decrease greatly across and within regions through time. Canopy loss dynamics in the NC and NE regions appear to be completely driven by changes in harvest regimes in the regions. Forest area estimates from ADS insect data appear to affect the largest amount of forest area in the SE, SC, IW and PAC region through time, but further work is necessary to incorporate measures of severity or confidence into the reported area for it to be truly useful for area estimates. Canopy loss dynamics in the SE and SC regions are more likely dominated by harvest activities though insects and other processes affect local dynamics as well. The IW and PAC regions have a more complex balance of overlapping canopy loss processes, where fire, insect and harvest processes alternate in which particular process is driving regional dynamics at a particular time.

In any region, canopy loss is caused by a combination of underlying processes. Previous estimates of forest area disturbed and converted mention that overlapping processes are double counted [*Birdsey and Lewis*, 2003]. The large variations in process specific patterns through time across the regions also support the need for a better geographic understanding of the processes underlying forest canopy losses (temporary and long-term). The different spatial and temporal methodologies of the NAFD and USFS estimates may sample underlying causal processes differently depending on the geographic distribution of the process.

Combining the many distinct data sets on forest change processes revealed large discrepancies and sources of uncertainty in the reported rates. For example, rates for fire and suburban/land-use conversion differed by 10-89% and 47-89%, respectively, depending on the region. The quantitative differences between these data sets may have implications for carbon studies that have evaluated US forest carbon sources and sinks from one or the other data source, but not both. ADS insect data needs better measures of density and severity across the landscape. Harvest area estimates have large temporal gaps and poorly documented methodologies. The different time steps of the available harvest area data make the cross-walk with FIA estimates of forest area changes (only recorded over decadal periods) problematic.

The original NAFD sampling scheme assumed that an unequal probability sampling scheme, most heavily weighted for forest diversity and forest area, would capture the dynamics of forest change across the CONUS. However, this work has shown that each region has its own signature of multiple forest disturbance and conversion processes at work and that those signatures can change through time. National and regional analyses are too coarse to understand the confounded effects from overlapping causal processes. NAFD temporal trajectories of forest canopy loss for each sample within the region highlight the changing local spatial and temporal variability of the phenomenon. However, the patterns cannot be explained without similar resolution ancillary data on the underlying causal processes.

The study provides empirical evidence that forest canopy loss events, within each region, are not normally distributed which has sampling and bias implications for aggregated estimates of change rates. The NAFD sampling scheme was not designed to specifically capture multiple causal processes each with its own shifting temporal and geographic dynamics. The number of samples was doubled between phase I and phase II in order to lower the uncertainty bounds from sampling errors; however, the bounds still show high inter-annual variability related to the scale (local or regional) of the underlying causes of the of the mapped disturbance events [*Goward et al.*, 2012]. Without knowing the spatial and temporal distribution of the underlying causal processes it is impossible to know how many large infrequent events were missed by the NAFD samples, or if the captured large events represent a type of over sampling.

In spite of the limitations of the NAFD data imposed by sampling across space and time, due to resource constraints, NAFD forest history maps represent a large step forward in the quality, amount and type of forest dynamics information available. First the NAFD methodology is consistent across the nation and through time, unlike

USFS or NRCS ground inventories or field studies. Second, the NAFD data has higher spatial resolution and contiguous coverage over large areas that provide information from strategic regional levels down through tactical landscape scale. Third, the NAFD data offers higher temporal resolution across large areas than other datasets available on forest history. Finally, the NAFD method continuously monitors the same location through time at scales germane to forest disturbance and conversion processes providing novel perspective on the context of the "current forest state" of land surfaces.

Chapter 3: A Geodatabase of Forest Change Processes towards better Understanding of Dynamic Processes

3.1. Introduction

Geomorphic processes, natural disturbances and human activities have created the complex spatial patterns that we observe in forests today. These forest change processes determine the composition and structure of forests, disrupt population distributions, and change resource and substrate availability [*Pickett and White*, 1985]. The patterns carved into forest landscapes by natural and anthropogenic processes are an integral component of forest systems leaving a legacy that helps determine future forest change processes [*Peterson*, 2002]. The spatial patterns also influence local processes such as the flow of nutrient cycling and biota, the spread of disturbances, changes in the levels of biodiversity, and future susceptibility to natural disturbances.

Forest "disturbance", as defined by Pickett and White [1985], is an umbrella term describing processes that lead to succession or free up local nutrients and resources. Each forest disturbance and conversion process leads to a different successional pathway. The frequency, severity (degree of forest changed), and size of the events determine the abundance and arrangement of the biological and abiotic legacies, or residuals, which determine future forest dynamics on that parcel of land [*Turner et al.*, 1998].

Each forest change process has a different regime which can be described by the patterns, central tendencies and variability of the frequency, severity, and extent of its events [*Pickett and White*, 1985]). The characteristic patterns associated with each disturbance regimes and how they change though time affect community equilibrium, stability and resilience [*Rydgren et al.*, 2004; *Sousa*, 1979]. O'Neill [1988] suggests that if the response times or recovery rates of a system increase or decrease, the system could move towards instability with repercussions on larger-scale processes.

In our increasingly human dominated world, drawing a line between human and natural categories grows increasingly difficult [*Vitousek et al.*, 1997]. Differentiating between natural and *anthropogenic* change and understanding those changes is an earth science goal. There is also a call to use the patterns from natural disturbance regimes as guidelines for human-managed disturbance and in the design of nature reserves [*Seymour et al.*, 2002; *Turner et al.*, 1994].

Natural disturbance regimes are affected by long-term climatic patterns, that are stable over 500-2000 year periods [*Lorimer*, 2001]. Forests and animals have adapted over many thousands of years to the historical frequency, severity, extent and geography of natural disturbance processes. Equally, the large pulses of carbon released by natural disturbance events to the atmosphere, and related periods of regrowth and elevated carbon sequestration, have been occurring for centuries [*Dale et al.*, 2001; *Zeng et al.*, 2009]. Though, it is unclear how stable the frequencies will remain in the face of current climate change [*Dale et al.*, 2001].

There are important differences between human-managed and natural disturbance processes. Anthropogenic disturbance and conversion trends are controlled by policy, economics, and cultural cycles that can have relatively short periods of stability [*Miller*, 1978]. Human-managed disturbances are more frequent and less random than natural disturbances [*Haynes*, 2002]. Research has shown that disturbance produces forests with more diversity in their structure, composition and function than undisturbed forests, unless the disturbance is human-managed, in which case there is less [*Franklin*, 1995; *Macie and Hermansen*, 2002; *Nelson et al.*, 2008]. Regrowth rates after natural disturbances are highly dependent on the site potential of the land while regrowth rates in relation to human–managed disturbance are largely dependent on the management intensity after the event [*Sader et al.*, 2006; *Schroeder et al.*, 2007]. The fate of biomass removed during human-managed disturbances has different carbon storage implications than that of natural disturbances [*Smith and Heath*, 2008].

Knowledge of baseline or normal conditions requires detailed information on historical disturbance regimes which can be difficult to generalize to other areas [*White and Jentsch*, 2001]. There are multiple sources of evidence of disturbance and conversion history such as historical texts [*Williams*, 1982], Land Survey records [*Radeloff et al.*, 2005a], paleoecology, palynology [*Hall et al.*, 1991] and dendrochronology [*Lorimer*, 1985]. However, fine grain information on the severity of damage and *forest* area affected across broad temporal and spatial scales is still lacking. The goal of this chapter is to develop a more integrated understanding of the occurrence of forest canopy loss from fire, wind, harvest, insects and conversion to developed land, to support science on forest dynamics over the CONUS. The combination of all of data on each of these processes into one analysis space, a spatial and temporally explicit geodatabase of forest change processes, creates the capacity for new types of analysis on the causal processes, their individual spatial and temporal variability and their combined overlap. Criteria for data set selection included national breadth, consistent recording methods through time, and the finest available spatial and temporal resolution.

3.2. Background

Forest change processes are often ecosystem specific and they are best characterized and understood in this context. For example, patterns of frequency and size of disturbance and conversion events varies with the dominant forest types and management regimes in an area. Generally the repeat frequency of disturbance events has an inverse relationship with its extent and severity [*Peterson*, 2000]. The characteristics of forest change processes vary affecting and can affect our ability to observe (and understand) them individually and as a suite [*Coops et al.*, 2007] (see Appendix C).

The types, drivers, factors affecting severity, and spatial and temporal regimes for each group of change processes are discussed briefly in the following sections. Other disturbance processes that affect forest land in small quantities but which are not discussed here include landslides, avalanches, debris flow, lava flow, blasts, floods, drought, disease, and pollution [*Barnes et al.*, 1998].

3.2.1. Fire

Fire is fundamental in shaping the world's forests [*Bowman et al.*, 2009] . Historically, the local forest composition and structure are adapted to and in some cases, dependent on the dominant fire type (ground, surface, or crown fire) in that region [*Barnes et al.*, 1998]. Repeating patterns of fire behavior are the basis for recognizable broad fire regimes such as understory, mixed and stand replacing regimes [*Brown and Smith*, 2000].

For millennia, weather, fuel availability, topography and the legacy of past disturbance events interacted to determine fire behavior with lightning the main ignition cause of fires. Now in the SE, SC, NE and NC regions humans are the main source of fire ignition on federal forest lands [*Stephens*, 2005]. As climate and humans' attitudes toward fire change, so do the large scale trends in forest fire behavior and their related regimes [*Dale et al.*, 2001]. Humans have always used fire to manage forest land; however, starting in the early 20th century they began to systematically suppress fire [*Stephens and Ruth*, 2005]. Suppression policies dramatically decreased the number and size of fires and consequently altered forest composition, encroachment, fuel loads and future fire behavior [*Coop and Givnish*, 2007; *Radeloff et al.*, 2005b; *Stephens et al.*, 2009; *Trani et al.*, 2001].

Vegetation type, weather conditions and fuel availability affect the severity of fires in a given location. Severity of fires varies within regimes though the guidelines of up to 20%, 20-80%, and 80% or greater mortality for understory, mixed and stand replacing regimes [*Stanturf et al.*, 2002]. In general, understory fire regimes do not substantially change the existing structure of forest. For example, prescribed burns, ground fires intentionally set to mimic natural understory regimes, are used to stop the establishment of competitive seedlings and burn off excessive ground fuels, leaving the overstory trees largely unaffected [*Mitchell et al.*, 2006]. Mixed fire regimes are well named as the morality and resulting structural changes vary greatly depending on the dominant vegetation type. Stand replacing regimes change the aboveground structure by killing the trees in their path and consuming most of the surface organic layer.

The spatial and temporal variability of fires and their effects in select ecosystems have been the topic of much research [*Amiro et al.*, 2001; *Brown and Smith*, 2000; *Collins and Smith*, 2006; *Malamud et al.*, 2005; *Noss et al.*, 2006; *Reilly et al.*, 2006; *Schoennagel et al.*, 2004a; *Shapiro-Miller et al.*, 2007]. The historic fire frequency varies dramatically within each type of regime depending on the dominant vegetation type and is well documented [*Amo*, 2000; *Wade et al.*, 2000]. Recent changes in the fine-scale patterns of fires are not as well characterized [*Morgan et al.*, 2001; *Schoennagel et al.*, 2004a; *Schwind et al.*, 2010].

3.2.2. Storms

Wind storms are the most common natural disturbance process in eastern forests where fire is rare [*Lorimer*, 2001]. Wind storms include hurricanes, tornadoes, and straight line wind storms that are conductively produced by thunderstorms, such as Derechos and down bursts of different sizes. Frost and ice storms also affect forested areas. The drivers of all of these storms are primarily climate variables, therefore different climate regions are characterized by distinct storm patterns.

Locally the behavior of wind and their effect on forest are a function of topography, wind direction, soil type, forest composition, and forest height and density [*Foster*, 1992]. Wind and ice storms predominantly affect large overstory trees releasing understory and encouraging already established species. Lag times between initial damage and mortality can take years, complicating assessments [*Sheffield and Thompson*, 1992]. Ice storms followed by wind result in more breakage. Heavy rainfall and saltwater storm surge from hurricanes also creates gaps in the forest landscape. Reports on the forest mortality rate of windstorms in forests are limited, and vary widely by event [*Everham and Brokaw*, 1996; *Foster and Boose*, 1995; *Jacobs*, 2007; *Zeng et al.*, 2009] though some generalities can be found [*Peterson*, 2000].

The location and frequency and severity classes of hurricanes and tornadoes regimes are well characterized [*Fujita*, 1971]. Major hurricanes, those that rank 3 or higher on the Saffir-Simpson scale, occur within 160 km of the coast every two out of three years [*Hooper and McAdie*, 1995]. Tornado events are spread across the East with the highest concentration in the North to South band of land between the Rocky and the Appalachian mountains and with frequencies that vary annually [*Broyles and*

Crosbie, 2010]. Derechos have different frequency corridors depending on the season (and related jet stream pattern) [*Bentley and Mote*, 1998; *Coniglio et al.*, 2004]. There is no comprehensive data set on ice storms.

3.2.3. Insects and Pathogens

There is little forest in the US that is not under some level of threat of disturbance from insects and disease, with some areas being under mortality risk from 7-9 agents at a time [*Krist et al.*, 2006]. The main killers are bark beetles, inner-bark borers, gypsy moth and root diseases [*Barnes et al.*, 1998]. Climate affects both the host trees resistance and the life history strategy of insects though the mechanisms are not well understood [*Wilkens et al.*, 1998]. Research suggests that climatic drivers can be amplified by human activities [*Raffa et al.*, 2008]

The forest area damaged and severity of damage by insects depends on factors such as the type and life cycle of insects, and the characteristics of forest stands in the 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 a normally, small rate of mortality [*DNR)*, 2008]. At endemic population levels they cause gap dynamics at small scales by killing weak trees. When trees are stressed from drought or over stocking, insect populations can reach epidemic levels causing high rates of mortality in host tree [*Raffa et al.*, 2008].

Biotic agents can be narrowly host species and age specific. Therefore the spatial and temporal patterns of any particular insect or disease is tightly correlated to the spatial patterns of its favorite host and its cold tolerance [*Bentz et al.*, 2010]. For current and historical patterns of individual pests and pathogens the USFS maintains copious statistical records [*(USDA)*, 1995; 2000; 2005; 2009].

3.2.4. Silviculture

Silviculture encapsulates a suite of forest management activities, including clear cut, partial and salvage harvesting, nutrient management, thinning, fire management and replanting of previously forest lands (reforestation). Harvest activities affect more land across the US than any other forest disturbance process [*Smith et al.*, 2009]. Harvest activities in the US are driven by policy, economics and land ownership across multiple scales [*Adams et al.*, 1998; *Bengt*, 2006; *Wear and Murray*, 2004; *Wear et al.*, 1988]. For example, federal laws such as the Endangered Species Act and Clean Water Act affect harvest activities on all public and private forest lands not just those under federal jurisdiction. All lands in the National Forest System are regulated under Federal law. Forestry on other lands in the US is regulated by a patchwork quilt of federal and state laws. As of 2000, 14 of the 48 contiguous US states did not have state laws on forest resources including, Connecticut, Georgia, Florida, Illinois, Missouri, Iowa, Nebraska, Kansas, Texas, Nevada, Utah, Arizona, Rhode Island, and Montana [*Wildlife*, 2000].

Harvest activities ranges across a severity continuum. The intensity and pattern of the cut affect the composition, structure and productivity of the stand as can management

[*Schroeder et al.*, 2007]. For example clear cuts if the resulting gap has a diameter twice the height of the stand, will favor the invasion of pioneer species where natural regeneration is allowed [*Barnes et al.*, 1998]. Research shows that a planted pine forest in the South, under intensive management, sequesters carbon twice as fast as a naturally regrowing pine stand over the first two decades [*Smith et al.*, 2006]. Clear-cut harvests remove >80 % of the tree basal area in a site, while partial-cuts range from removing 79% of basal area to creating small gaps in forest cover to encourage establishment of pioneer species (WB smith, personal communication).

The spatial and temporal patterns of harvest regimes vary across space and time (see figure 2-12). Forest harvest intervals and regrowth cycles vary according to site productivity and management intensities. Research has highlighted the fine scale patterns of harvest and their change over time over limited extents [*Evans and Perschel*, 2009; *Gustafson*, 1998; *Jin and Sader*, 2006; *Sader et al.*, 2006; *Schroeder et al.*, 2011].

In effect, human-managed disturbance has created a new forest change regime. In the southern U.S. forests, the rapid growth and removal of trees on pine plantations is unprecedented. The 20+ year commercial harvest rotation interval on southern pine plantations is made possible due to extremely fast recovery rates that depend on intensive inputs and forest management [*Fox et al.*, 2004]. Also, there is no natural precedent for single-cohort silviculture, the logging practice of creating and maintaining even-age stands [*Seymour et al.*, 2002].

3.2.5. Conversion to developed land

Deforestation and afforestation are processes that decrease and increase the overall amount of forest land, respectively. Over multiple decades, conversion between forest land, agriculture and grassland are often cyclical, and do not necessarily result in net forest loss. Forest land conversion to suburban/urban land is the only wide spread, one way transition change process explicitly considered in this study. Forest conversion processes are driven by the interaction across multiple scales of policy, markets and the personal interests of land managers [*Alig et al.*, 2003].

Deforestation events do not just alter a select part of forest composition and structure, they erase it. Therefore, the associated severity of these events is always high. Afforestation has no associated severity.

The spatial and temporal patterns of forest conversion vary with the specific process and time period examined. For example, peaks in total forest area in the South occurred in history at the same time that afforestation was fiscally supported by federal legislation [*Alig et al.*, 2003]. However, these forest lands may undergo deforestation if fiscal support declines or does not stay competitive with land rent paid for other land uses, such as agriculture [*Roberts and Lubowski*, 2007]. Conversion of forest land to agricultural land was the major type of deforestation at the turn of the 20th century; at the turn of the 21st century it is conversion of forest land to residential [*Houghton and Hackler*, 2000; *Wear and Greis*, 2002]. In small amounts, other types of deforestation still occur in the US, such as conversion to grassland, or water reservoirs [*Alig et al.*, 2010; *Birdsey and Lewis*, 2003].

3.2.6. Multiple Disturbance Interactions

Often one type of disturbance will follow another in the same stand through time, making the effects on vegetation difficult to assign to one specific process. Fire, windfall, disease and bark beetles are disturbance processes that often interact [*Everham and Brokaw*, 1996; *Liu et al.*, 2008; *McIntire and Fortin*, 2006; *Saveland and Wade*, 1991].

Harvest patterns can mitigate or exacerbate damage from other disturbances in the same location. The severity and damage from wind storms is affected by the legacy of previous harvest patterns [*Larouche et al.*, 2007]. Salvage logging after insect or wind is used as a tool to prevent severe fires [*Lindenmayer et al.*, 2004; *Nelson et al.*, 2008; *Radeloff et al.*, 2000; *Robinson and Zappieri*, 1999]. McNulty [2002] estimates that 13% of damaged trees are salvage logged after catastrophic storms, but the rate varies depending on access and timing of events. For overstocked forest stands salvage and sanitation harvests are recognized as important forest management tools to prevent outbreaks and control severity of insect damage and fires [*Radeloff et al.*, 2000; *Samman and Logan*, 2000]. Reports on the frequency and extent of these practices are limited.

Neighboring processes also affect each other. Catastrophic storms affect local harvest rates [*Prestemon et al.*, 2001]. The location of population centers affects nearby harvest rates [*Nowak et al.*, 2005; *Wear et al.*, 1999]. The demand of water and nutrient resources for high rotation harvests may stress neighboring vegetation stands making them more susceptible to other disturbance processes [*Sun et al.*, 2001]. Currently, there is evidence of long-term damage to soils and alteration of southern pine beetle outbreaks related to harvest activities [*Coulson et al.*, 1999; *Jackson et al.*, 2005].

3.3. Data and Approach

For tornado, hurricane, fire, harvest, insects and suburban/urban conversion processes raster and vector data of varying spatial and temporal scales were modified and compiled into a single database in ARCGIS 9.x. Table 3-1 summarizes the data source, type, scale and gaps (in space and time) specific to each data set. Value added layers, such as total number of disturbances per area, duration of insect outbreaks, and others were calculated with custom python and IDL code. The geodatabase with original data layers and value added layers are being archived at the ORNL DAAC (http://webmap.ornl.gov/) and will be available for download.

Table 3-1: Ancillary Geospatial Data for Forest Change Processes

Change Process	Measurement method	Data Source	Spatial		Temporal	
			Grain	Extent	Grain	Extent
Fires	Landsat, DNBR change	MTBS http://MTBS.gov	30m grid	national	annual	1984-2007
Hurricanes & Tornadoes	Ground measurements-wind speed	U.S. National Hurricane Center http://www.nhc.noaa.gov/pastall.html	lines	national	annual	1851-2008

Suburbanization/ Urbanization	Decadal Census - # new housing units	[*Theobald*, 2005]	100m grid	national	decadal	1940-2030
Suburbanization/ Urbanization	Landsat, Land Use Change	NLCD Retrofit Change Datahttp://www.mrlc.gov/changeproduct.php	30m grid	national	Decadal	1992-2001
Suburbanization/ Urbanization	Landsat, Land Use Change	NLCD 2001/2006 Land cover Change http://www.mrlc.gov/nlcd2006_downloads.php	30m 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
Pests & 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 & OR: 1980-2010; CA: 1993-20009; AZ: 2000-2009; NM: 1998-2010; states in the NC and NE regions: 1997-2009; NV,UT and southern ID: 1991-2010; Northern ID, MT ND: 2000-2008; most of Wyoming, CO,SD, NE, KS: 1994-2010
Southern Pine Beetle	Aerial Spot Detection Surveys	[*Williams and Birdsey*, 2003]	County polygons	SE and SC states (except OK)	Annual	1987-2004

3.3.1.Fire

MTBS project provide annual geospatial data for individual fires that are greater than 404 ha (1000 acres) in the west and greater than 202 ha (500 acres) in the East. Severity of each fire, the degree to which the above ground vegetation on the site has been altered, is assessed by a mixture of using the calculated difference in the normalized burn ratio (DNBR) vegetation index for pre and post fire imagery and analyst interpretation [*Eidenschenk et al.*, 2007]This data source is still under production and there are many data gaps in time and space, especially in states east of the Mississippi river.

A series of synthesis maps of fires from the MTBS data were created. Raster datasets for fires that occurred between 1984 and 2008 in the CONUS were downloaded from the MTBS project. Fires were filtered by their severity class into low, moderate and high severity fires for each year. Individually the fires in each of the three categories were summed across all years in three separate maps. Also a frequency map for only moderate and high severity fires was created.

3.3.2. Wind

The datasets on tornado and hurricane events are available in text file and shapefile formats, respectively. Only tornado and hurricane events with wind speed violent enough to cause significant forest damage, category 3, 4 and 5 on the Saffir-Simpson Hurricane Wind Scale, and which occurred between 1984–2008 were used.

Text files with the geographic coordinates of tornado touchdown, take off, width and length data were downloaded, imported into ARCGIS, converted to line data and buffered to create polygons using their associated width data. Hurricane path shapefiles were downloaded. No geographic precision is documented for the tornado or hurricane data. The shapefile lines were buffered out to 50 km (19 miles) in ARCGIS to create area polygons, following a more conservative version of the approach in Costanza *et al.* [2008]. Polygons were then converted to points located in the center of 250m grid cells to create annual maps of the area of land potentially affected by moderate to severe hurricane and tornado winds. A synthesis frequency map of the area potentially affected by moderate to severe hurricane and tornadoes was created by summing the number of points per cell across all years of data (1984-2006).

3.3.3. Insects

The USFS Forest Health Protection (FHP) program has collected aerial digital sketch (ADS) maps of insect and disease related forest damage, observed remotely from an aircraft and documented manually onto a map, since the 1940's [*Johnson and Wittwer*, 2008]. The general purpose of these data has been to detect and delineate new pest outbreaks and generate maps over large areas.

Data users are warned that the technique has spatial and thematic inaccuracies, with unknown sampling biases. It is suggested that the ADS maps are best used as coarse portraits of landscape level forest conditions, not precise for precise measurements, since observers have roughly 20 seconds per kilometer to recognize, classify and record the activity they see [*Johnson and Ross*, 2008]. In 2005, a limited assessment over the Rocky Mountain region found overall accuracies of 61% that increased to 79% when a ± 500m spatial tolerance was allowed [*Johnson and Ross*, 2008]. Availability of annual digitized aerial surveys varies widely by FHP region (Table 3-1).

The FHP program is divided into 8 regions for the contiguous US. Regional ADS data was downloaded, imported into ARCGIS, converted to shapefiles were necessary and reprojected to a common projection, the USA Contiguous Albers Equal Area

Conic projection.

A synthesis document outlined national standards for the ADS data collection [*(USFS)*, 2005]. However, when the 146 ADS shapefiles were explored, high variability in the coding for different damage types across regions was found. For example, ADS guidelines specify that the 'severity' attribute be used only for defoliation events, yet it was found to be used sporadically across all regions for mortality events as well. Also, ADS guidelines suggest the dead trees per acre ('TPA') attribute be used to record the measure of severity for mortality events. In the East, measures of mortality severity were more often coded using a combination of the 'host pattern' and 'severity' attributes instead of 'TPA'. Only % of eastern mortality polygons had a 'TPA' value recorded. Most of the West followed the mortality-'TPA' guideline. However, region 6, which covers OR and WA states, uses a completely different coding system than any other region across the country.

Using custom python code, each ADS polygon was ranked according to a severity-confidence (S-C) rank of high, moderate and low. Due to differences in data collection across the FHP regions, three different logic sets had to be developed for the ranking. One for region 6 (covering OR and WA), one for region 9 (covering all of the NE and NC states) and one logic set for all other regions. Region 8 (covering the Southeast and South Central US, see figure 2-1) does not release digital ADS data. The S-C ranks, outlined in appendix D, were developed during data exploration of the following four attributes (or their equivalent) in each region: 1) damage type,

2) damage agent, 3) pattern of the host species, and 4) severity. For this work, the damage type attribute was recoded into only 3 categories: 1) mortality 2) defoliation and 3) damage. The latter category includes discoloration, dieback, top kill, branch breakage, main stem broken/uprooted, branch flagging and other damage. Region 6 does not provide damage type or pattern of host data. Damage agents not related to insects and disease such as fires, wild animals, domestic animals, abiotic damage, competition, and human activities were filtered out of the analysis. In most cases the polygons in these categories represented only a small portion of the recorded polygons in the ADS data sets. Insect and disease polygons that fell into the low, moderate, high S-C categories were mapped for each year.

A series of synthesis maps related to insect disturbance across the CONUS was produced to highlight the cumulative area of low, moderate and high severity/confidence across all years. To accomplish this, each shape file was converted to a 30m raster and exported out of the GIS for further processing with IDL (due to the less than 2GB file size constraints of geoprocesssing with ARCGIS). IDL code was written to import, query and sum the large annual rasters for each region. A cumulative frequency map of only moderate to severe insect and disease disturbance was created by weighting the severity-confidence ranks then summing the annual data layers. The frequency and severity of events in the same location were used to calculate the cumulative frequency map. For example, low S-C events had to occur more than 4 years, moderate S-C events more than 2 years, high S-C events once, or a combination of low and moderate events had to occur through time in the same pixel for the damage to be represented on the cumulative damage map.

The South only releases data at the county level, so data from this region was processed with a different approach. Although many insects and diseases affect the southern forests of the US, only data related to Southern Pine Beetle (SPB) was used here as it is the most destructive pest in the South [*Price et al.*, 1997]. SPB is a boring insect that has a 100% mortality rate among host species, which includes all types of pines in its distribution range. The distribution range of this pest is heaviest in the south central and southeastern United States but also stretches up to NJ and PA over to AZ and NM and down through Mexico and parts of Central America [*Coulson et al.*, 1999]. SPB prefers certain pines for hosts including, Shortleaf, Loblolly, Virginia, and Pitch pines. The first two are commonly grown on pine plantations. Some pines, such as Longleaf and Slash pine, have lower susceptibility to infestation [*Martinson et al.*, 2007]. Data on SPB spots are aggregated and released at the county level across the South. These data was summed to create a frequency of infestation layer across Southern counties.

3.3.4. Harvest

The USFS Timber Product Output (TPO) uses surveys to record the measure of the volume of timber that has been harvested as it passes through local mills to be processed into products [*Johnson*, 2001]. Data includes estimated volume of removals calculated from round wood, residuals and other events. The latter category includes salvage and land clearing activities, while the first two are specifically related to logging activities.

Logging volume removals data are normalized by the amount of county forest land in 1997, the first national level TPO reporting period, or the closest possible previous year [*(USDA), U S D o A*, 2010; *(USDA), U S D o A F S*, 2010] (see appendix E for the specific year of the USFS inventory used for each state). The tabulated harvest intensity for 1997-2002, 2002-2007, and 1997-2007 periods are summed and mapped to county boundaries. The USFS cautions data users on the spatial accuracy of the data because lumber may pass county and state boundaries before it reaches the mill destination.

3.3.5.Conversion

Theobald [2005] assembled census data and other ancillary layers to produce decadal geospatial records of housing density across the US, mapped to a 100 m grid. 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) were used to threshold the 1980 -1990 and 1990 -2000 data sets. All forest conversion to suburban/urban land use was assumed to be high severity. Individual rasters for housing density increases (HDI) between 1980-1990 and 1990-2000 were created. The two rasters were summed to create a frequency of HDI from 1980 - 2000. No forest layer was associated with the original dataset, so these layers are not specific to HDI on forest land only.

The National Land Cover Data (NLCD) set change products, from 1992-2001 and 2001-2006 are derived from image differencing Landsat imagery [*Fry et al.*, 2009;

Xian et al., 2009]. NLCD measures land cover changes, at three snapshots in time over 15 years (circa 1992, 2001 and 2006), and is a better source of data on area of affected by long-term conversions than those affected by rapid cyclical forest disturbance and regrowth [*Fry et al.*, 2009]. Error assessment of change classes is not available.

Separate rasters were created from the NLCD retrofit change dataset (1992-2001) and the 2006 NLCD change layers 2001-2006). The two data sets record different amounts of forest for the 2001 epoch. Supporting texts indicate that the 2001 data was updated for change analysis with the 2006, so cross walking from the 1992, 2001, and 2006 datasets is not advised [*Xian et al.*, 2009]. Individually the two datasets were masked for classes related to forest to suburban/urban development type changes only, using codes specific to each of the two NLCD datasets. The two outputs products were summed to create a 1992-2006 cumulative conversion map. There were no cases where in a pixel the two datasets overlapped through time. All of the NLCD forest conversion events are assumed to be of high severity.

3.4. Results and Discussion

This work builds on the observations and data sets of previous research efforts. It is not meant to be an in-depth investigation of any one particular forest change process, but rather to provide a better geographic perspective on each process and their overlap. The geodatabase provides a new environment for integrated analysis on all of the processes affecting forest lands across the US at any particular period. As such, this work is a first step towards building the capacity to understand forest dynamics as the product of many overlapping processes and how they interact with other earth systems.

3.4.1. Individual Processes

3.4.1.1. Fire

The MTBS project releases annual images of burn severity for 6 different regions across the CONUS. When synthesized into one data set, these data summarize the repeat frequency for high, medium, and low severity fires across all years of the MTBS record, 1984 -2008. Statistics generated from the summary fire data layer can be used to show for each fire severity class the total area affected and frequency of repeat fire events that occurred in the same location (Figure 3-1).   The mapped data show the location of the singular and repeat events of all fires, not just those in forest cover, and are useful for fine scale spatial analysis (Figure 3-2).

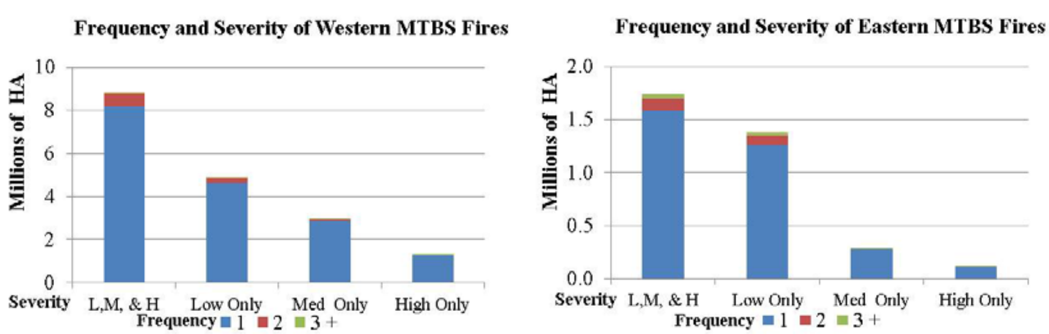


Figure 3-1 : The area (ha) of fires recorded for MTBS are for all land cover categories, not just forest cover. Low severity fires had the highest occurrence of fire reoccurring in the same location.

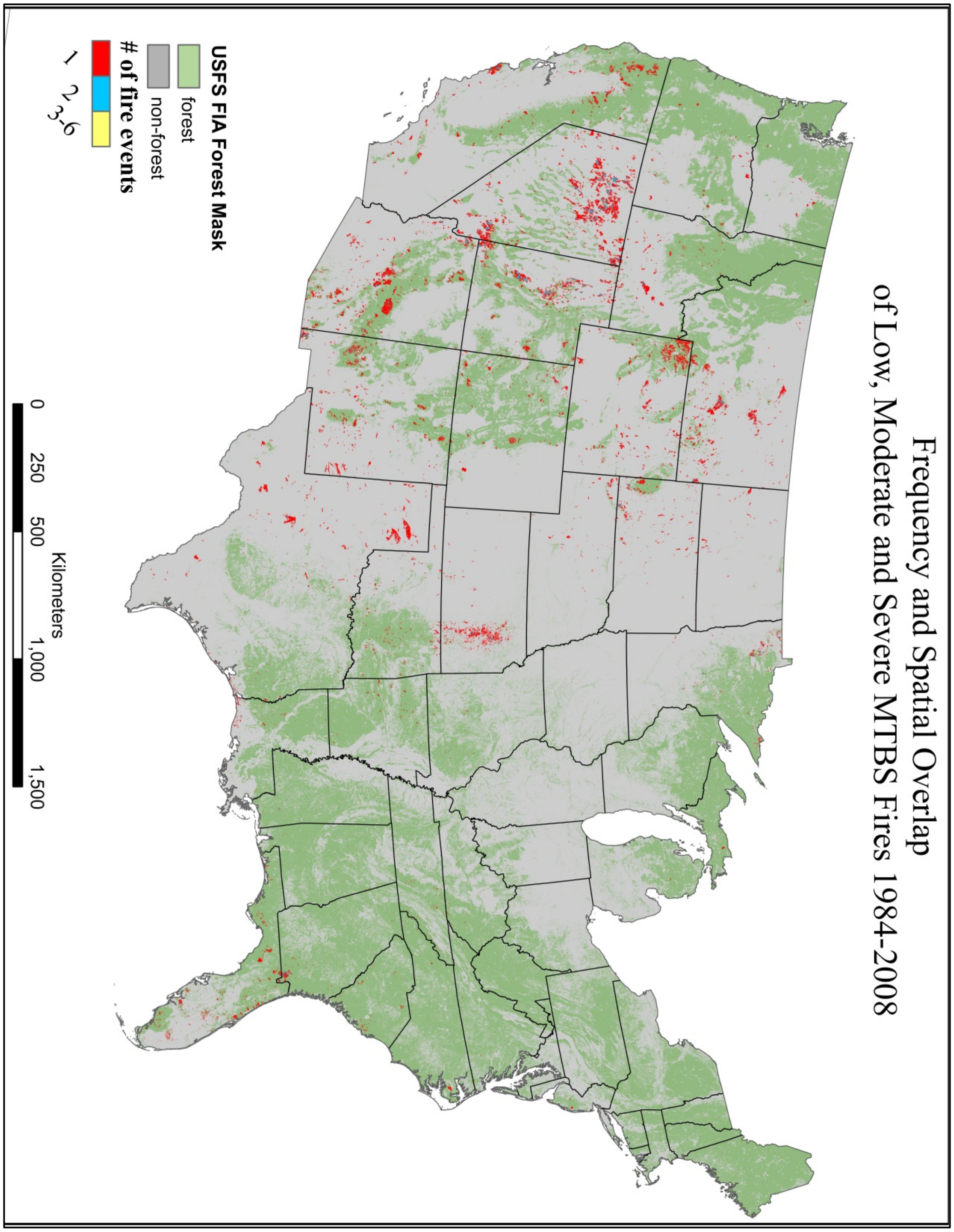


Figure 3-2: According to the MTBS fire record, the frequency of fires is much higher in western states, than eastern. Imagery for all states East of the Mississippi have not been processed and

released to the public yet [*(MTBS)*, 2010].

For multiple reasons, the reported fire damaged area by MTBS may be an underestimate of "true" area burned. In the case of ground fires, which burn under the canopy, optical remote sensing data will have trouble detecting the signal if leaf on images are used [*Frolking et al.*, 2009]. The minimum threshold of fire size (see section 3.2.1.1) will miss many of the small prescription fires used to prevent wildfires and prevent competition on timber plantations. Finally, the imagery used in the MTBS study may have data gaps due to a known failure on the Landsat 7 satellite with the scan line corrector (SLC) that began in 2003 [*Markham et al.*, 2004]. When the SLC is not functioning properly telltale 'no data' lines appear in the imagery. It is clear that the MTBS project uses some SLC-off Landsat 7 data, but it the quantity and cumulative effects on fire detection are unknown (Figure 3-3). On the project website, MTBS lists statistics for fires by life form type, which were calculated by masking the classified MTBS images with the NLCD 2001 forest class. A quick analysis shows that if the 2001 NLCD mask is used 7,436,231 ha of forest were burned, while if the FIA forest mask (250m) is used 4,751,266 ha of forest were burned. These counts are for absolute forest area, meaning locations that have multiple fire events were only counted once. This quickly shows that, the version of forest mask used for such analysis can add extra sources of uncertainty. These two forest masks are from roughly the same time period.

Figure 3-3: Original MTBS data from the East Zone Complex Fire of 2007 in Idaho. The map legend shows the data categories of the classified images. Areas where the Landsat 7 imagery had dropped scan lines show as parallel black stripes in the finished product.

3.4.1.1. Wind

The changing number, size and intensity of wind storms through time has been focused on in discussion on the impact of climate change and future predictions [*Peterson*, 2000; *Webster et al.*, 2005]. What remains missing is spatially explicit data on forest area affected by hurricanes and tornadoes. The actual amount of land area affected by individual hurricanes is not well characterized. Costanza [2008] used swath widths of 100km on each side when estimating hurricane affected areas. This work used 50 km swaths, an area supported in the literature for the widths of some major U.S. hurricanes [*Jacobs*, 2007]. Each individual tornado record included data about the width of the storm that was used to create a tornado specific buffer size. Maps for individual years (1984-2006) of the extent of moderate to severe hurricane and tornado events were created. Because the data was brought into the geodatabase, data for all years could be combined into a new spatial data set on the frequency of storms, 1986-2006. This data highlights the limited spatial range and degree of repeat events of this disturbance process through time (Figure 3-4).

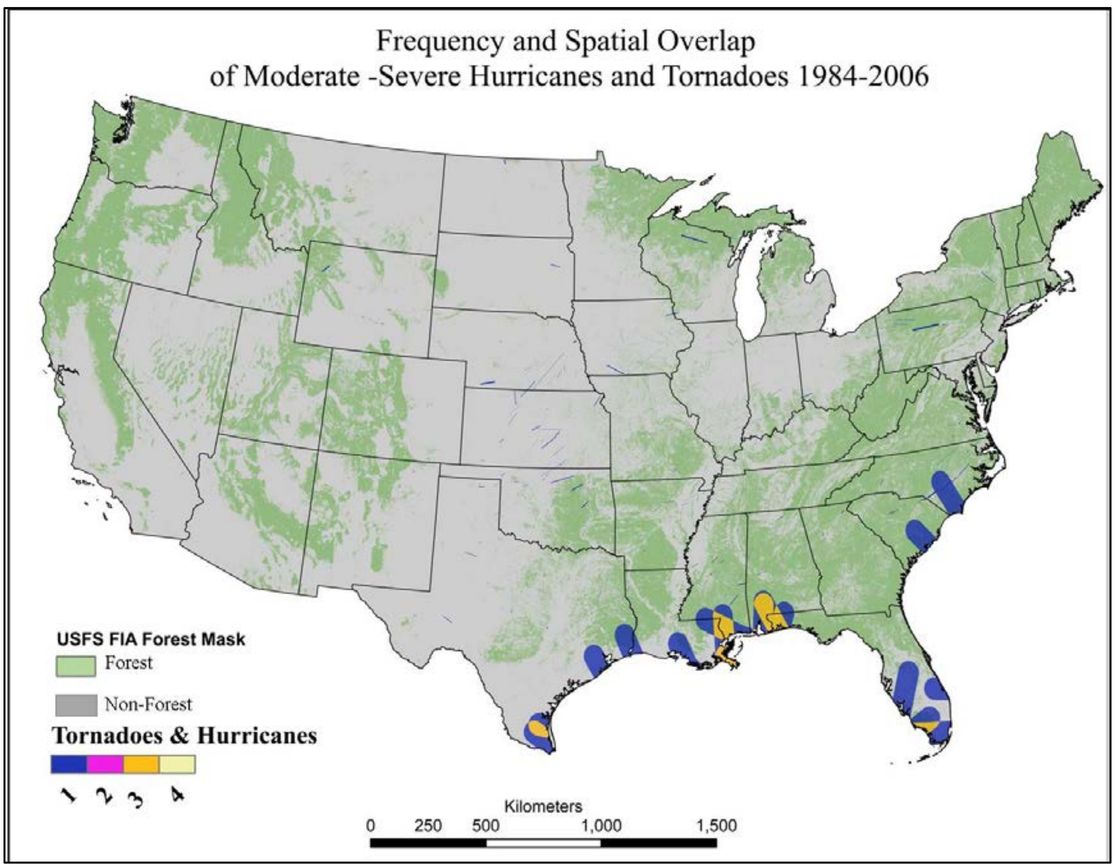


Figure 3-4: Subset of storms occurring between 1984-2006, categorized as H3-H5 and capable of substantially damaging trees. The wind frequency layer is represented at 30 % transparency to show where the wind events overlapped with forest areas from Ruefenacht et al. [2008].

The actual area of forest damaged within the wind storm paths is difficult to estimate. Within each storm area footprints there is a spectrum of disturbance severity from completely unaffected to complete mortality. Forests located within the paths of wind storms are more at risk of disturbance; however, vegetation characteristics, site factors, physiography, etc. affect the severity at any particular location. Therefore, the spatial paths of storms themselves are not always reflective of the spatial distribution of damaged forest areas. Modeled wind swaths for hurricane events may improve estimations of the area of exposure to severe winds [*Powell et al.*, 2010] compared to the coarse polygons used here. No concise spatial data set exists for Derecho and ice storms so the amount of forest area potentially damaged by storms is higher than what was mapped here.

Estimates of the forest area within hurricane and tornado paths can be generated, but will have uncertainty specific to the mask used of forest land location. Forest extent is not well documented at high spatial and temporal resolutions. For example, the map is shown with a 2004 era 250 m mask of forest area [*Ruefenacht et al.*, 2008]. However, the forest extent in 1984 at the beginning of the wind data series would have been somewhat different. The earliest available forest location data is from the early 1990's. For example, if the FIA (250m) forest mask is used then 6,292,838 ha of forest were located in moderate to severe hurricane and tornado paths. However, if the NLCD forest mask is used (30m) only 3,158,488 ha are located in storm paths (storm data was resampled to agree with the resolution of the NLCD forest mask). If the NLCD data is resampled to match the resolution of the wind layers than 3,281,815 ha are located in the storm paths. These counts are for absolute forest area, meaning locations that have multiple storm events were only counted once. The difference in area estimates calculated using different forest masks is an added source of uncertainty. These two forest masks are from roughly the same time period. Further work will is needed to characterize the local heterogeneity in severity of damage across these areas.

3.4.1.2. Insects

Historical insect ADS data contains fine scale spatial and temporal patterns that are not resolved by the tabular state reports released by the USFS. A synoptic map of the frequency and distribution of known insect damage events was created showing the general disturbance regime of forest insects and pathogens across the CONUS at finer scales (Figure 3-5). The forest area affected by insects and pathogens calculated from the synthesis insect layer would be lower than those calculated from the individual year maps, since multiple low and moderate severity events must be observed in the same location before they are counted with this methodology. Because of temporal and spatial data gaps particular to each region, opportunistic sampling methods employed and uncharacterized measurement errors, these maps should not be taken for “truth” about the presence or absence of insect or disease damage to forest areas. For example, the recording ‘style’ of the aerial analysts impacts the spatial accuracy and precision of the derived maps and can vary dramatically (Figure 3-6).

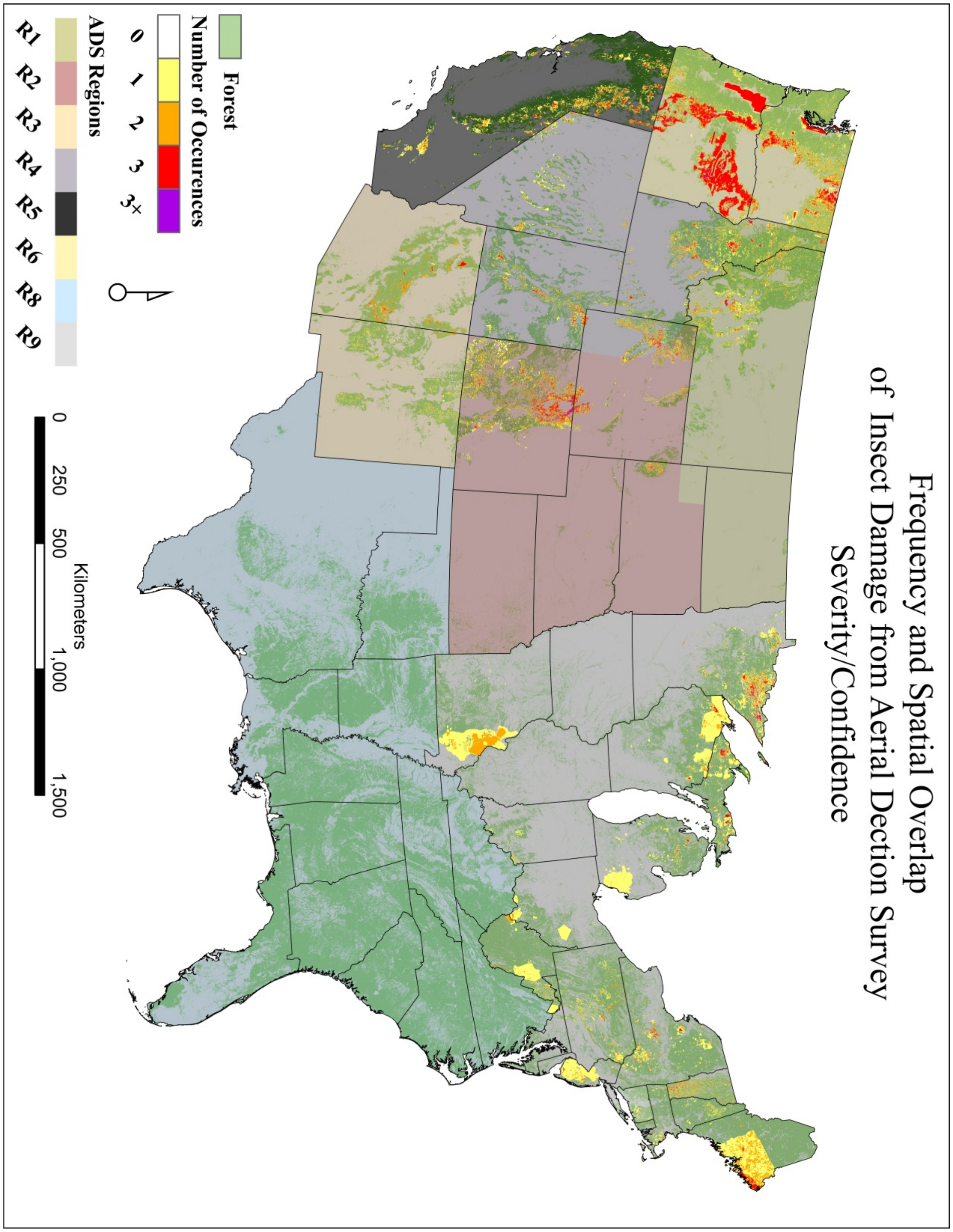


Figure 3-5 : The amount of damage in a single ADS polygon of tree damage could be patchy and affect less than1 tree per acre. In such cases the ability to use the ADS polygon as a verification or reference layer is low. So, a measure of "confidence" was added to the ADS severity codes, by

adding the individual years of ADS data together. The more years that observations are available for that location, the more confident an analyst can be that other methods of observation will detect the insect disturbance in that location.

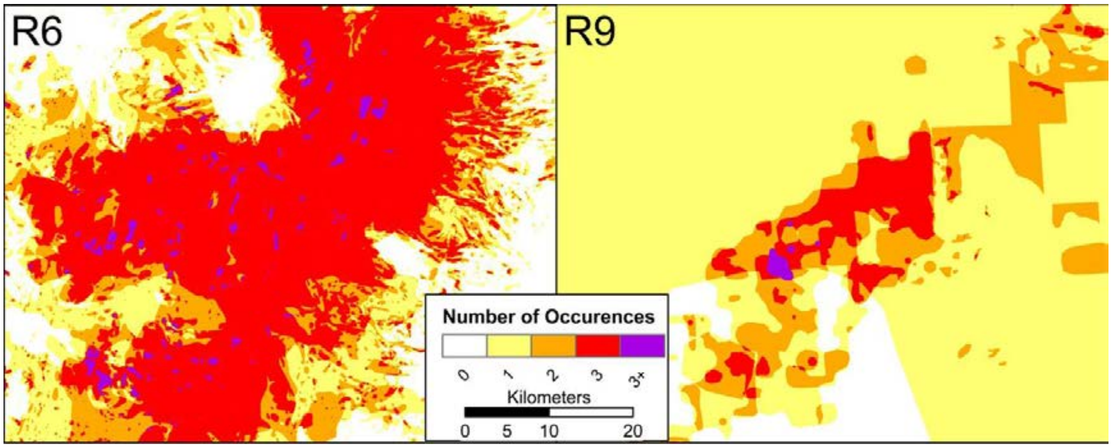


Figure 3-6 : Insect damage polygons on the left are from an area in the Cascade Mountains of Oregon in ADS Region 6 (R6). Insect Damage Polygons on the left are from an area in Northern Wisconsin in ADS Region 9 (R9). The blocky polygons in the R9 example, with hard right angles were recorded with a different style than the more organically shaped polygons in the example from R6. Both insets are at a scale of 1: 500,000.

The data manipulations used here are unique in that they combine the severity and frequency of observations into a confidence metric which is then summed through time. Complete temporal coverage outside of region 8, which includes all of the southern states, only exists between 2000 and

2009. In other years, one or more of the 6 regions does not publically release ADS maps. The graphs in Figure 3-7 and 3-8 show which regions are missing digital data for each year and the total area of *observed* insect disturbed forest area. Appendix F contains annual maps of severity-confidence that show which regions are missing data across the period of observations and were used to calculate estimates of forest area affected.

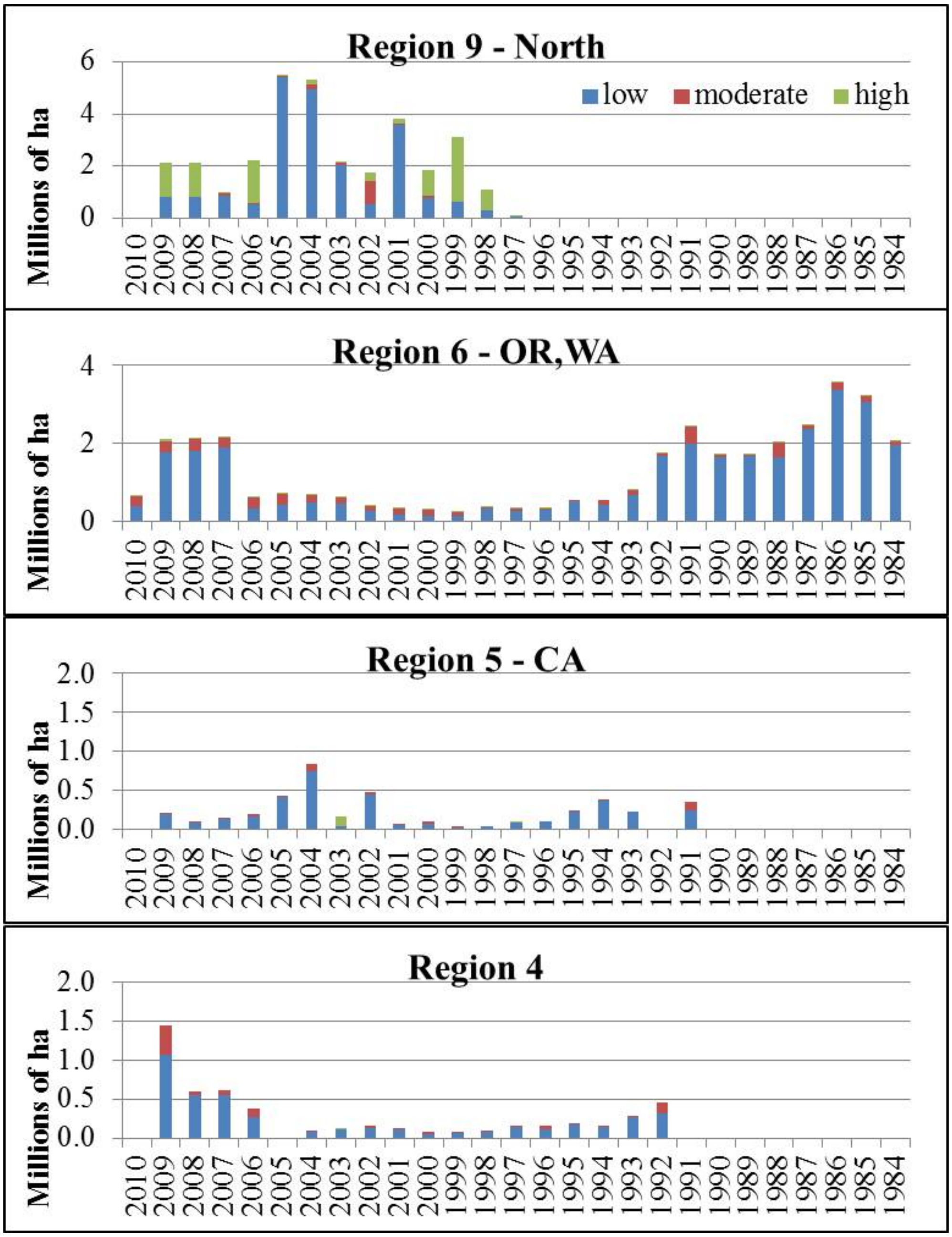


Figure 3-7 : Estimated forest area affected by insects and pathogens and temporal coverage for

region 4, 5, 6 and 9 of the USFS Forest Health Monitoring Program.

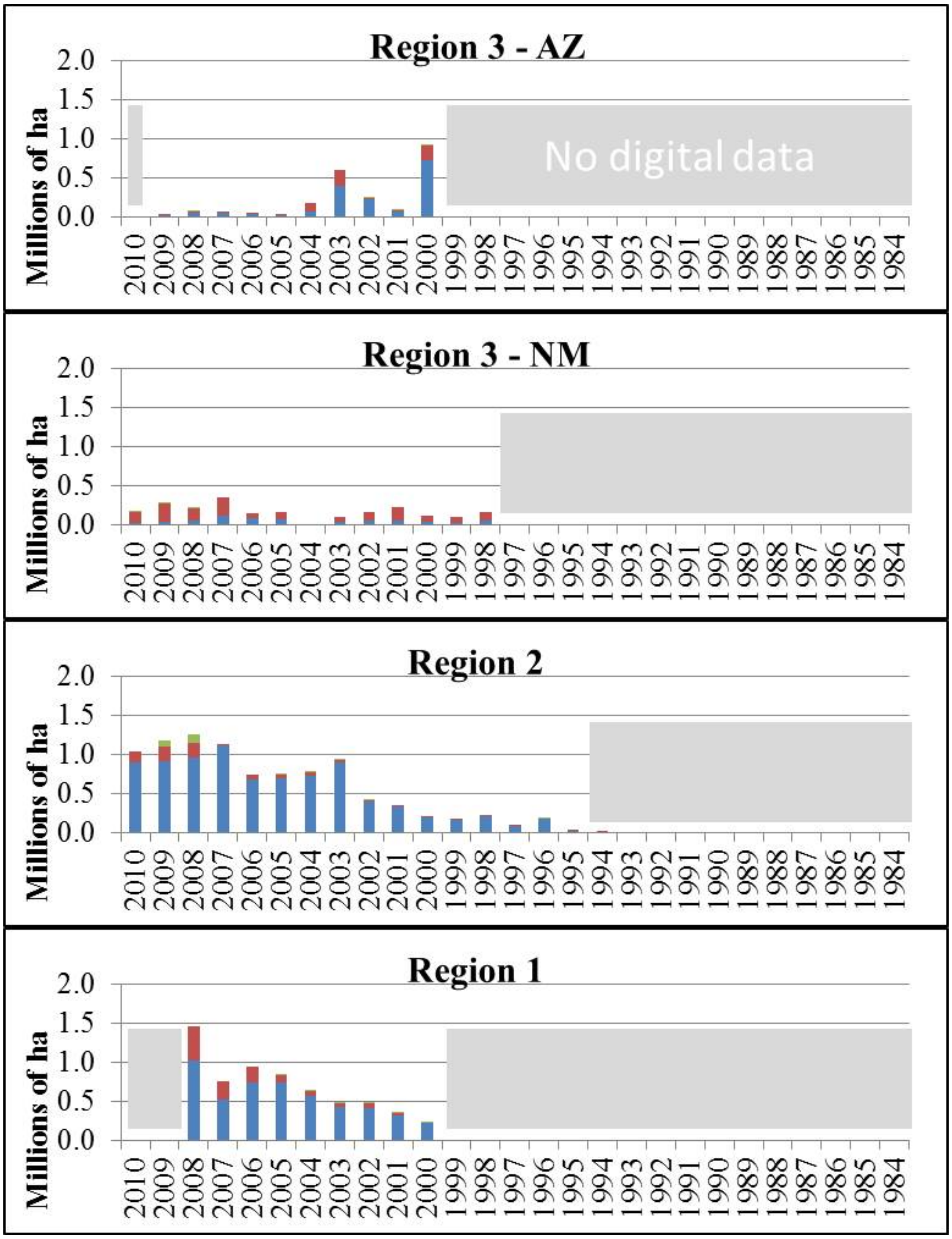


Figure 3-8 : Estimated forest area affected by insects and pathogens and temporal coverage for region 3, 2 and 1 of the USFS Forest Health Monitoring Program.

The idea of using the number of ADS observations in one location through time as a measure of ‘certainty’ when using ADS as a reference for satellite remote sensing studies is not completely new. Vogelmann et al. [2009] used ADS data for reference by combining ADS data into two separate classes, the first showed locations with 5-9 defoliation events, the second 2-4 events, and discarded areas that had only 1 defoliation event. Williams and Birdsey [2003] digitized ADS sketch maps and calculated a frequency map for spruce budworm defoliation then used the counts in a mortality function to calculate range of % at 1 km resolution.

The Southern states (Region 8 – R8) from Texas to the Atlantic do not release their ADS data at the same scale as the other regions. R8 only releases county wide data. Spatial patterns in the frequency map of Southern Pine Beetle infestations follow the general distribution of the Loblolly/Shortleaf pine species group distribution (Figure 3-9). The actual forest area affected per outbreak is likely to vary greatly. The minimum reporting unit averages out to 0.15 acres of mortality to thousands of acres. The minimum is calculated by dividing the average density of SPB host trees per acre (150 trees per acre) by the minimum reporting number for trees affected per outbreak (10 trees per outbreak minimum reporting rule). Appendix G contains individual year maps depicting the total number of SPB infestations recorded.

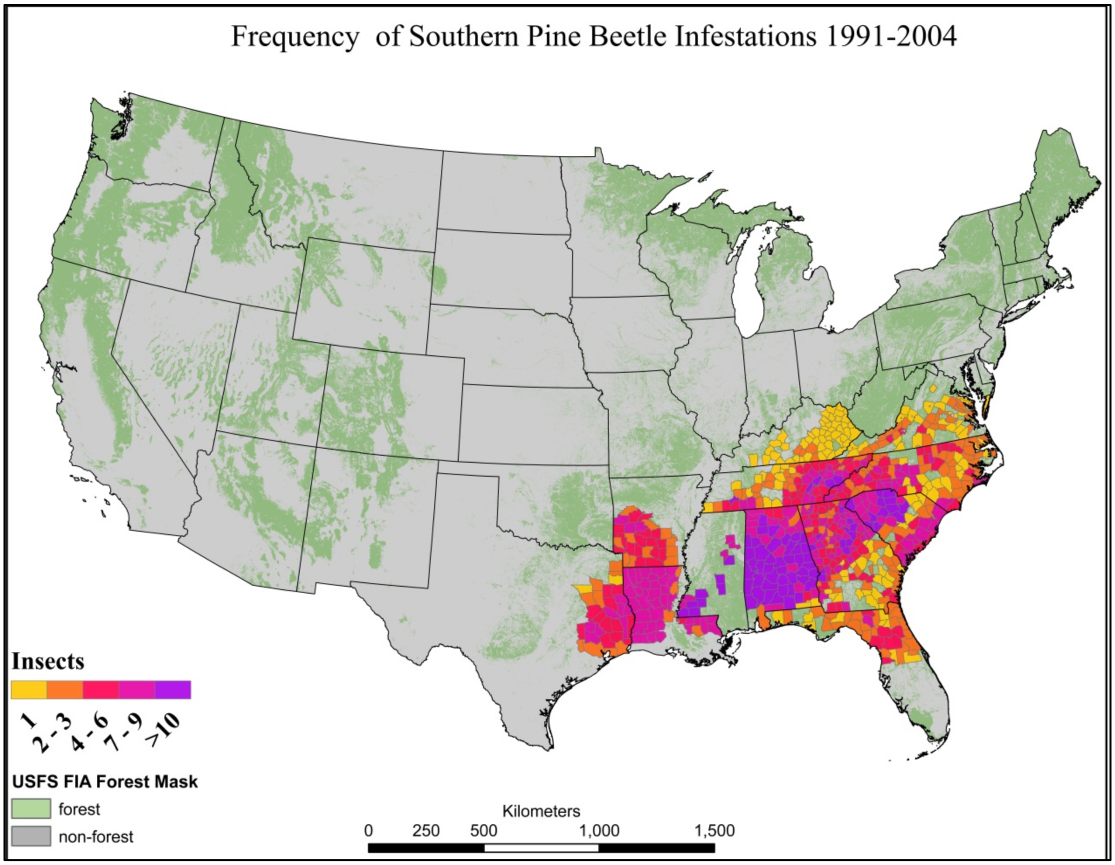


Figure 3-9 : An infestation is recorded when a 'spot' of trees, generally 10 or more trees, are observed to be infected with SPB. The average density of host pines in the South is 150 trees per acre.

"Flight polygons" of the surveyed areas exist for some years of the insect ADS (availability varies by year and by region). In theory, the flight polygons could provide a measure of areas surveyed where no insect damage was detected during the aerial survey. However, due to inconsistencies in the recording of the flown/ not flown polygons, they are impossible to use programmatically across regions or even across different years within the same region. For example, sometimes the entire state is depicted as being flown, but this is not likely a reality because of resource constraints. In other cases damage polygons are recorded in locations where there are no flight polygons.

3.4.1.3. Harvest

Timber Product Output (TPO) data are the finest spatio-temporal data that exists for the U.S. on harvest activities and therefore, are a valuable resource for understanding human-managed harvest disturbances patterns across the country. When summed and mapped the spatial patterns of harvest volume rates through time can be visualized (Figure 3-9). The largest stretch of contiguous counties with high volumes harvested are in the South, east of the Plains states, an area known as the 'wood basket' of the U.S.

To visually compare the harvest volumes for different size counties, the volume data were converted to a density measure using the county level forest land area in the denominator. The measure of forest land area per county is a static variable from one FIA inventory period and so do not account for losses or increase from growth of established stands or the establishment of new stands (from reforestation or afforestation) in volume over time. Discrepancies between earlier and later FIA inventories of forest land area suggest cautious use of the data. For example, in the 1984 and 2000 inventories of Washington State, forest land estimates for the two counties that cover the majority of Yellowstone National Park, Park and Teton counties, vary incredibly (Table 3-2). County level TPO data was mapped for each of the three times periods (Appendix H).

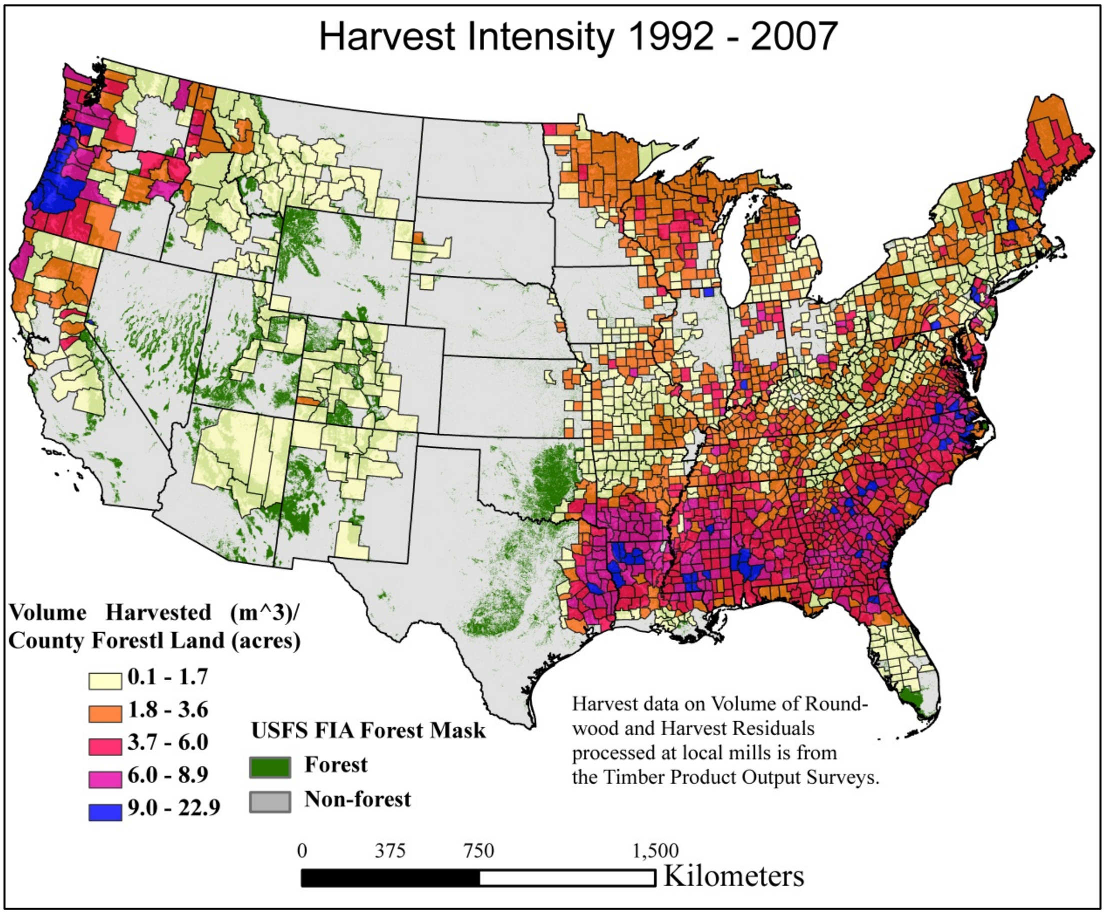


Figure 3-10 : Counties with high rates of logging are shown on this map of cumulative harvest density per county which uses the total TPO recorded volume of harvest removals (roundwood + residuals) normalized by the amount of forest area per county, extracted from FIA state inventories prior to 1997.

Table 3-2 : USFS estimates forest land area from different inventories

county	1984		2000	
	Acres FL	Std. Error	Acres FL	Std. Error
Park	109,771	23.80%	2,040,399	4.50%
Teton	5,926	108.80%	1,923,592	3.90%

When cumulative intensity is mapped, the TPO data reveals coarse trends of harvest intensity, such as low intensity in the intermountain west, high harvest intensity in Oregon and Washington State along the coast and across most of the Southeast and South Central states (Figure 3-10). When the time periods are mapped separately a decline in harvest rates in the western U.S. counties that are east of the great divide and west of the plain states and an increase in harvest rates along the Appalachian ridge in the East stand out (Figure 3-11).

Uncertainties in the TPO data set are uncharacterized and may lead to erroneous assumptions. Suspicious anomalies appear in the data but are difficult to explain. For example, it is assumed that all mills cooperate with the surveys, but there is no public record of the mills that participated for each time period or estimate of error in the volume estimates. Of the 23 counties in Wyoming, only five report roundwood removal volumes in the 1992-1997 TPO data. However, in the 1997-2002 report, 21 counties reported substantial roundwood removal volumes.

There is no way to be certain of the cause of the large increases in reported volumes for the 17 counties in question, but this trend only manifests in the data for Wyoming state. It is possible that harvested volumes increased substantially, though unlikely given the non-forest land cover that is dominant in many of these counties. For counties on the borders of other states imported harvested wood processed in Wyoming mills would be recorded in the state it was processed in. USFS reports record that in 2000 only 14 of Wyoming's counties had wood processing facilities

[*Morgan et al.*, 2005] Another possible explanation is an error in the records.

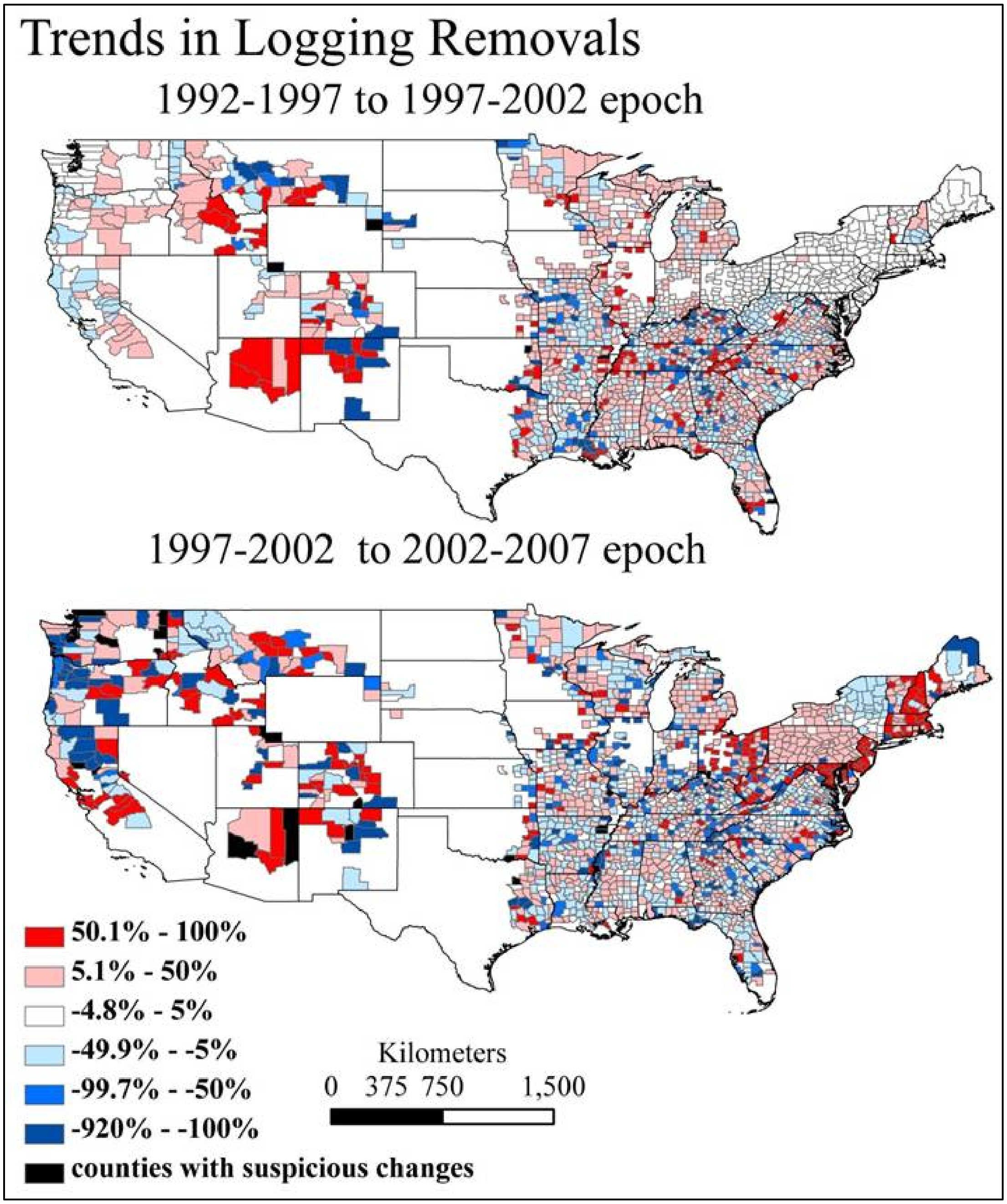


Figure 3-11 : Changes in the volume logged between different TPO surveys is represented by the amount of volume change as a percentage of the volume harvested during the prior period. Counties with less than 10% forest area, according FIA inventories of forest land area, were not

mapped. Counties with unusual trends, such as no volume reported for the first and last period, and really large volumes for the second TPO period are flagged for suspicious change rates and represented with black on the map. Large decreases in the percentage of harvested volume, such as in New Mexico counties, can have relatively low absolute harvest removal volumes.

3.4.1.4. Suburbanization

Changes in housing density are a better proxy for suburbanization than changes in population [*Radeloff et al.*, 2005a]. The census based suburbanization geospatial data from Theobald [2005] extends the temporal coverage of reference beyond the start of the NLCD data in 1992. However, ancillary data on forest location must be used to relate the data to forest canopy change. Uncertainties from the time stamp and accuracy of the ancillary forest layers add complexities for quantitative estimates of forest area converted to suburban/urban cover. Overlaying the NLCD data with polygons outlining census defined metropolitan statistical areas showed that NLCD data do capture changes outside of heavily populated areas.

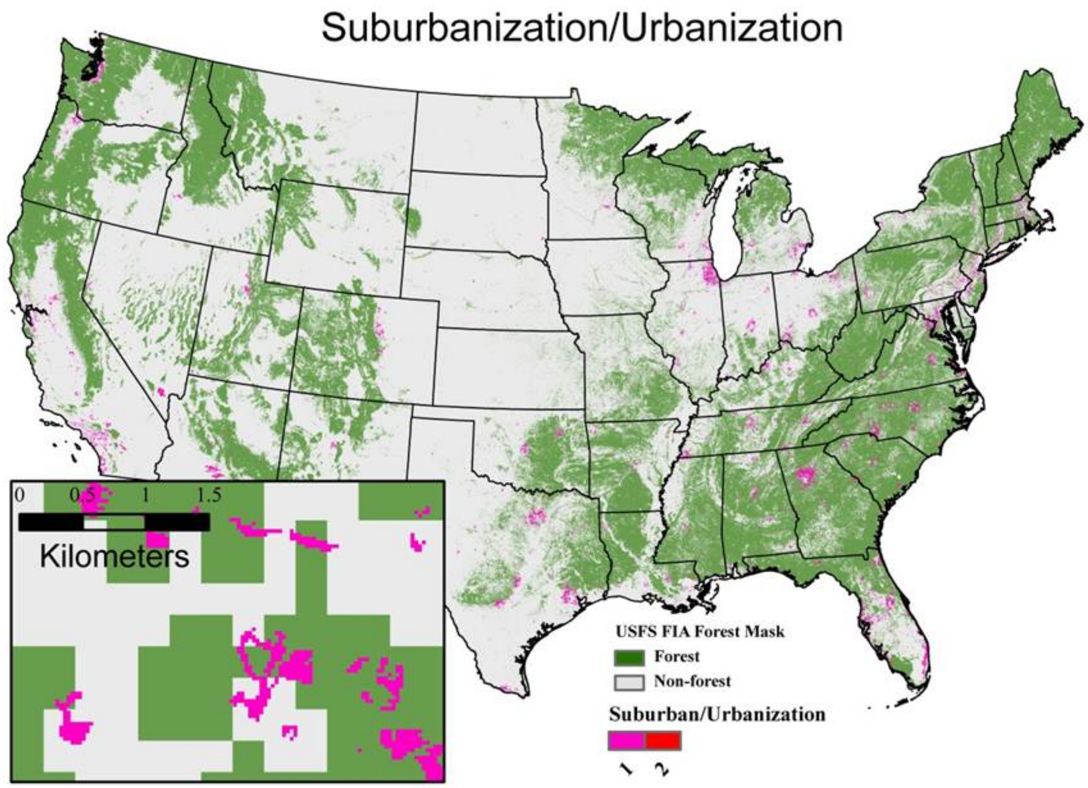


Figure 3-12 : Canopy loss from suburban/urban development is spatially localized and clustered making it difficult to see on national scale maps. Patches of tree cover loss from development are easier to observe and detect at finer scales. The inset map shows areas of suburbanization detected in the 30m NLCD data over the 250m USFS forest mask.

3.4.2.Overlapping Processes

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]. The lack of data available to support analysis of multiple disturbance processes has been an obstacle for doing integrated analysis. The multi-process database created here is a step towards filling this information gap, providing evidence of overlapping processes, across wide spatial breadths with fine spatial and temporal scales. The geodatabase provides a first look at how all of these forest change processes overlap through time and space (Figure 3-13).

Fire and insects, and insect infestations after wind storms are disturbance processes with well documented cycles of synergistic interactions [*Barnes et al.*, 1998]. However the opportunistic sampling methods of the ADS insect data prohibit a synoptic estimate of the overlap of these processes using the geodatabase. Currently a fine scale harvest geospatial data set for the CONUS does not exist for any year, so understanding the amount of salvage logging that occurs after wind, insect or fire damage is also still only possible through localized case studies. Due to the many data gaps and sources of poorly characterized uncertainty and error in the geodatabase data sets a conclusive estimate of the area of forest affected by multiple processes through time across the country is implausible.

Focused local analysis can suggest a quantitative basis for the overlap between synergistic disturbance processes through time adding a new perspective to the many local case studies on such topics. For example, local examples of the relationship between fire and hurricane events were explored using the MTBS fire frequency, wind storm, and NLCD forest land layers of the geodatabase. Analysis of these coincident layers suggested that there were few forest fires within 4 years after Hugo in 1989. The same type of analysis, using the buffered path of hurricane Katrina, shows that the forest area burned in the 12 years prior to Katrina was only 4,000 ha less the forest area burnt in just 1/3rd that time (4 years) after the storm.

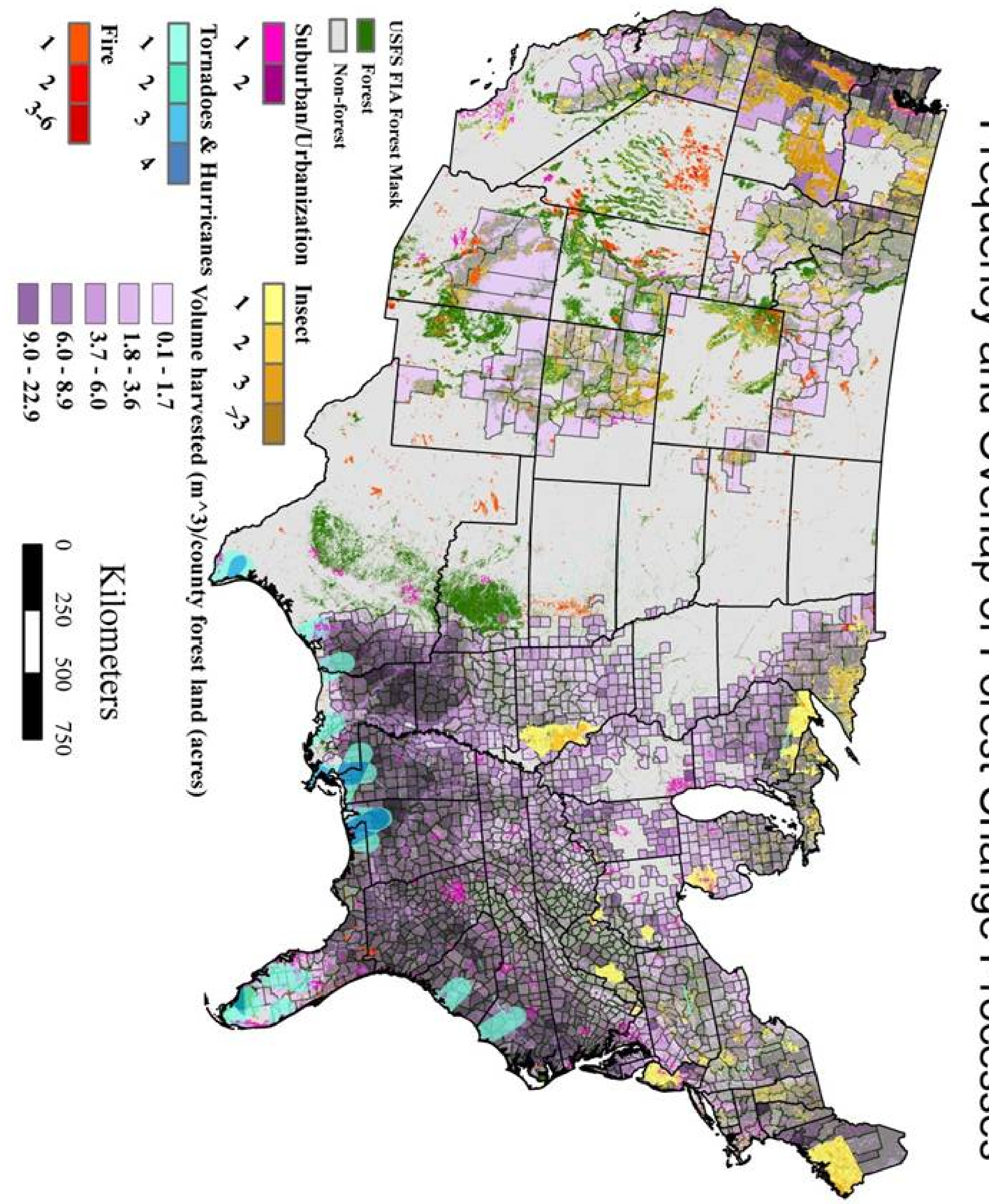


Figure 3-13 : This map represents the overlap of 5 forest change processes including, fire, harvest, insects, windstorms and suburbanization. Layers were represented as semi-transparent to better visualize of areas where more than one process was active through time. Data source for the map are listed in table 3-1. The Harvest intensity shows accumulated volume of harvest

from roundwood and residuals 1992-2007. Fire data shows the frequency of high, low, and medium fires between 1984 and 2008 on all land cover classes. The frequency of moderate and severe tornadoes and hurricane that occurred between 1984 and 2006 on any land cover category are displayed in blues. The years of data used for the insect region vary by region (see section 3.3.3), except for the southern regions data which is not shown on this map. Two suburbanization/urbanization data sets are used (see section 3.3.5) with one valid from 1980-2000 and the other from 1992-2006.

3.5. Conclusions

The goal of this chapter was to develop a more integrated understanding of the occurrence of forest change processes across the CONUS at fine temporal and spatial scales. Raw data was gathered from disparate sources and transformed where necessary to allow for analysis inside of a GIS geodatabase. The geodatabase offers new perspectives of the frequency of repeat overlapping events in space through time for individual change processes and for multiple processes.

The work here was meant to be a starting point for a better geographic model of forest change processes, and therefore is not conclusive. As such, the work has uncovered a number of future research applications that would further our understanding of the forest area affected by these process. Better characterizations of forest locations through time are necessary. This work found that rates of forest area affected by fire and wind varied by roughly 50% and 90%, respectively depending on which forest mask was used in the analysis. Insect data would be greatly improved if measures of host density across the forest landscape were included in the calculations of severity. TPO harvest data provides a better spatial and temporal resolution record of harvest intensity; however, uncertainties in the data need to be further investigated and cross-walking the data to county level FIA ground inventories, which have better quality control measures, would make the data more reliable. A short analysis of the overlap of fire and hurricanes was done in this study. New opportunities exist to use the geodatabase to investigate the synergy between fire, insects and wind across broad regions of space and time.

New temporal and confidence/severity metrics were created for different processes offering unique information on the amount of forest area affected by each change process. No attempt was made to interpolate of fill data gaps, as this information is important for studies were reference data is needed. The geodatabase was used to make the highest temporal and spatial resolution maps possible for each process revealing the high interannual variability in the distribution of each process. This level of geographic characterization could be important for future validation and/or sampling schemes related to CONUS forest canopy dynamics. The spatially and temporally explicit maps may also be of use to parameterize and validate models related to forest canopy changes and their underlying processes.

Another important contribution of this work is the understanding and synthesis of appropriate uses of these data sources, their limitations and sources of error and uncertainty. This work cataloged specific gaps and limitations of each change process data set, providing examples of possible sources of errors and their effects on estimates of forest area affected a change process. Uncertainty in estimates of forest affected arose (1) from poor documentation and scrutiny of unlikely patterns in the harvest data, (2) from undocumented events due to sampling and recording methods of the fire, insect and wind data, (3) from subjective definitions or complete lack of information on the severity of damage from insect, fire, suburbanization processes, (4) from spatial imprecision of the insect aerial detection surveys data, and (5) from coarse resolution of harvest and southern regions insect and pathogen data and (6) from a lack of geospatial mask of forest locations through time. More work is needed to quantify and map the uncertainty in these data sets.

Quantitatively more is known about individual disturbance events for each process than about the aggregated patterns of frequency, severity, and variability of the different regimes, particularly harvest. A synoptic approach that focuses at local through to regional and national scales, on more than one process at a time is necessary to analyze how trends in forest change process regimes alter forested landscapes and how they interact with other earth systems. The new geographic model constructed herein is a step towards such synoptic analysis. A major obstacle that remains is the limited temporal extents of many of the data.

Chapter 4: Detailed Regional Synthesis of Forest Dynamics across Six U.S. Regions

4.1. Introduction

Contemporary attitudes and technology impact the way we to observe, interact, and understand forest systems. Humans' attitude toward forest land has varied from borderline hellish to holy through time [*Nash*, 1967]. The popular scientific model of a forest has gone from a large homogenous body with climax states and steady equilibriums, to a heterogeneous shifting landscape of small patches of trees sharing similar characteristics in a highly dynamic system [*Wu and Loucks*, 1995]. Methods of observation have evolved from observations of the immediate surroundings in place and time, to strategic designs intended to capture slow broad scale trends, to analysis of space-based imagery to meet the monitoring demands for capturing rapid local dynamics across large space and time scales.

Each set of attitudes and observations on forest dynamics provides a unique perspective and inherent limitations. Combining multiple data designed to capture different aspects of the same phenomenon offers a bridge over the data gaps and scale barriers that exist when forest change dynamics and their causes are considered from only one perspective.

Understanding the processes underlying the forest canopy change captured in the NAFD forest history maps is of use to a broad scientific community as NAFD forest history maps provide new landscape level information on forest canopy dynamics, showing steady ‘base’ rates and episodic ‘peaks’ as well as new information on the amount of regional and national inter-annual variability in forest dynamics. Also, the audience of NAFD users is growing as the USFS has been quick to adopt NAFD methods for applied research [*Nelson et al.*, 2009; *Stueve et al.*, 2011; *Vogelmann et al.*, 2011]. NAFD products are not the only national Landsat time series product that measures forest canopy [*Griffith et al.*, 2003b; *Hansen et al.*, 2010a; *Masek et al.*, 2008]. The forest dynamics observed in each of these products are the result of multiple overlapping processes requiring further analysis to understand the individual processes that are responsible for change signals in local space and time.

Coarse regional data showing broad trends in the amount of forest area affected by various forest change processes, and how they vary by region through time provide another perspective on forest dynamics. In chapter 2, these data sources were assemble from historical inventories and discussed in relation to NAFD forest history maps, and FIA estimates of forest dynamics over the last two decades.

In chapter 3 of this thesis, multiple geospatial data sets were brought together, standardized across the nation, and then used to create synoptic data sets that highlight the finer scale spatial and temporal overlap of individual and multiple change processes. The disturbance and conversion geodatabase, created in Chapter 3, supports integrated analysis of the multiple underlying causes of forest canopy loss across the U.S.

The goal of Chapter 4 was to use these disparate data sources across scales to ‘verify’ observations of forest dynamics and their underlying causal processes within six US forest regions. Areas where these distinct data converge or diverge should give a new view on forest dynamics and their causal processes and our ability to characterize them, which the individual data sets do not elucidate when used alone. This is not the first study to try to integrate ancillary datasets to understand trends observed in long time series of satellite observations of forest canopy change [*Drummond and Loveland*, 2010; *Mildrexler et al.*, 2007; *Potter et al.*, 2005]. However, the national scope and local to regional scale of this study make it a unique contribution of research on forest ecology and remote sensing.

The following sections, for each of the 6 CONUS regions (see Figure 2-1), discuss general forest land characteristics, coarse reports of forest canopy change dynamics, statistics of forest and change rates across NAFD samples for the region, then what we know of the spatial and temporal characteristics of the underlay change processes (suburbanization, harvest, insects, wind, then fire) and how they are or are not reflected in the change rates of NAFD samples.

4.2. <u>Northeast (NE)</u>

Through the twentieth century, abandonment of farmland led to widespread afforestation across the North East [*Houghton et al.*, 1999; *Pacala et al.*, 2001]. For example, in New England only 16 % of the farms (37% of cropland) that existed in 1945 remained by 1999 compared to 26% of farms (70%) of cropland in the Middle Atlantic [*Trani et al.*, 2001]. The rate of afforestation has been steadily decreasing to the current low of 0.06% increase in forest land annually (1987-1997), down from the high of 7.28% between 1939-1953 [*Birdsey and Lewis*, 2003]. USFS inventories suggest the amount of forest land in the NE has been nearly constant since the 1970's [*Smith et al.*, 2009].

Research attention has also focused on more subtle forest canopy dynamics in the region. If disturbance or conversion rates decrease, the average stand age increases. With lower average replacement rates come changes in forest species composition, such as the loss of pioneer species, which carries biodiversity and carbon storage consequences [*Lorimer*, 2001]. FIA inventories suggest that the rate of mortality (from wind, fire and insects) has increased more than 15 percent between each decadal survey since 1977 (Figure 4-1). Increased mortality would be expected in the region as early pioneer species, which generally live less than 100 years are killed off by natural processes. NAFD disturbance history maps for the seven NAFD samples in the NE, record 106% more forest land area with canopy cover loss between 1986-2004 than was captured by the FIA inventory for the NE region in roughly the same time period (Figure 4-2a). NAFD samples also record a gradual decrease over the 20+ year period of observation with a drop in the decadal annual change rate, from 0.70% (1986-1994) to 0.54% (1995-2004) (Figure 4-2b).

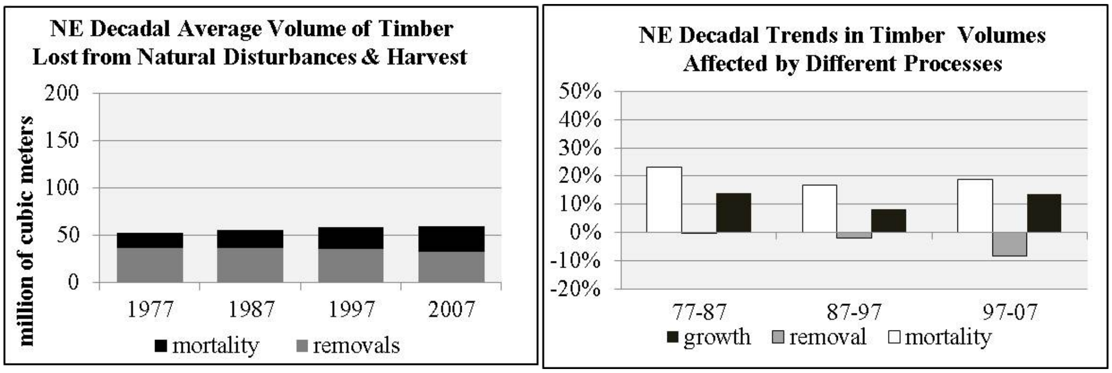


Figure 4-1: The volume of timber removed from NE forests because of harvest has declined at increasing rates over the last 3 decades. The graph on the right shows decadal trends in averaged timber volumes due to growth (used as a measure of productivity), removals and mortality. Growth is the average growth in tree volume less the volume lost through mortality. Mortality is the average volume of timber dying due to natural causes. Removals are the volume removed during timber harvesting or other cultural treatments. Decadal change is calculated as the difference between volumes reported in the two inventories and given as a percentage of the volume from the previous inventory. Tabular inventory data and definitions from Smith et al. [2009].

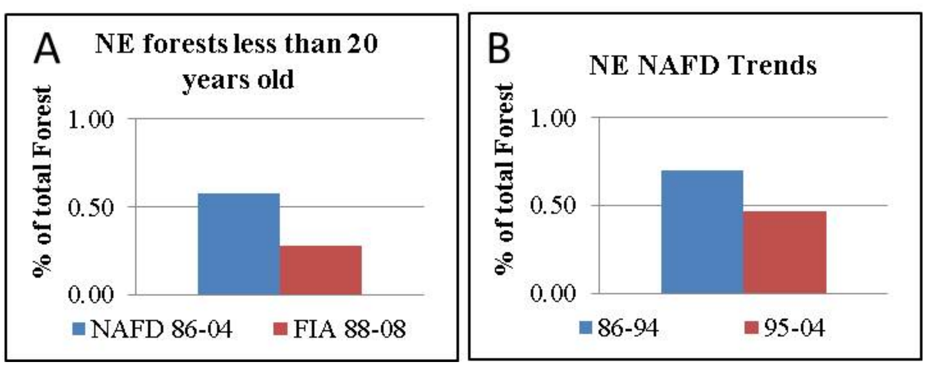


Figure 4-2 : NAFD disturbance history maps show a decrease in the rate of forest canopy loss through time. Overall NAFD results show much more forest area as disturbed over the last

twenty years as does the FIA inventory of the region.

NE NAFD samples represent the characteristic forest group types of the region well (see Chapter 2 section 2.4.2). Each of the seven NAFD samples covers a similar amount of the total forest area sampled in the NE region (Figure 4-3). The samples individually and as a group have low interannual variability around the median change rate, as shown by distance of the rates in 2nd and 3rd percentiles from the median (Figure 4-3). Four of the seven samples are located on the densely populated coastal corridor, which may have had unanticipated consequences on the types of forest change processes captured (Figure 4-4). For example, there is an inverse relationship between the location of large population centers and commercial forestry operations [*Polyakov et al.*, 2008; *Wear et al.*, 1999].

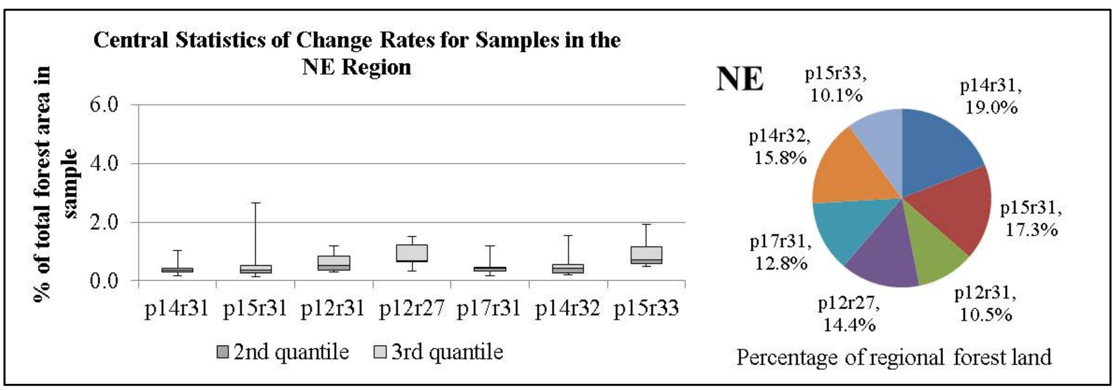


Figure 4-3 : Box plots of the annualized change rates for each NAFD sample show low variability around the median. P15r31 has some anomalous rates, but the tight percentiles show that it is an isolated occurrence. The amount of forest land samples by NAFD in the region is evenly divided between the 7 samples. So it is unlikely that the outlier in p15r31is heavily skewing the regional average.

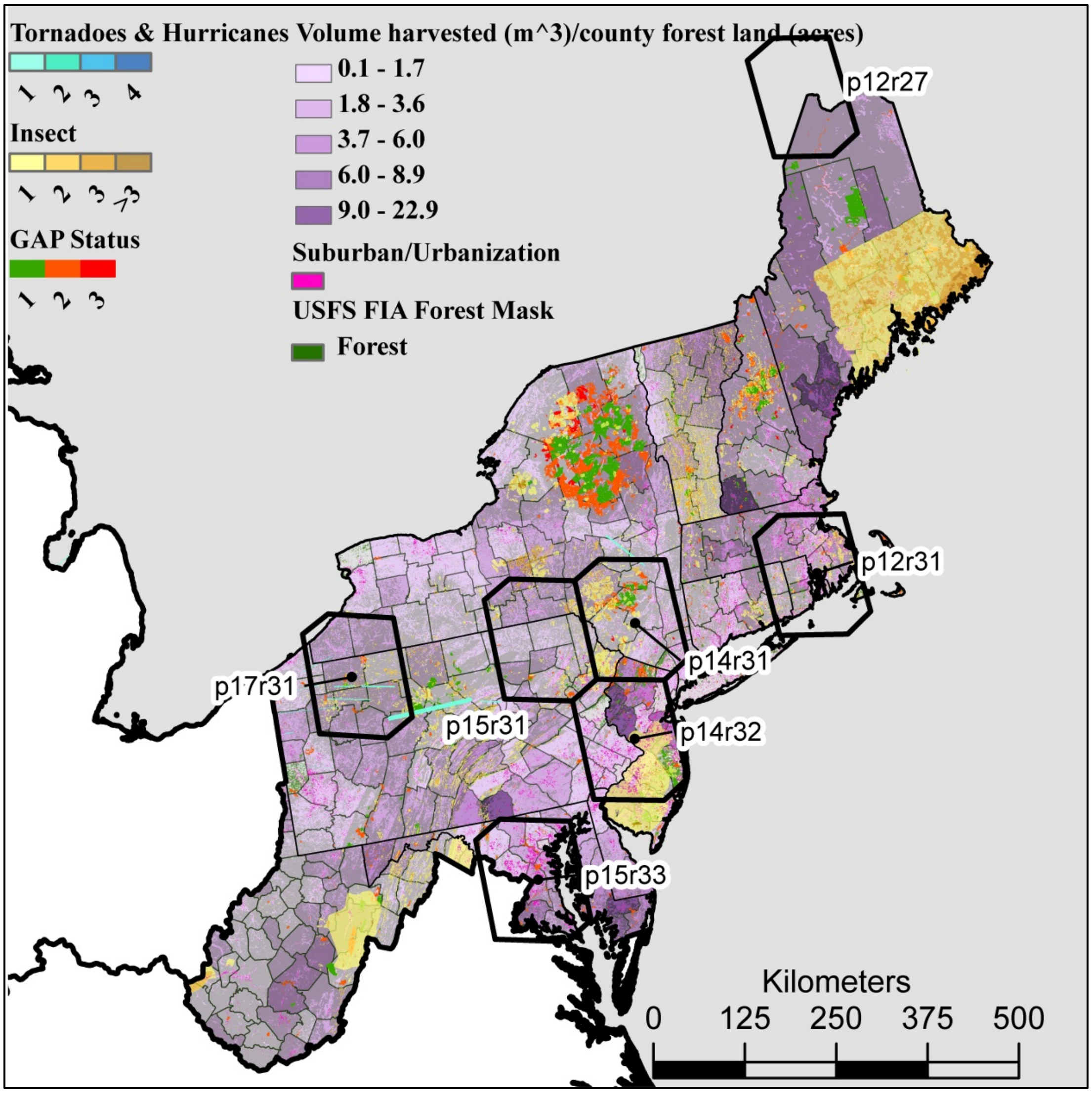


Figure 4-4 : NAFD sample locations and the locations of documented disturbance and conversion events in the North East region.

At the regional level, forest conversion and insect infestations show decreasing rates through time supporting NAFD results of a gradual decrease in forest canopy turnover during the 20+ year period of observation. FIA harvest removals show an increase in area and intensity (Figure 4-5). To interpret how well the observations of forest canopy changes captured each of the underlying causal processes, the spatial and temporal characteristics need to be disaggregated where possible. NAFD forest history maps coupled with the geodatabase of ancillary data provide a finer look into these patterns and processes.

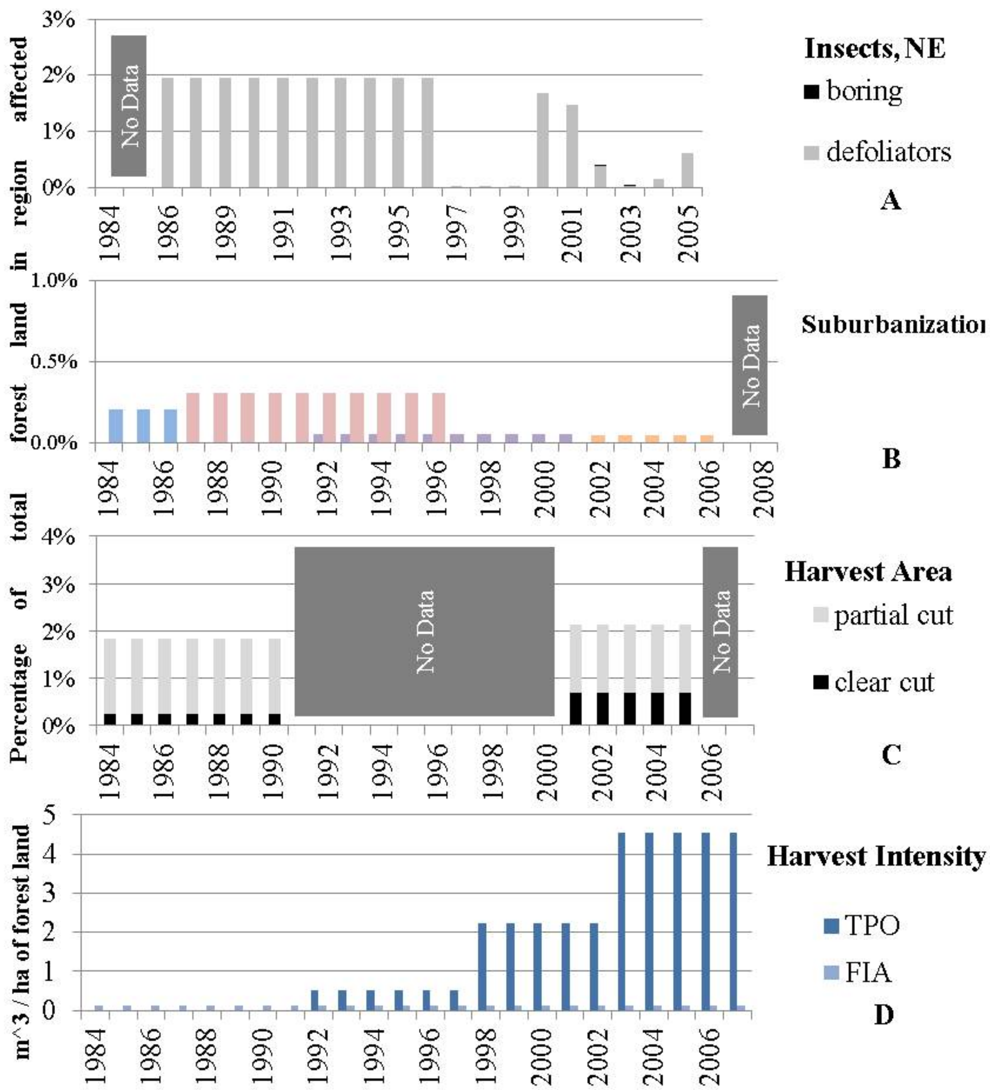


Figure 4-5 Graphs of the temporal patterns for forest change process in the NE region are punctuated by periods of missing data. Averaged rates across multiple years hide the true temporal patterns of each process. Graph A 1986-1997 data is from Birdsey et al. [2003], 1997-2007 data are from USFS reports. Graph B 1984-1996 and 1987-1996 data is from NRCS

surveys in Birdsey et al. [2003], 1992-2001 and 2001-2006 data is from the NLCD change products [*Fry et al.*, 2009; *Xian et al.*, 2009]. Graph C 1984-1989 harvest data is from Birdsey et al. [2003] and 2001-2005 data is from Smith et al. [2009]. Graph D 1984-2007 volume of removal data is from Smith et al. [2009].

Though conversion rates for the region vary by an order of magnitude depending on the source, they both suggest that minimal forest land is converted to developed land in the NE region (Figure 4-5b). The NRCS data which ends in 1997 showed substantially higher rates than the NLCD data in the 3 years that the two data collections overlapped. NLCD data record a 15% decrease in forest conversion to suburban land cover between the 1992 – 2001 and 2001-2006 epochs. It is possible that the NAFD samples over largely populated areas are picking up this trend, but the low amount of forest area affected by conversion, if the NLCD is accurate, could only explain a small part of the decrease in NAFD rates. The census housing density data set, where it overlapped with NAFD change, was useful for confirming conversion events captured by NAFD before 1992, the first year the NLCD product is available. The NAFD forest history maps provide biennial forest masks back to 1984, but only exist in seven locations across the region. Wall to wall forest cover masks for 1984 combined with the geospatial housing density increases could extend the understanding of suburbanization across the region back another decade.

USFS area harvest records show that more forest land is consistently affected by harvest activities than any other process in the NE region (Fig 4-5c). The annual average area harvested increased slightly from 1.8% to 2.1% of total forest area (between 1980-1990 and 2001-2005) with the majority of the rise due to the increase in clear cuts. The rate of clear-cut harvest rose 189% from 0.02% to 0.7% of forest land annually (Fig 4-5c).

TPO volume data show an increase in the volume of merchantable timber removed from forest lands in the region, like FIA inventory volumes (Figure 4-5d). Different measurement units, space and time scales, and sampling methods, of the logging volume and area datasets in the region confound direct comparisons. TPO data when mapped in the geodatabase show that the counties with the highest increase in the volume of logging removals between 1997-2002 and 2002-2007 are in the states of NH, WV and ME. If the locations where the volume of removals increased are the same where the area logged increased, then it's unlikely that the NAFD samples would have captured the trend. Only one of the counties with large increases in removals was partially covered by a NAFD sample location.

There was a substantial drop in the average annual rate of forest area affected by insects from 1.9% to 0.5%, between 1986-1997 and 1997-2005 respectively (Figure 4-5a). The second worst outbreak of gypsy moths since the 1940's started in the region in 1989 causing high inter-annual variability over the 1986-1997 epoch. PA was the hardest hit state reporting 7 million acres defoliated over a three year period [*(USDA)*, 1995]. These dynamics or not reflected in the decadal average reported in Birdsey and Lewis [2003]. Epidemic levels of gypsy moth can lead to mortality after repeated years of defoliation; however, the severity in any location will depend on the density of host in the forested landscape and the health of the forests attacked.

Four NAFD samples overlap PA forests (Figure 4-4). Of those samples p14r31, p14r32, p15r33 have numerous anomalous years (change rates that are 2 standard deviations larger than their respective twenty year means) pre-1990, and are in states that record high levels of forest area affected by Gypsy Moths [*(USDA)*, 1995]. p15r31, in Northeast PA, has the highest rate of change for any one year in the region, 1.92% of forest land in 1989. The digital FHP data for the state begins in 2000 so an overlay analysis cannot be done regarding the amount of the NAFD rates during those times, with insect damage. NAFD forest history maps are better at picking up severe, compact mortality than low severity or scattered mortality in the landscape (see Chapter 2 section 2.3.1.4).

Ancillary geospatial data show that there are many severe tornadoes in the region, particularly in NAFD sample location p17r31 (Fig 4-4). Because, the events are of limited spatial extent, they do not register as anomalies in the average annual NAFD change rates. In 1985, a cell of tornadoes touched down in western PA, near Alleghany state forest. The area falls within the NAFD sample p17r31. The maps in Figure 4-6 show locations of tornado tracks from the NOAA storm track dataset laid over the NAFD forest history map. The NAFD disturbance rates for p17r31 are only one standard deviation higher than the 20 year average rate in 1985 and 1986. In 1988, however, the change rate of forest in the sample jumped 300% above the twenty year median rate and Pennsylvania emergency records record severe tornadoes in the area. The NOAA data set does not record wind storms in these years. Using the

2001 retrofit NLCD data forest class is used as a mask, we calculated that 0.004% of the NE forest (1,576 ha) was *exposed* to moderate to severe tornado winds in the 22 years between 1984 and 2006.

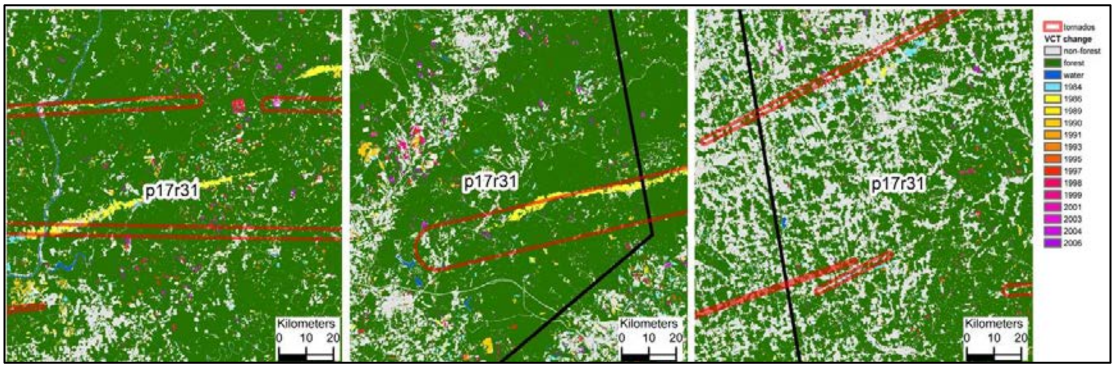


Figure 4-6 : NOAA tornado tracks laid over VCT disturbance history maps.

After examining the multiple datasets many questions are left unanswered about the causes of observed disturbance rates in the region and the conflicting directions of trends observed. Harvest is the most spatially contiguous disturbance process in the region and increased in average intensity and extent during the period of NAFD observations. NAFD trends show a decrease in the amount of forest canopy loss over time. Due to NAFD sampling locations, it's possible that NAFD regional rates are not representative of harvest disturbance regimes in the region. It is also possible that the trends shown in the two harvest data sets do not fully represent the spatial and temporal dynamics of harvest in the region. FIA natural mortality rates, a volume measurement, increased consistently through time. However, individual datasets on area affected by wind and insects do support the same trend. MTBS and historic USFS records agree that fire has contributed little to disturbance rates in the region

(Figure 2-14).

4.3. North Central (NC)

Forests in the North Central region share many general characteristics of the forests in the North East, including a legacy of farm abandonment and afforestation [*Brown et al.*, 2005]. Fire suppression has also played a major role in shaping current forest distribution and disturbance regimes in the region [*Baker*, 1992; *Goodale et al.*, 2002; *Stephens and Ruth*, 2005]. NC forests are undergoing composition shifts as poplar and birch, short lived pioneer species, age and die off [*Lorimer and White*, 2003]. More than 90% of NC forest land is timber land, capable of supporting sustained harvest activities [*Smith et al.*, 2009].

For the last two decades coarse volume-based inventories across the NC region show increasing rates of growth, harvest removals and timber affected by fire, wind and insects (Figure 4-7). Increases in the volume of removals have been less than the increase in volume added from growth, suggesting better stocked forest lands through time. As the timber stock has increased so has the rate of volume affected by natural mortality. NAFD disturbance history maps for the eight NAFD samples in the NC, record 40% more forest land area with canopy cover loss between 1986-2004 than was captured by the FIA inventory over roughly the same time period (Figure 4-8a). Decadal NAFD average change rates were flat at 0.8 % of total forest land between 1986-1994 and 1995-2004 (Figure 4-8b).

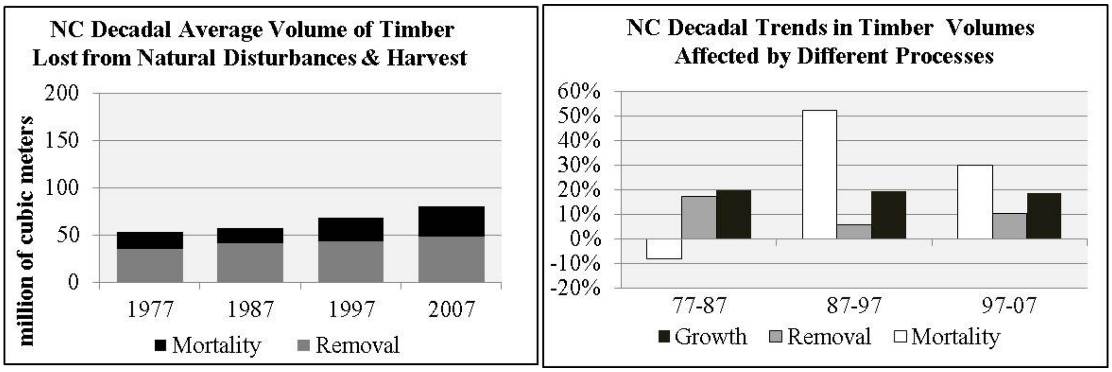


Figure 4-7 : USFS FIA ground inventories for the North Central region show the absolute volume of timber (m^3) lost to timber harvest (removals) has been increasing for decades [*Smith et al.*, 2009]. The graph on the right shows decadal trends-relative to the volume levels in the previous inventory- in averaged timber volumes due to growth (used as a measure of productivity), removals and mortality. Growth is the average growth in tree volume less the volume lost through mortality. Mortality is the average volume of timber dying due to natural causes. Removals are the volume removed during timber harvesting or other cultural treatments. Decadal change is calculated as the difference between volumes reported in the two inventories and given as a percentage of the volume from the previous inventory. Tabular inventory data and definitions from Smith et al. [2009].

.

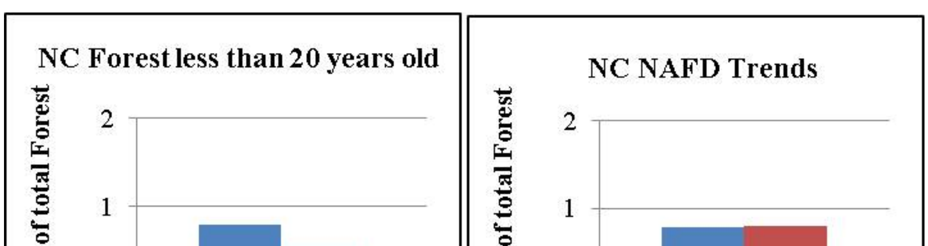


Figure 4-8 : Disturbance history maps for the 8 samples NC NAFD samples record a higher percentage of total forest area in the under 20 forest age class than USFS inventories.

NAFD samples across the region have similar distributions, with median rates of canopy loss (temporary and/or permanent) of less than 1% of the total forest area (Figure 4-9). The 2nd and 3rd quartiles are close to the median values suggesting little variance in annual rates for each of the samples. The maximum change rates of two NAFD samples, p23r35 and p21r30 stand out from the other samples in the region. These two samples contain only 6.8% and 11.2% of forest land sampled by NAFD in the region, so do not weigh heavily in the regional averages.

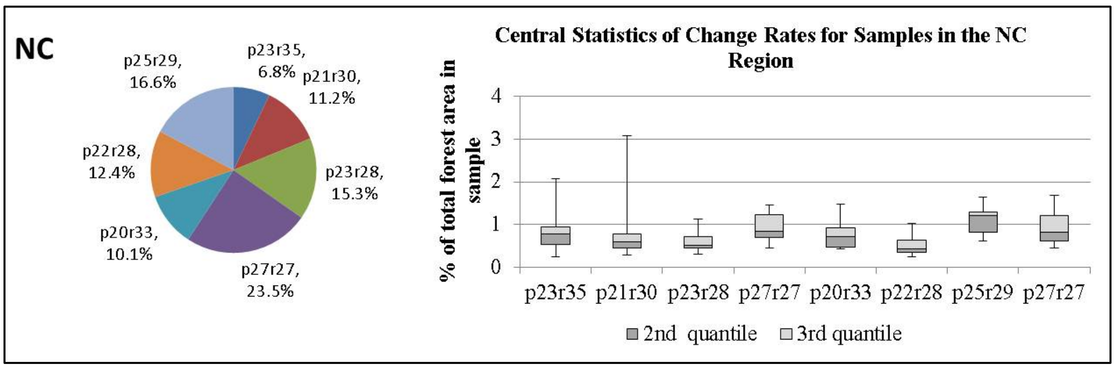


Figure 4-9 : The regional average calculated for NC NAFD samples is weighted by the amount of forest area per sample. Therefore, the average is affected the most by the change rates in p27r27 which contains nearly ¼ of the forest land sampled by NAFD in the region, and the least by p23r35. Median change rates across the NC samples were stable and error bars on the box chart, representing maximum and minimum annual change rates for each sample are low except in p23r35 and p21r30.

At the regional level, graphs of the temporal patterns in data for the individual change processes show mixed trends. Forest conversion and insect infestations have generally decreasing rates through time while harvest area and intensity both increase (Figure 4-10 a-d). NAFD decadal average regional rates may be flat because changes in different disturbance regimes are canceling out, or because the sampled locations are not representative of all processes in the region. Both MTBS and historic fire data show negligible fire rates in the region and so will not be discussed further (Figure 2-14).

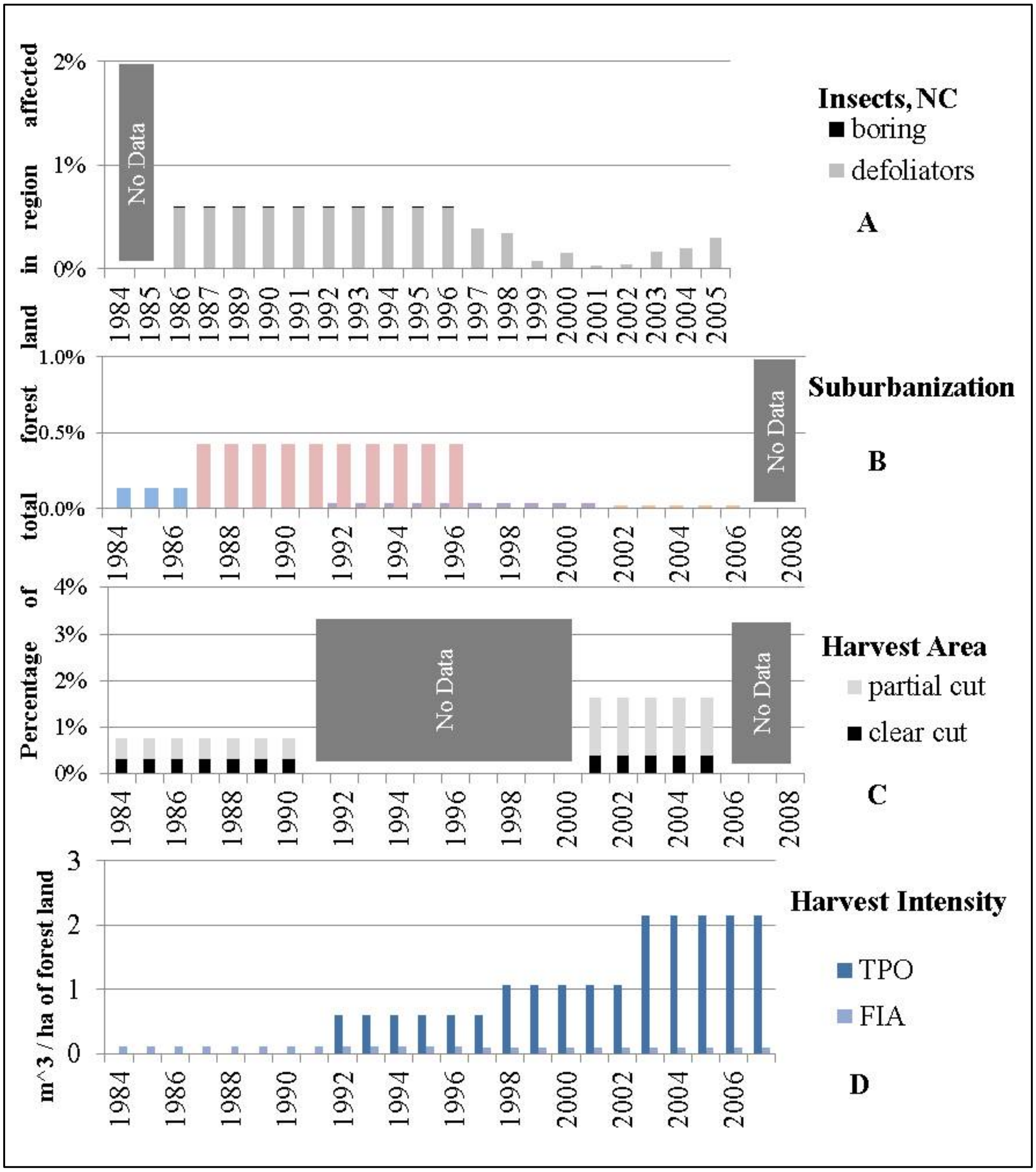


Figure 4-10: Graphs of the temporal patterns for forest change process in the NC region are punctuated by periods of missing data. Averaged rates across multiple years hide the true temporal patterns of each process. Graph A 1986-1997 data is from Birdsey et al. [2003], 1997-2007 data are from USFS reports. Graph B 1984-1996 and 1987-1996 data is from NRCS surveys in Birdsey et al. [2003], 1992-2001 and 2001-2006 data is from the NLCD change products [*Fry et al.*, 2009; *Xian et al.*, 2009]. Graph C 1984-1989 harvest data is from Birdsey et

al. [2003] and 2001-2005 data is from Smith et al. [2009]. Graph D 1984-2007 volume of removal data is from Smith et al. [2009].

The rates of forest land conversion to suburban/urban land use are low across the NC region, regardless of the data source referenced. As in the NE, NC rates from the NRI inventories are an order of magnitude higher than NLCD rates in the years where there is data from both sources (Figure 4-10b). The NC region had the highest rates of conversion of all regions according to the NRI data and the second highest rate according to NLCD data. NLCD rates drop 100%, from an average of 0.04% of NC forest land converted annually (11,602 ha yr^{-1}) to 0.02%. Conversion processes could only contribute minimally to NAFD change rates since hotspots of conversion do not fall within NAFD sample boundaries and the process overall affects little forest area (Figure 4-11).

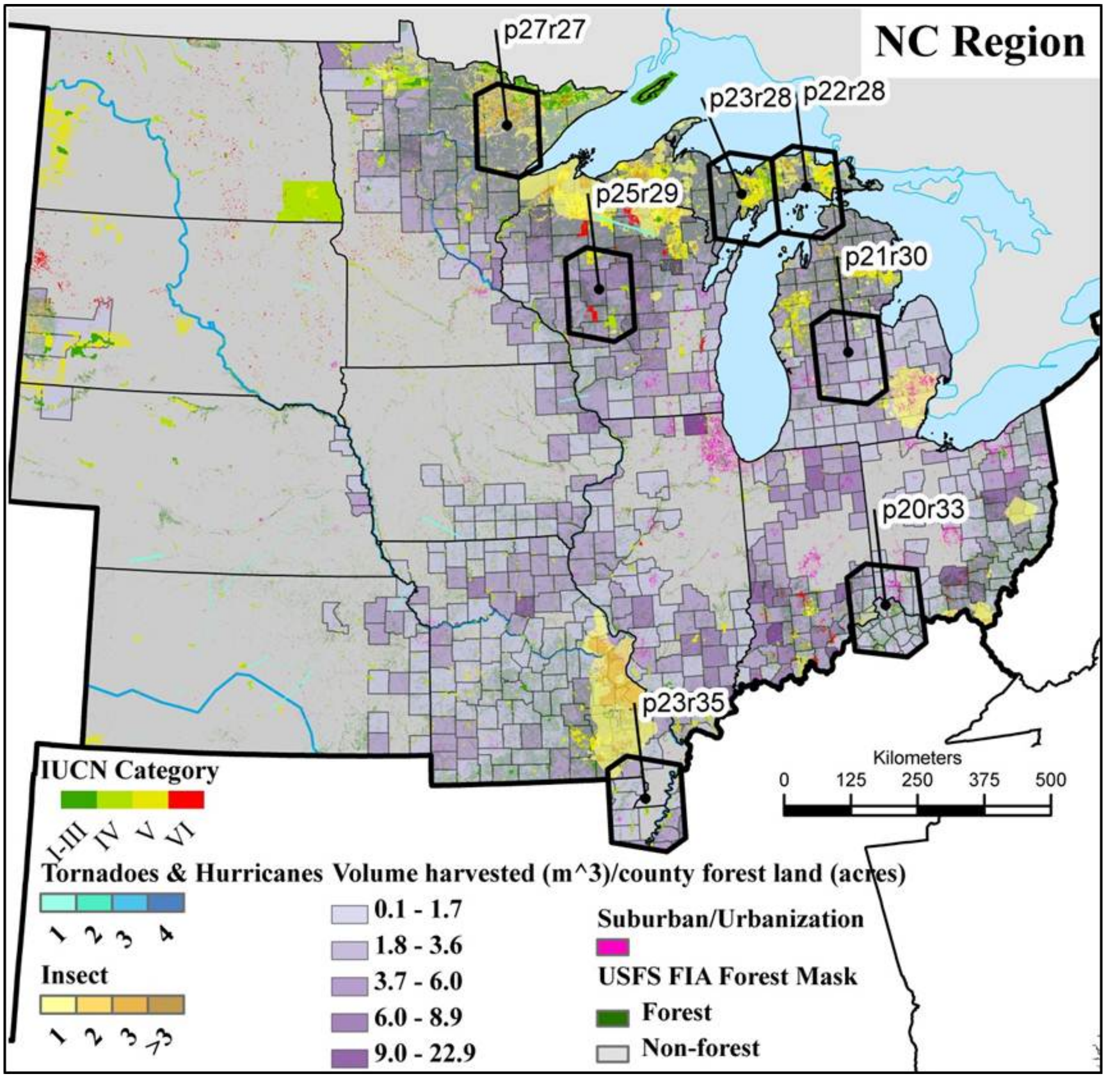


Figure 4-11 : Ancillary geospatial data for the North Central region suggests that most forest area is affected by one or more change agents.

Ancillary data suggest that harvest is the dominant change process in the region and responsible for the 'base', or steady and persistent, disturbance rates of forest change in NAFD results. Data gaps, aggregated rates, and coarse reporting resolution in harvest area records warrant closer investigation with other data sources. The rate of forest land harvested annually went up between 1980-1990 and 2001-2005. Almost all increases were due to the 173% increase in partial harvest rate to 1.23% of total forest land (Figure 4-10c). Biennial NAFD forest history maps results do not capture partial harvest as well as clear cuts, which may account for the stagnant NAFD rates in spite of the large increase in harvested area suggested by the two harvest area data sets. Mapped TPO data of cumulative removals (1997-2007) suggest that harvests are more concentrated across the northern forests in the region (Figure 4-11). When per county trends in removals between the nominal TPO reporting dates are viewed, it appears that NAFD samples capture more counties with decreases in their removal for the 1997-2002 period. No clear trend stands out in the 2002-2007 period for counties that fall within NAFD samples.

At the regional level, FIA data show an increase in volume of timber (on timberland) affected by natural mortality in each decadal survey. However, insect area data suggest declines in the already low rates of forest land affected by these natural disturbance regimes (Fig 4-10a). The area of insect infestations, which dropped across inventory periods, was mainly due to defoliators, which, under average conditions, are related to low rates of mortality in their hosts.

Mapped FHP aerial surveys show forests repeatedly damaged by beech bark disease in the upper peninsula of MI (p22r28 & p23r28), Emerald Ash Borer in eastern MI starting in 2004, jumping oak gall wasp in southeast MO, Spruce budworm (defoliator) in upper MN in the late 1990’s then again with increasing extent and mortality beginning in 2004 up through 2009, and forest tent caterpillar (defoliator) across wide swaths of upper MN and MI starting in 2000 and spreading across millions of ha with each year. Visual comparisons show that the beech bark damage is not visible in NAFD forest history maps. It is difficult to assess whether the detected disturbance in p27r27are due to forest tent caterpillar, spruce budworm, or some other process. So much of the forest area is marked as defoliated multiple times in the ADS data, including many areas the VCT categorizes as persisting forest (did not undergo significant canopy loss during the time series) that conclusive attribution using only the ADS data as reference is impossible. The other insect outbreaks mentioned do not overlap spatially with NAFD samples.

Although wind is acknowledged as the dominant natural disturbance process of the NC and NE regions [*Lorimer*, 2001], there are no formal estimates of the total area of forest affected by windstorms (of any size) across years. In two of the NC NAFD sample forest change trajectories, the *staccato* events appear to be due to wind storms that are not reflected in the NOAA wind geospatial data set (see section 3.3.2). In 1999 an intense *Derecho*, a type of wind storm – in this case the strength of a category 3-4 hurricane – caused widespread forest blowdown across 193,000 ha of the Superior National Forest in MN [*Nelson et al.*, 2009]. The FHP ADS digital sketches, record localized abiotic damage from "wind-tornado" in 1999 and 2004. The 1999 ADS data have a grid of regular sized polygons suggesting a special survey to capture storm data (Figure 4-12). Part of the disturbance event occurred within the boundaries of NAFD sample p27r27. From 1999 to 2004, NAFD annual disturbance rates in sample p27r27 were 50% higher than the twenty year median rate for the sample area. The area was also under forest tent caterpillar outbreak, so direct attribution to either event is difficult. NAFD data for p25r29 (central WI) also recorded damage in locations that experienced powerful Derechos in 1998 and 2001. NAFD methods have the potential to answer nationwide questions about the prevalence and trends of windstorm damage across US forests; however, the sampling scheme used in the first two phases of the project exclude inferences of regional patterns for this stochastic change processes from local results.

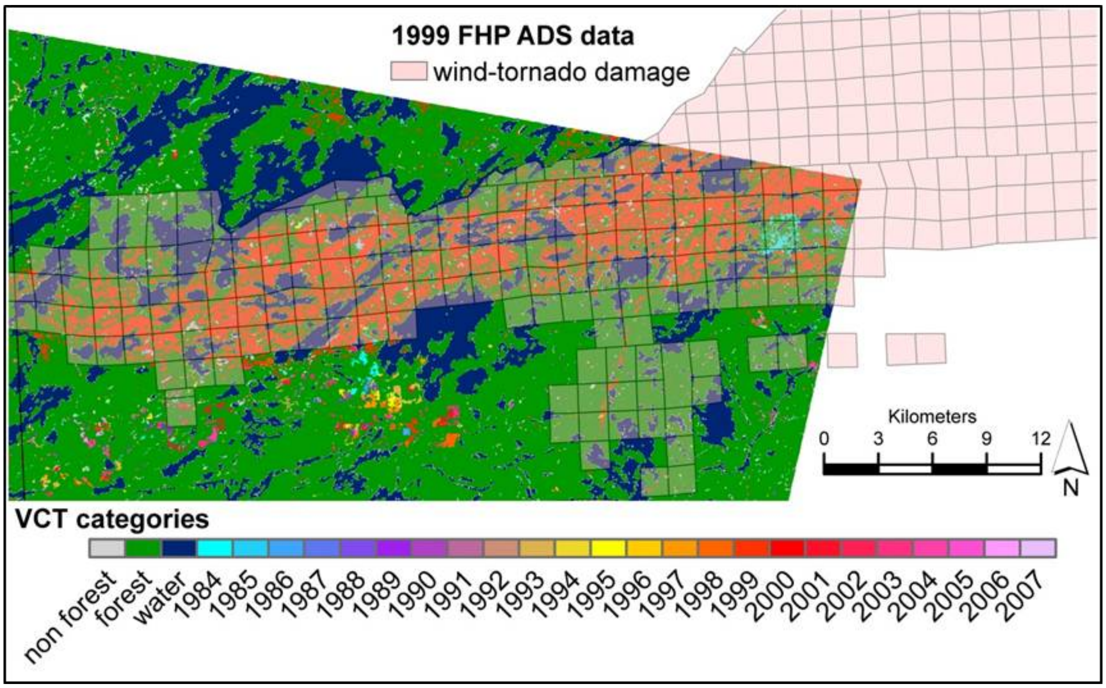


Figure 4-12: A large swath of forest area was labeled as disturbed in 2001 by the VCT algorithm. Without reference data, in this case, the 1999 ADS data it would be difficult to know that the forest canopy loss was caused by wind-tornado damage.

Combing the coarse regional data, VCT maps and ancillary geospatial data helps explain some of the observed forest canopy changes in the region and their underlying causes. However, there are anomalies in the VCT change trajectories that cannot be explained with available reference data, such as the high rates early in the series in p21r30 and p23r35 or the elevated rates in p25r29 between 1993 and 2002 (Figure 4-13). Reference data show that the NAFD sampling scheme missed localized disturbance events in the region that may have affected regional averages of forest change if they were captured. Because wind, suburbanization, and insect canopy related loss are highly clustered in space, the majority of VCT changes in the region and those captured by the NAFD samples are likely harvest related. Since harvest is not evenly distributed across forests in the region, it is possible the NAFD sampling scheme does not capture forests that mimic the direction and magnitude of regional harvest rates.

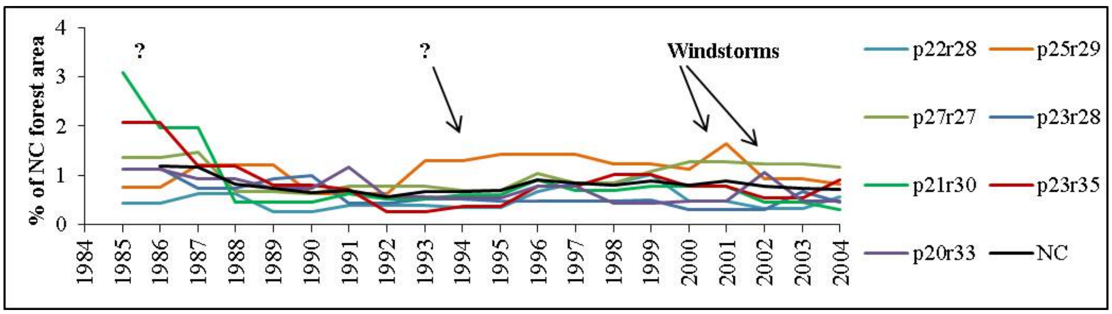
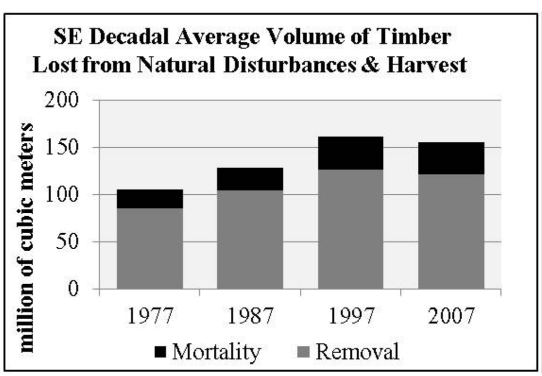


Figure 4-13 : Available sources of reference data are not adequate to fully explain the temporal dynamics in the NAFD forest disturbance history maps.

4.4. <u>Southeast (SE)</u>

The lands in the SE are known for their transformation between agriculture and forest land processes; however in this region the conversions have been more frequent and add up to little net change, unlike in the NC and NE . The coastal plain, which has some of the most productive land in the south U.S., is on its “fourth” forest since the large scale clearings of the 1800's [*Trani et al.*, 2001]. Government policies and land economics have driven the land cover transitions [*Adams et al.*, 1998; *Nagubadi and Zhang*, 2005]. For example, planting of marginal agricultural land with tree seedlings, has been fiscally supported in the Farm bill leading to peaks in total forest area in the south, in 1960s and 1980s [*Plantinga et al.*, 2001; *Roberts and Lubowski*, 2007]. The Southeast region is more than 95% timberland [*Smith et al.*, 2009], with large forest industry management of coastal pine areas acquired during the Great Depression [*Williams*, 1982]. SE forests are also home to a wider range of biodiversity than any other region in the CONUS [*Olson et al.*, 2001].

Regional volume inventories suggest that harvest and mortality are the dominant disturbance process in the region (Figure 4-14). The volume of timber surveyed grew more than 20%, while volume from growth increased more subtly between the 1977-1987 and 1987-1997 FIA inventories. The 2007 inventory shows a decrease in harvest and mortality rates, suggesting a change in broad forest disturbance regimes of the region.



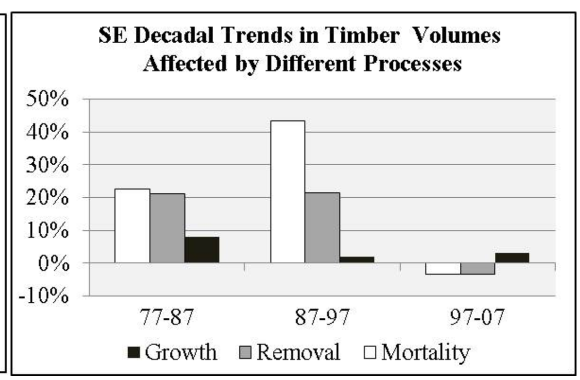


Figure 4-14 : USFS FIA ground inventories for the Southeast region show broad decadal trends in volumes of timber affected by harvest removals and natural mortality. - The graph on the right suggests that the large relative increases in harvest and mortality between the earlier inventories tapered off during the last inventory. The volume of timber removed from NE forests because of harvest has declined at increasing rates over the last 3 decades. The graph on the right shows decadal trends in averaged timber volumes due to growth (used as a measure of productivity), removals and mortality. Growth is the average growth in tree volume less the volume lost through mortality. Mortality is the average volume of timber dying due to natural causes. Removals are the volume removed during timber harvesting or other cultural treatments. Decadal change is calculated as the difference between volumes reported in the two inventories and given as a percentage of the volume from the previous inventory. Tabular inventory data and definitions from Smith et al. [2009].

Forest stands less than twenty years old have been disturbed in the last twenty years or newly growing forests resulting from afforestation. FIA inventories estimates of SE forest land that is less than twenty years old are 0.14% higher than NAFD estimate, a difference of 9% (Figure 4-15). If land is converted from forest use to suburban/urban between two FIA inventories, it will no longer be counted as forest land. NAFD estimates are based on time since disturbance, not forest age, so they include land that may have been converted. NAFD rates of canopy loss for the SE increased only 8% between the two decadal averages to 1.4% of total forest area affected annually.

The averaged SE NAFD estimates exhibit one of the highest consistent or “base” rates of change, equal to an average forest replacement rate of 73 years. Within the group there are noticeable differences between the distributions of the annual change rates for each sample (Figure 4-16). For example, the maximum annual change rate for p16r37 is more than two times higher than the median annual rate, the minimum and median annual rate of p18r35 are much lower than those of the other samples and finally, the 3rd quartile of annual rates for p16r41 shows a large distance from the median. Sample p16r41 has the least forest area of all samples in the region, so its annual rates receive the least weight in the calculation of the regional mean. Change rates are given as a percentage of the total forest area in the scene. So the rates for this sample could be high, due to the small denominator of the ratio, even though the absolute amount of area with canopy change is low. The samples are well distributed spatially throughout the region (Figure 4-17).

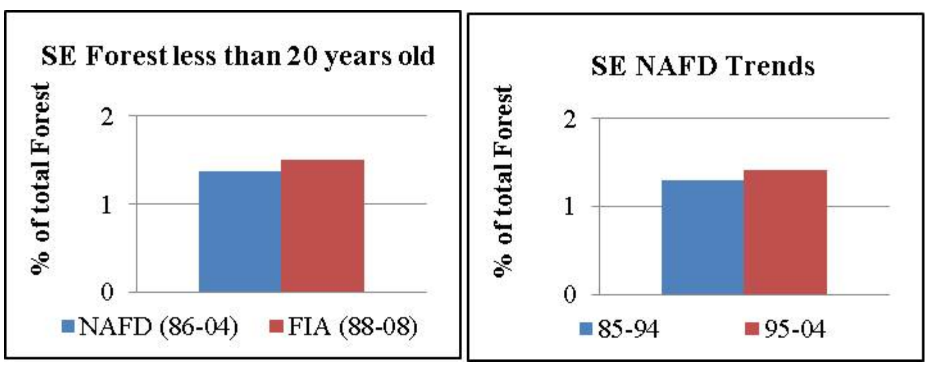


Figure 4-15: Forest canopy loss (temporary and/or permanent) appears static in decadal averages from the 8 NAFD samples in the SE region. FIA and NAFD estimate nearly the same amount of forest land in the 0-19 age class (assuming all NAFD detected canopy losses are from disturbance not conversion).

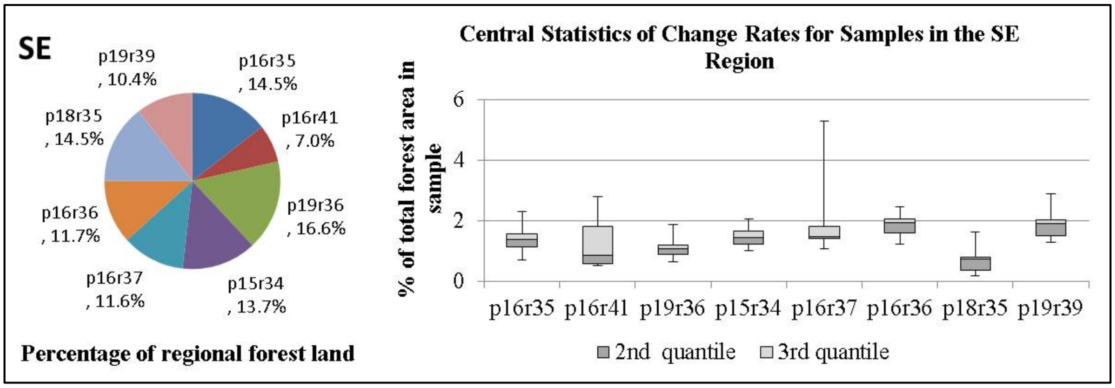


Figure 4-16 : Forest land is evenly distributed among 7of the SE NAFD samples. P16r41 which lies over the Everglades has substantially less forest area than the other samples.

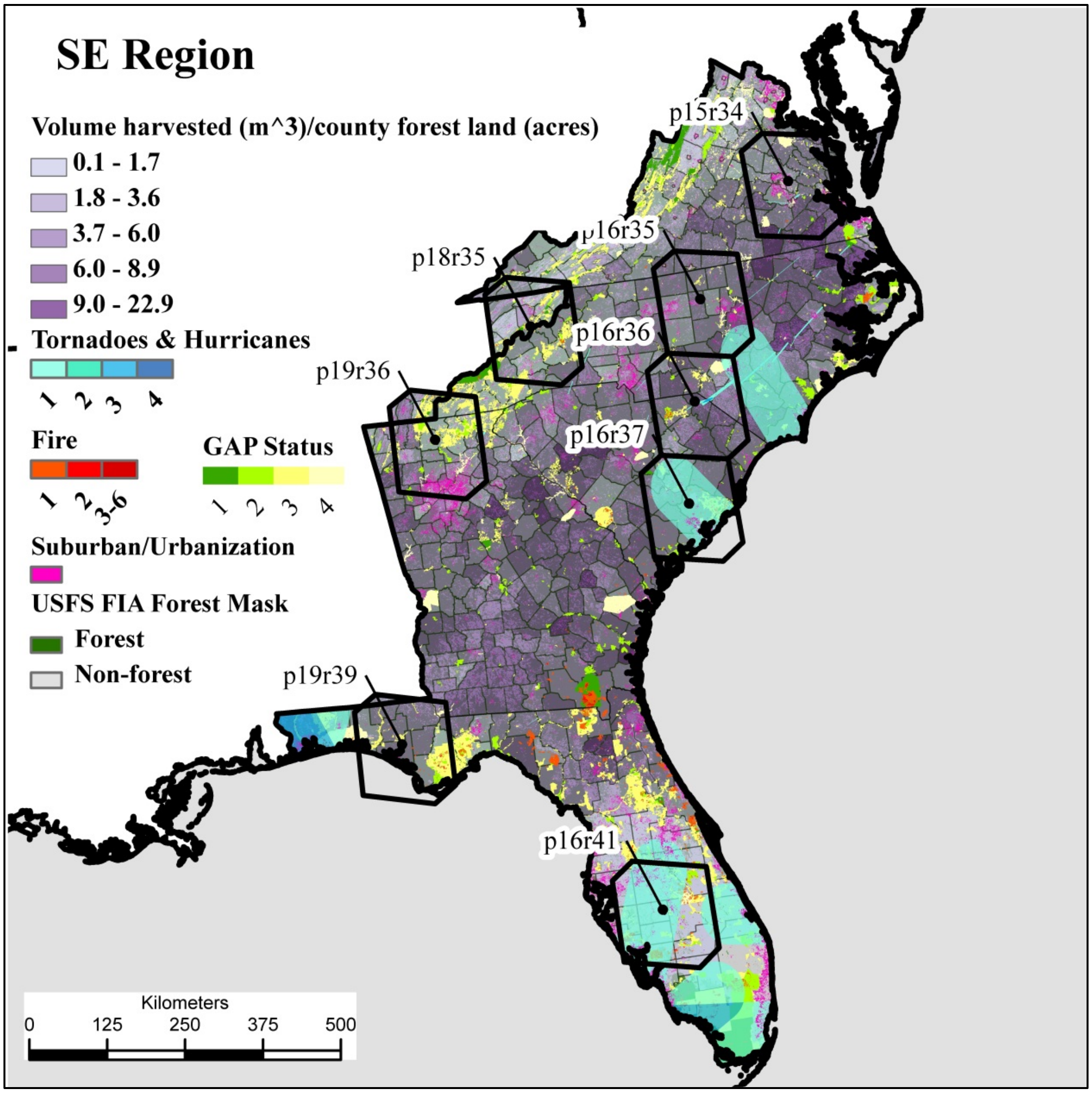


Figure 4-17: The map of the forest change processes in the SE region and NAFD sample locations also shows GAP status codes. Gap status 1 is managed strictly for biodiversity, 2 is land where disturbance processes are actively suppressed, 3 is land that is under protection, but use for extractive purposes and 4 is land that is publically owned without a clear land management assignment, for example Department of Defense lands.

Finer geospatial data is necessary to disaggregate the spatial and temporal characteristics of the processes at work and explain the processes underlying observed canopy changes in the region. Regional decadal reports suggest that harvest, wind, and insects all have footprints that affect large amounts of forest in the SE region (Figure 4-18a-d).

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 was the only region where forest conversion to developed land-uses increased over observation periods (1992-2006). Rates only increased 1% to 0.17% (24,828 ha yr^{-1}), respectively (Figure 1-18b). The NRI data on suburbanization are an order of magnitude higher than the NLCD data, and are the second highest rate across the CONUS [*Birdsey and Lewis*, 2003].

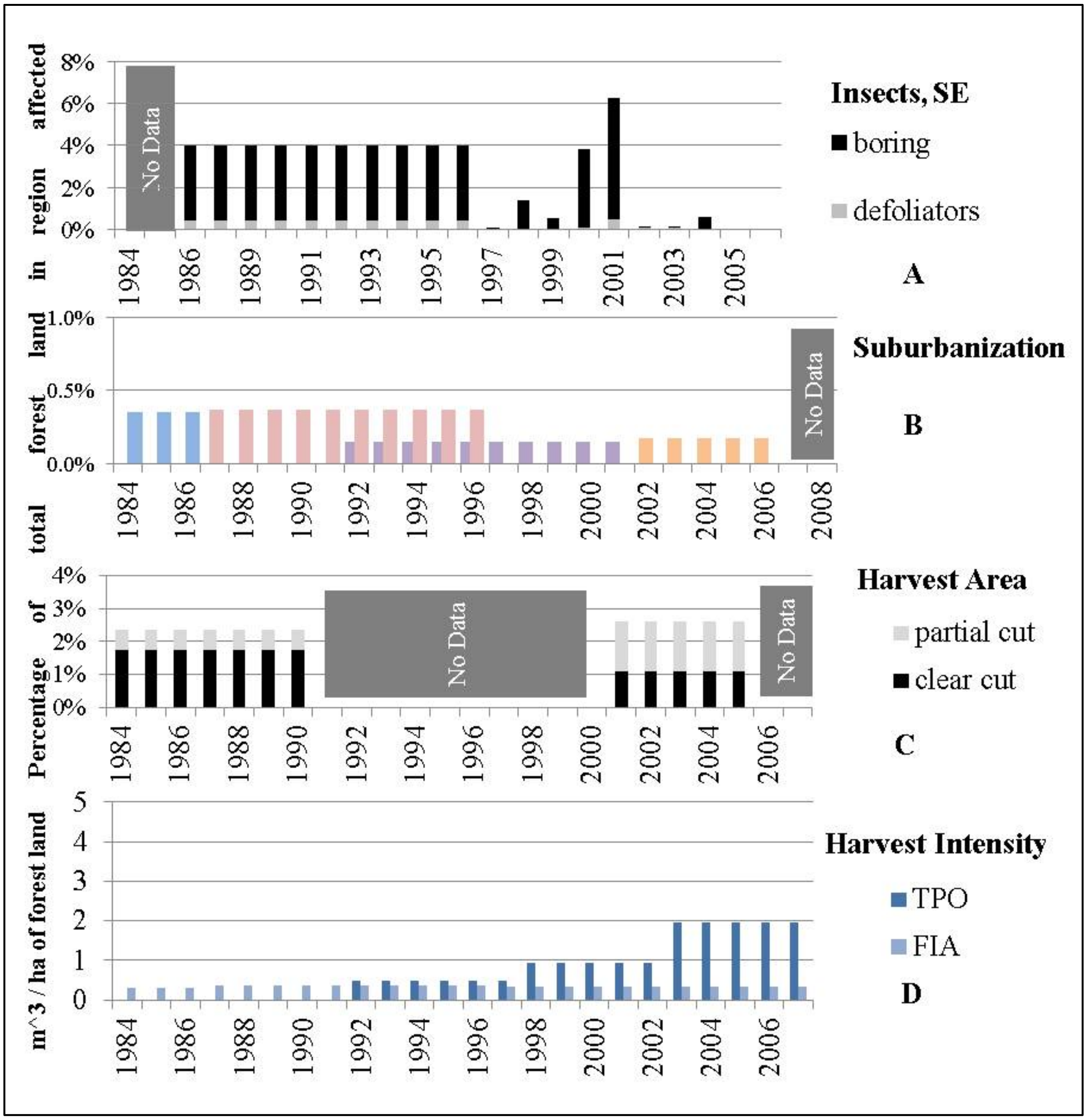


Figure 4-18: Graphs of the temporal patterns for forest change process in the NC region are punctuated by periods of missing data. Averaged rates across multiple years hide the true temporal patterns of each process. Graph A 1986-1997 data is from Birdsey et al. [2003], 1997-2007 data are from USFS reports. Graph B 1984-1996 and 1987-1996 data is from NRCS surveys in Birdsey et al. [2003], 1992-2001 and 2001-2006 data is from the NLCD change products [*Fry et al.*, 2009; *Xian et al.*, 2009]. Graph C 1984-1989 harvest data is from Birdsey et al. [2003] and 2001-2005 data is from Smith et al. [2009]. Graph D 1984-2007 volume of removal

data is from Smith et al. [2009].

NAFD samples cover part or all of many of the growing urban areas in the region including Atlanta, Raleigh, Norfolk, Richmond, and Tampa. The NAFD sampling scheme may have inadvertently sampled a higher amount of suburbanization than is representative of the region. Both census housing density [*Theobald*, 2005] and NLCD data have a decadal time step. This resolution is not sufficient to evaluate if the temporal patterns of suburbanization are consistent, episodic, of have some type of periodicity through time.

It is hard to draw regional conclusions on SE harvest patterns from only USFS harvest statistics, with their coarse temporal scales and different temporal ranges. USFS ground inventories of harvest volume removals increased 20% from the 1977 to the 1987 inventory, 20% again from the 1987 to the 1997 inventory, then dropped a small amount in the 2007 inventory. TPO harvest volumes increased 95% between the 1997 and 2007 surveys (Figure 4-18d). Through time, USFS estimates of total harvested forest area increased a negligible amount, 0.2% of forest area, while average harvest intensity decreased. The percentage of clear cuts harvests dropped from 75% to 41% of all harvests (Figure 4-18c).

An increase in the number of multiple harvest events on the same patch of forest land could account for the increase in total volume removed as the area of more intense clear-cut harvests was decreasing. NAFD, tracts the trajectory of the same forest patches through time, and so can recorded multiple disturbances in the same location

[*Huang et al.*, 2010]. NAFD results show 4.6% of the forest land in the SE NAFD samples had multiple or repeat disturbances, the highest repeat disturbance rate of all regions (see section 2.5.2).

In the mapped TPO data the highest cumulative logging removals are in the counties sandwiched between the coast and the Appalachian ridge (Figure 4-17). Five of the eight SE NAFD samples overlay areas of high harvest activity according to the mapped TPO data. This supports the assumption that harvest contributes significantly to NAFD base rates and that the NAFD sampling scheme could adequately capture the trends of harvest in the region. There were no clear spatial trends of increase or decrease in TPO harvest volumes for the counties that fell within each NAFD sample.

Large infrequent natural disturbances are known to cause occasional peaks in mortality [*Foster et al.*, 1998]. In 1989, hurricane Hugo made landfall on South Carolina's coast and the center of NAFD sample p16r37. The total forest area affected by 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]. McNulty [2002] estimates that 10% of the carbon normally sequestered by forests was transferred from living to dead wood, which immediately starts to decay. The NAFD disturbance trajectory of p16r37 increased nearly 400% immediately after the storm (equal to 118,130 ha of forest change between 1989-1991). The NAFD sample to the North, p16r36, also shows anomalous rates in the year of and year after Hugo.

Ten other moderate to severe hurricanes made landfall in the region between 1984-2008, including Charley in 2004. Charley crossed through the center of NAFD sample p16r41 on August 13, 2004. In 2004, Francis and Jeanne also hit the same area after Charley, but were of weaker strength. NAFD used a July 8th image in for 2004. Therefore, the damage from the three storms could not have been detected until the next image in the NAFD series, June 28th, 2006. The disturbance rates for 2005-2006 (interpolated to fill in the missing year) were 165% above the twenty year median disturbance rate for p16r41. The p16r41 disturbance rates were elevated in 2002 as well, perhaps in response to hurricane Gabrielle (F1) that passed through the area on September 14, 2001 (after the August 25, 2001image used by NAFD). More work and ground reference data is needed to evaluate the coincidence of the damage detected by NAFD and the hurricane paths that crossed through p16r41 to evaluate the ability of the VCT to accurately detect hurricane related forest damage in this area.

Insect data for the South (SE and SC regions) are recorded differently from the rest of the country and lead to greater uncertainty in reported numbers of forest area affected. However, the southern FHP defines a (SPB) outbreak as the number of hectares of a host tree species having *one or more* locations with multiple trees infected per 405 ha (1000 acres). SPB is a boring insect with near 100% mortality rates. In 1995, a particularly bad year, SPB infested 4.16 million ha of forest in the region [*(USDA)*, 2000]. If the lowest density of infestation is assumed, then in 1995, across the affected 4.16 million ha infected, there may have been only 10,271 locations with multiple trees that died. The assumed density of SPB hosts is 150 trees per acre.

The rate of insect infestations dropped 25% to 2.8% of forest land affected per year between 1997-2005 (Figure 4-18a) [*(USDA)*, 2000; 2009] . Unfortunately, the county scale resolution of FHP data in the South is incompatible with the scale of NAFD forest history maps, so they cannot be used to 'verify' one another. The spikes in the SE rate of forest area affected by insects in 2000, 2001, and 2002 is due to sudden intense outbreaks in Northern GA and north west SC [*(USDA)*, 2005] (see appendix G). The periodicity and spread of SPB cycles vary with local factors [*Gumpertz et al.*, 2000]. The insect affected areas reported for 1987-1998 were averaged across the decade and so do not reveal the true episodic cycles of this process (Figure 4-18a). There are many other insects and pathogens causing forest damage and mortality in the SE besides SPB that are not being considered here.

The SE has many ecoregions that are prone to frequent burning [*Stephens*, 2005]. According to Birdsey and Lewis [2003], on average 0.54% of SE forest land (129,487 ha) burned annually between 1986-1997. Less than 0.01% of forest in the SE burned annually according to the MTBS data over the same time period. Except for NAFD sample p16r41in Florida, detected MTBS fires largely lay outside out NAFD sample boundaries (Figure 4-17). There is good overlap between NAFD detected change and MTBS medium-severe fires in this location. Direct area comparison of NAFD detected forest change with MTBS data is problematic as the latter does not discriminate between fire in forests vs. fire in grasslands or in other land cover types.

If ancillary data is used to mask the MTBS fires than disagreement between NAFD and MTBS could be a byproduct of whichever forest mask was used. The spatial and temporal accuracies of high resolution national scale forest maps are not very well documented.

Some of the change rate peaks in Southeast NAFD samples were explainable using ancillary data sets; however, others were not (Figure 4-19). For example, the causes behind the high rates in p18r35 and p16r41 in the beginning of the time series and the bump in change rates that occurred in p16r36 and neighboring p16r37 in 1999-2000 are unknown.

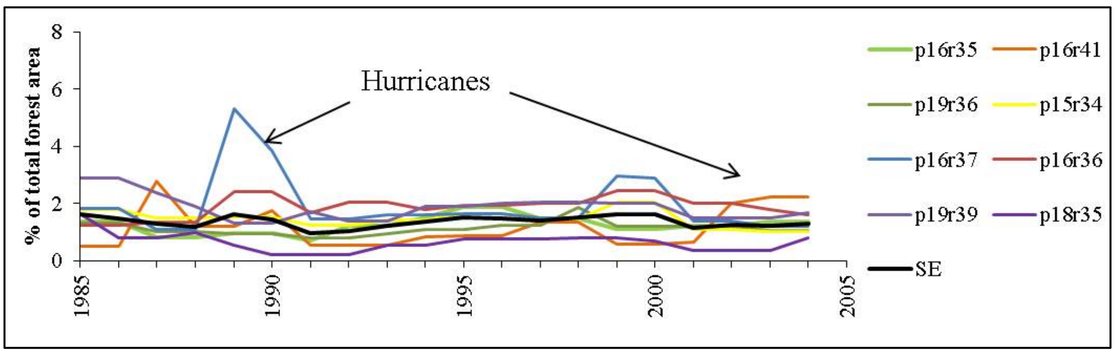


Figure 4-19 : The change trajectories of the SE samples show both high consistent base rates and episodic short spikes, some of which were explainable with ancillary geospatial data.

4.5. <u>South Central (SC)</u>

As in the SE, the South Central region has experienced changes in forest land due to government policies. However, the largest changes have been caused by the increase in commercial pine plantations and the evolution of their industry [*Fox et al.*, 2004].

SC forests have more low productivity forest land, almost 5% of total forest area, than the other eastern regions combined [*Smith et al.*, 2009].

Coarse inventories suggest that the percentage increase in volume (from growth) has been on a steady positive trend for the last three decades (Figure 4-20), suggesting an overall steady increase in the productivity of inventoried timber. The inventories also show large increases across inventories in the rate of losses from natural morality. Between the 1997 and 2007 inventory the mortality loss rate increased more than 60% (relative to the 1997 rate) (Figure 4-20). The average annual amount of forest disturbed over the full observation periods were 25 % higher according to NAFD disturbance history maps than USFS FIA ground inventories (Figure 4-21). The average rate of forest canopy loss calculated from the seven NAFD samples in the SC region, increased 80% to 2.1% of the total regional forest area between the 1985-1994 and 1985-2004 periods. The SC weighted NAFD regional canopy change rates are the highest in the nation, equal to a median forest replacement rate of 60 years.

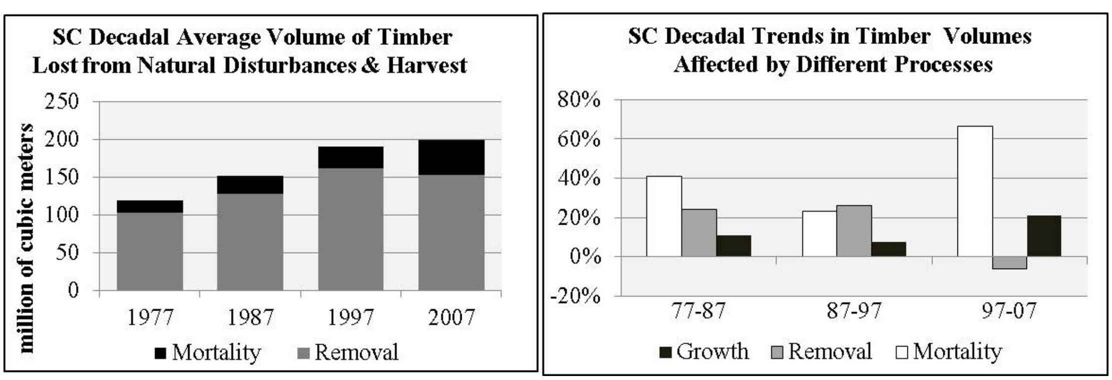


Figure 4-20 : In the Intermountain West region, timber volume losses from mortality have been increasing over the last three decades according to FIA decadal inventories. The graph on the

right shows decadal trends in averaged timber volumes due to growth (used as a measure of productivity), removals and mortality. Growth is the average growth in tree volume less the volume lost through mortality. Mortality is the average volume of timber dying due to natural causes. Removals are the volume removed during timber harvesting or other cultural treatments. Decadal change is calculated as the difference between volumes reported in the two inventories and given as a percentage of the volume from the previous inventory. Tabular inventory data and definitions from Smith et al. [2009].

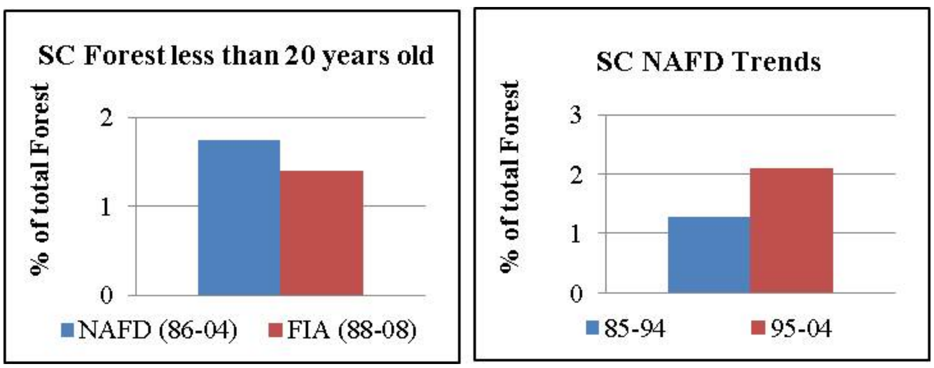


Figure 4-21: NAFD SC averaged annual rates of change, for the period between 1986 and 2004 were the highest across all regions in the CONUS. FIA estimates are from field measurements of stand age. NAFD measurements are from satellite based measurements of the time since disturbance.

The scale of NAFD forest change products allows for coarse regional analysis (through aggregation, see chapter 2 section 2.5.1) and finer scale spatial and temporal trends. The variable spatial distribution of forest land in the region is captured by the variability in the percentage of forest land in each of the NAFD samples ranging from 27.7% to 3.3% (Figure 4-22). The box plot graph of central statistical tendencies summarizes the differences in the distribution of the annual change rates for each sample in the region (Figure 4-22). p24r37, the sample with the highest amount of forest area which weighs heaviest in the regional average, has the highest maximum change rate for any year and the highest median change rate across the samples.

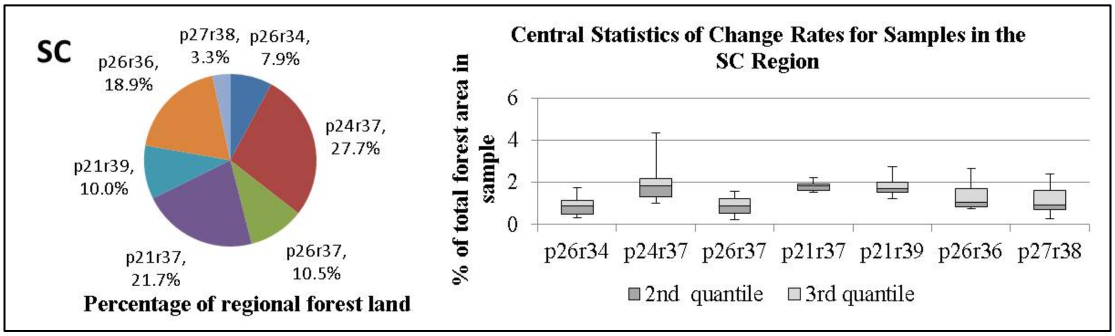


Figure 4-22 : The box plot graph of central statistical tendencies summarizes the differences in the distribution of the annual change rates for each sample in the SC region.

To understand if the forest change rates of NAFD samples that most heavily influence the regional average are representative of the region, it is necessary to know the spatial and temporal distributions of the underlying causal processes in relation to the NAFD sample locations. Temporal statistics and maps of forest change processes in the SC region are evidence that insects, harvest, conversion, fire and wind are all affecting forests in the South Central with varying quantities across space and time (Figure 4-23a-d and 4-24).

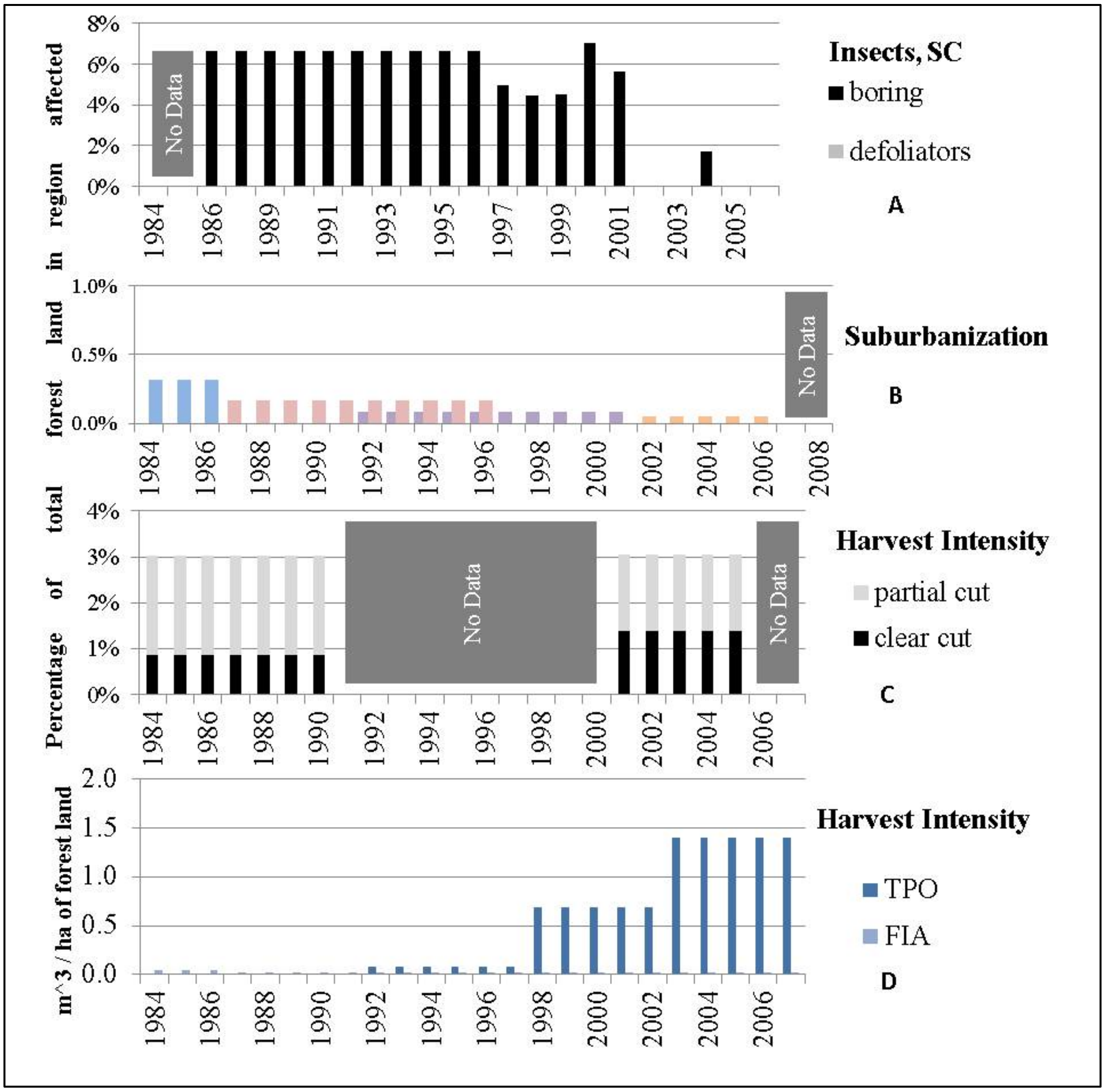


Figure 4-23: Graphs of the temporal patterns for forest change process in the NC region are punctuated by periods of missing data. Averaged rates across multiple years hide the true temporal patterns of each process. Graph A 1986-1997 data is from Birdsey et al. [2003], 1997-2007 data are from USFS reports. Graph B 1984-1996 and 1987-1996 data is from NRCS surveys in Birdsey et al. [2003], 1992-2001 and 2001-2006 data is from the NLCD change products [*Fry et al.*, 2009; *Xian et al.*, 2009]. Graph C 1984-1989 harvest data is from Birdsey et al. [2003] and 2001-2005 data is from Smith et al. [2009]. Graph D 1984-2007 volume of removal data is from Smith et al. [2009].

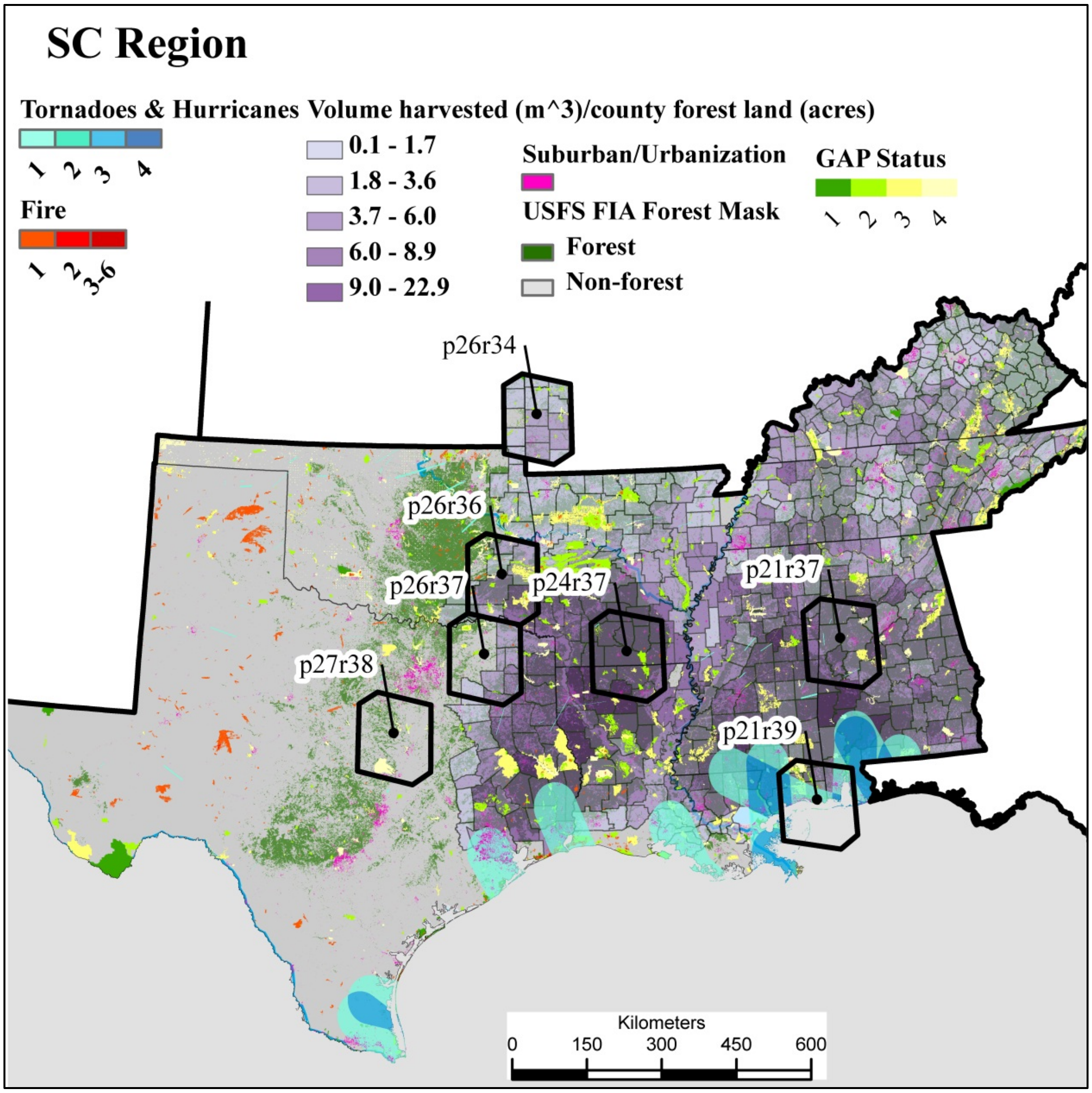


Figure 4-24 : Mapping the known occurrences of forest disturbance and conversion in the SC region visualized the distribution and spatial variability of the different processes in the region and how well NAFD sample locations capture the full range of variability for each.

The total areal impact of conversion of forest land to suburban/urban land use in the SC region is low and has been declining according to national inventories (Figure 4-

23b). The average annual rate drops 99% to 0.3% of total forest area in the NRI data and 28% to 0.05% between the two observation periods available for both datasets. Few of the large population centers fall within NAFD sample boundaries.

The SC region has the highest average annual rate of harvest area, 3.0% (1.5 million ha yr^{-1}), and of clear-cut harvests 1.3% (713,625 ha yr^{-1}) of forest land across the 6 CONUS regions, between 2000-2005 (Figure 4-23c). The average intensity of harvest increased with the proportion of clear-cut harvests nearly doubling from 28% to 45% of harvests. Rates of harvest removals from volume based removals (given as a percentage of total SC forest land) are steady according to FIA inventories, but increase steadily according to TPO surveys (Figure 4-23d). Differences between the trends of the two datasets may be an artifact of their differing observation methods and periods.

Mapped TPO data suggest the highest intensity harvest activity is concentrated in the counties in the center and south center of Alabama and Mississippi (Figure 4-24). NAFD sample p24r37, which has the highest median and maximum annual change rates, lays directly over this area in Alabama. No clear spatial trend across SC counties emerges when the difference between the TPO surveys are mapped (Figure 4-25).

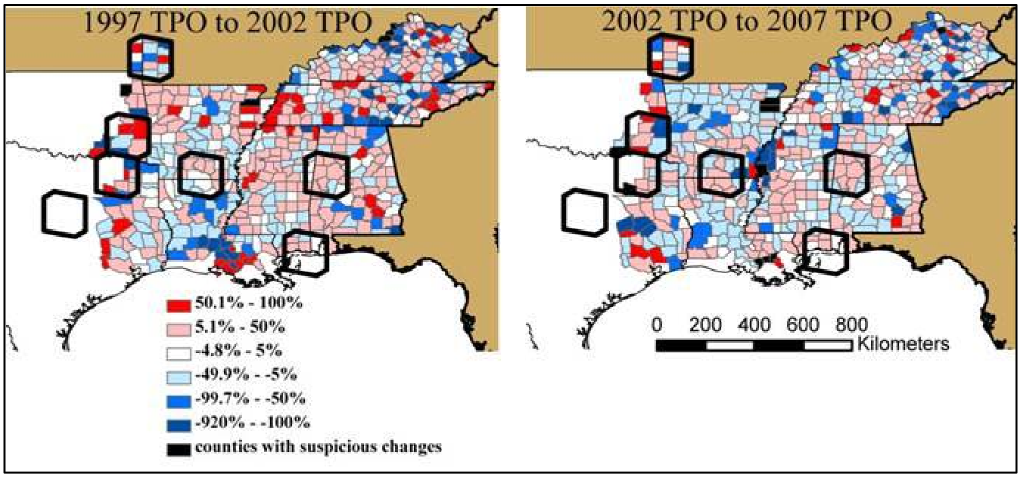


Figure 4-25: Timber Product Output surveys provide estimates of harvest volumes that have been processed in county mills. Though given the date of 1997 the state survey might have occurred in any of the 3-5 years previous to the nominal year of the survey (http://nrs.fs.fed.us/fia/topics/tpo/).

NAFD change products offer another perspective on the temporal patterns of logging activities in the region. The change trajectory of two samples, p26r36, in southeast Oklahoma and its neighbor to the south in Texas, p26r37, show sudden jumps in their annual rates of canopy change that persist for years and then decline rapidly. The sudden increase in rates for these samples is of sufficient magnitude that it is can be seen in NAFD national level estimates of annual forest disturbance and associated sampling errors (Figure 2-16). Between 1997-2000, the annualized rates for p26r36 and p26r37 spike, to 5.4% and 4.5% of total forest land disturbed equaling 274,172 ha and 115,094 ha of forest land disturbed, respectively. These change rates are 300% above their respective twenty year average rate.

TPO harvest data is the only forest change process dataset with records of activity in the locations of the abrupt increase in NAFD canopy change rates for p26r36 and p26r37. Pushmatah, Le Flore and McCurtain counties had the highest increase in NAFD change rates in southeastern OK. TPO harvest removal volumes in these counties changed (-) 7%, (+) 114% and (+) 39% respectively, between the 2002 and 2007 surveys. The VCT disturbance history maps shows that the disturbance activities are not distributed evenly across the county (Figure 4-26). The year of the TPO survey is standardized for reporting purposes between states. The actual year of the survey was 3-5 years before the reporting year. The USFS alerts TPO data users that mills may be reporting receipts for timber that was logged across county and state lines and transported to the mill for processing.

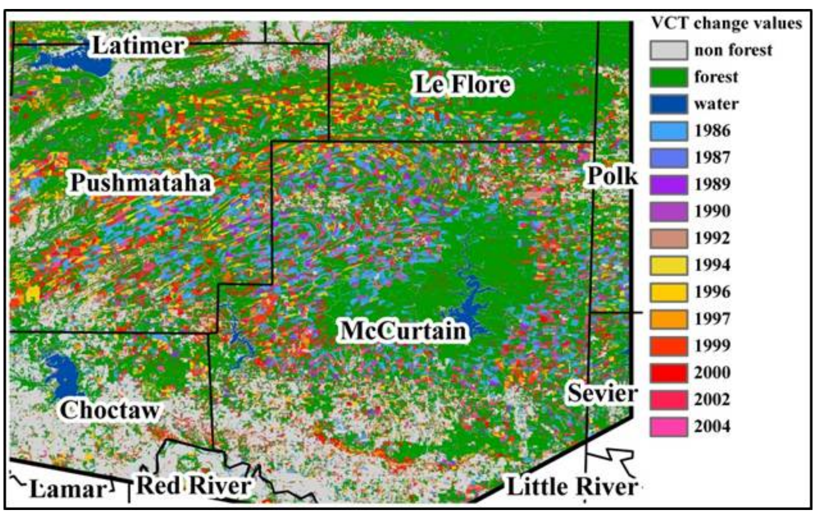


Figure 4-26 : NAFD forest history maps show a large amount of forest area was disturbed in the southeast counties of Oklahoma.

To further investigate the local forest dynamics behind the NAFD results, I contacted the Oklahoma assistant state forester at that time, Kurt Atkinson. 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 were suggested as possible reasons for the increase in local harvest that his office also noted at the time (K. Atkinson, personal communication 2009). Visual inspection of the Landsat time series imagery for p26r36 and p26r37 corroborated that the majority of the detected canopy change in the anomalous years was due to harvest.

Historic FHP rates of average forest area affected by insects dropped 77% to 3.77% of total forest area per year between 1986-1997 and 1997-2005 (Figure 4-23a). Infestations were all attributed to SPB. Annual data (1998 to 2010) show the rate dropping off in 2003 and remaining low into 2008 [*(USDA)*, 2009]. Counties with high counts of reported SPB spots (1991-2004) did not fall within the SC NAFD samples [*Williams and Birdsey*, 2003]. Uncertainties about the location and severity of forest mortality due to SPB across the landscape (density) are similar to those in the SE region which prohibit linking location specific NAFD forest change observations to insect disturbances in the region (see sec 4.4).

Wind is another natural disturbance process that has shaped the distribution and species composition of Southern forests through time. Episodic wind storms may not affect much total area across the region, but can be catastrophic in terms of the amount of timber they damage in such a short amount of time. Tree mortality and damage caused by hurricane Katrina was predicted to release, through slow and gradual respiration, 50% -140% of the carbon sequestered by US forests annually [*Chambers et al.*, 2007].

Wind storms have a prominent presence in SC forest dynamics, but are almost unrepresented in the NAFD sampling scheme. The geospatial hurricane data show seven major (H3-H5) hurricanes hitting the SC coast between 1984 and 2006, including hurricane Katrina. Using the buffered severe hurricane and tornado layers in the process geodatabase and a forest mask created from all areas that were forest in 1992 NLCD retrofit data, I calculated that an annual average of 14,537 ha SC forest was *exposed* to extreme wind storms. NAFD site p21r37 (southern MS) overlaps spatially with the severe hurricanes Ivan (2004), Katrina (2006) and Helen (1985), however, the time-window of imagery used for the sample (1985-2004) excludes the possibility that NAFD captured the storm related forest disturbance.

Fire has played an important role in forest ecosystems across the South and is necessary to maintain long leaf pine landscapes [*Stanturf et al.*, 2002]. Birdsey and Lewis [2003] report 0.36% of forest burning annually between 1988-1997. The MTBS averaged annual forest fire rate increased from 0.1% to 0.27% (135, 032 ha yr^{-1}) over the 1986-1997 and 1997-2005 time periods. The South has a long record of using small prescribed burns for wildfire management [*Stephens*, 2005] and understory burns as a treatment to improve harvest returns. These small fires may not be captured with MTBS results [*Eidenschenk et al.*, 2007].

The majority of moderate to severe MTBS fires in the SC region would not be reflected in NAFD observation as they occurred outside of NAFD sample boundaries. NAFD sample p26r36 (SE OK), had the most overlap with MTBS fire perimeter polygons. Of the fires that spatially overlapped with NAFD data in the sample, only two were of moderate to severe intensity, occurred within the time-window of NAFD acquired imagery, and occurred on forest according to the NLCD 92 forest layer. For the unnamed fire in March of 2004, NAFD results detected only previous disturbances in the area of overlap. In the second, the HEE MTN II fire in August, 1998, NAFD change results overlap with the MTBS results 100%, but were labeled 1999.

Ancillary geospatial data and NAFD products show the variability in the temporal and spatial characteristics of the process that are not captured by coarse regional data. As in all regions, more work needs to be done to understand the fine patterns of forest damage caused by the interaction of wind storms, other abiotic factors, and biotic factors. This work gives an approximation of the potential impact across the region which in forest area extent, may be small compared to wider spread phenomenon such as harvest and insects. The lack of fine scale harvest and insect data across the region leaves gaps in the ability to separate the underlying causes of forest dynamics in the region. Since wind events in the region can be catastrophic and brief, they sometime receive more attention than the episodic and unclear patterns of insects and harvest disturbances.

NAFD maps helped to reveal some of the temporal patterns of harvest dynamics not shown in regional harvest statistics. However, many anomalies in the NAFD change trajectories were not explicable with available ancillary reference data (Figure 4-27). It is unlikely that the increase in the change rate in p27r38, south central Texas, which coincided in time with the harvest increases in Oklahoma and north Texas, is also related to harvest. Ancillary data and image inspection suggest low overall harvest activity in that area.

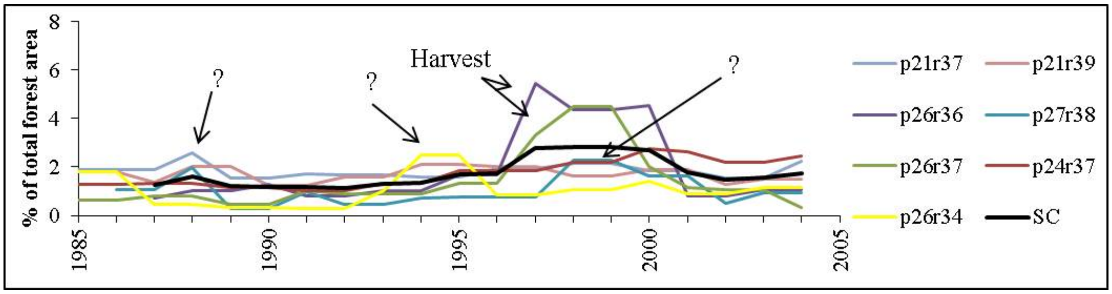


Figure 4-27 : Ancillary geospatial reference data was not sufficient to explain the seemingly random increases in NAFD forest canopy change rates for different path rows in the SC region. Large increases in two of the samples were attributed to changes in the local harvest regime after visual inspection of imagery and discussions with local forest managers from that time period.

4.6. Intermountain West (IW)

The IW region covers a vast land area and has the largest total forest area of all regions (58,628,480 ha). ¾ of IW forest land is publically owned and 14% is reserved from harvest activities, the highest percentage for both classes across the CONUS regions [*Smith et al.*, 2009]. The forest land productive enough to be classified as timberland by the USFS is located at higher elevations and in the north of the region and equals less than ½ of the forest land in the region (Figure 2-9). The majority of the 40% of forest land classified as ‘other’ with low productivity is in the arid south of the region is in the states of NV, NM, AZ, UT and western CO

FIA data shows that the IW has the lowest volume of timber lost to disturbances, including both human-managed and natural, across all CONUS regions [*Smith et al.*, 2009]. The volume of harvest removals steadily increased in the region until declining 5.8% in the 1997-2007 inventories (Figure 4-28). Increases in volume due to growth steadily increased across three decades as did mortality from wind, fire and insects. FIA and NAFD estimate similar amounts of forest land have been disturbed annually in recent times, 0.82% and 0.91% respectively (Figure 4-29). However, NAFD rates can be disaggregated to decadal averages of the annual amount of forest land disturbed which increased 170% to 1.3% between 1985-1994 and 1995-2004.

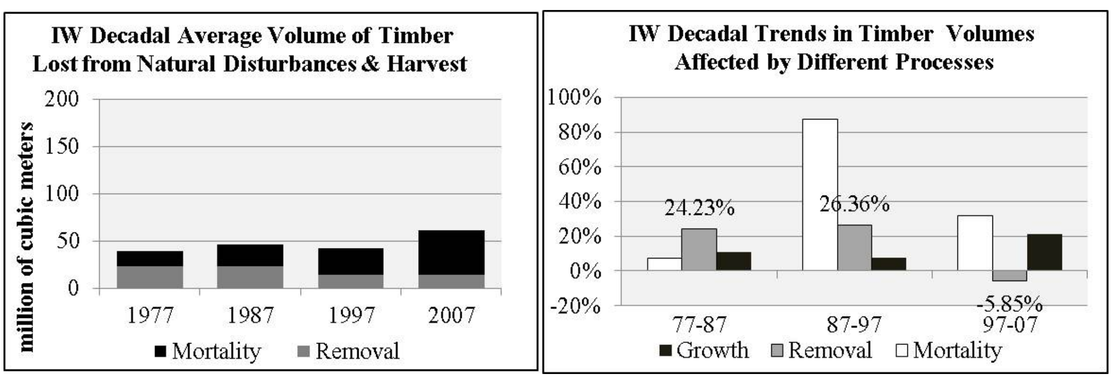


Figure 4-28: The IW had the lowest volume losses to harvest and mortality of all CONUS regions. The graph on the right shows decadal trends in averaged timber volumes due to growth (used as a measure of productivity), removals and mortality. Growth is the average growth in tree volume less the volume lost through mortality. Mortality is the average volume of timber dying due to natural causes. Removals are the volume removed during timber harvesting or other cultural treatments. Decadal change is calculated as the difference between volumes

reported in the two inventories and given as a percentage of the volume from the previous inventory. Tabular inventory data and definitions from Smith et al. [2009].

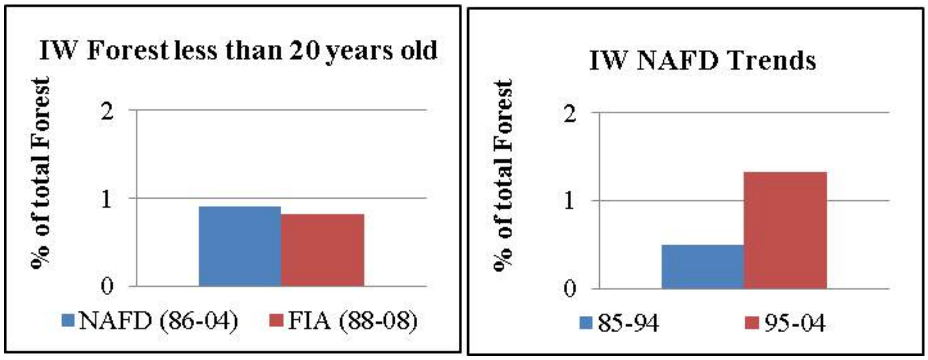


Figure 4-29: Despite very different approaches, NAFD and FIA estimate similar amounts of forest land were disturbed in the IW.

Because of the spatial variability in forest area distribution across the IW region and reflected in NAFD samples, not all samples contribute evenly to the regional averages reported here (Figure 4-30). The three samples in the northern part of the region account for 40% of the forest area sampled by NAFD and therefore 40% of the averaged regional rates. Two of those samples, p42r29 and p42r29 had the second and third highest median change rate across the region. P37r34 has the highest rate of change for any one year, but only contains 2% of the regions' forest area, so the absolute amount of forest area actually disturbed would be very low. Eleven of the thirteen samples show anomalously high annual rates suggesting that a region-wide disturbance phenomenon occurred. Without disaggregating the spatial and temporal characteristics of the change observations and of the forest change processes in the region, it is difficult to know with any certainty if it there is a region wide driver or not.

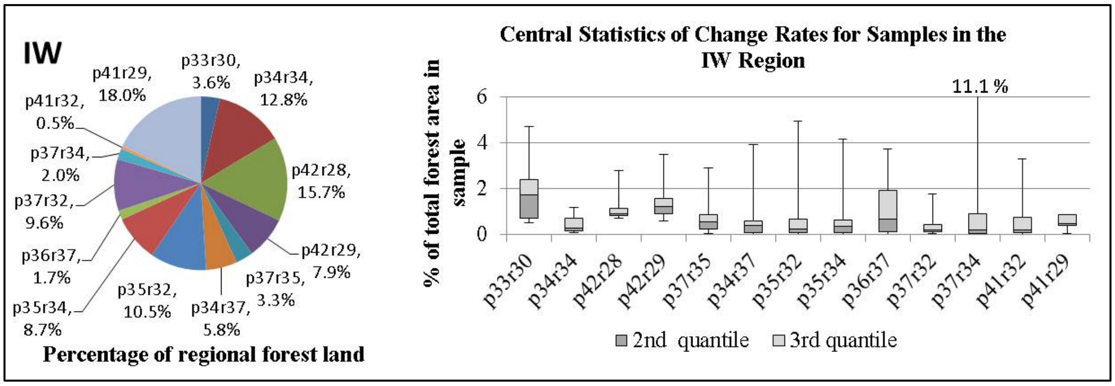


Figure 4-30 : The diversity in the statistical distribution of annual NAFD forest change rates for the 13 IW samples reflects the diversity of forest types, productivity and management categories.

Regional statistics suggest that fire, insects, and harvest are the dominant processes underlying forest change in the IW region (Figure 4-31a-d). The rate of forest area affected by all three of the dominant process increase in the latter half of the time series as do NAFD disturbance rates. Wind storms and conversion to suburban/urban land-use have tiny footprints on forest land in the region and so will not be discussed further in this section.

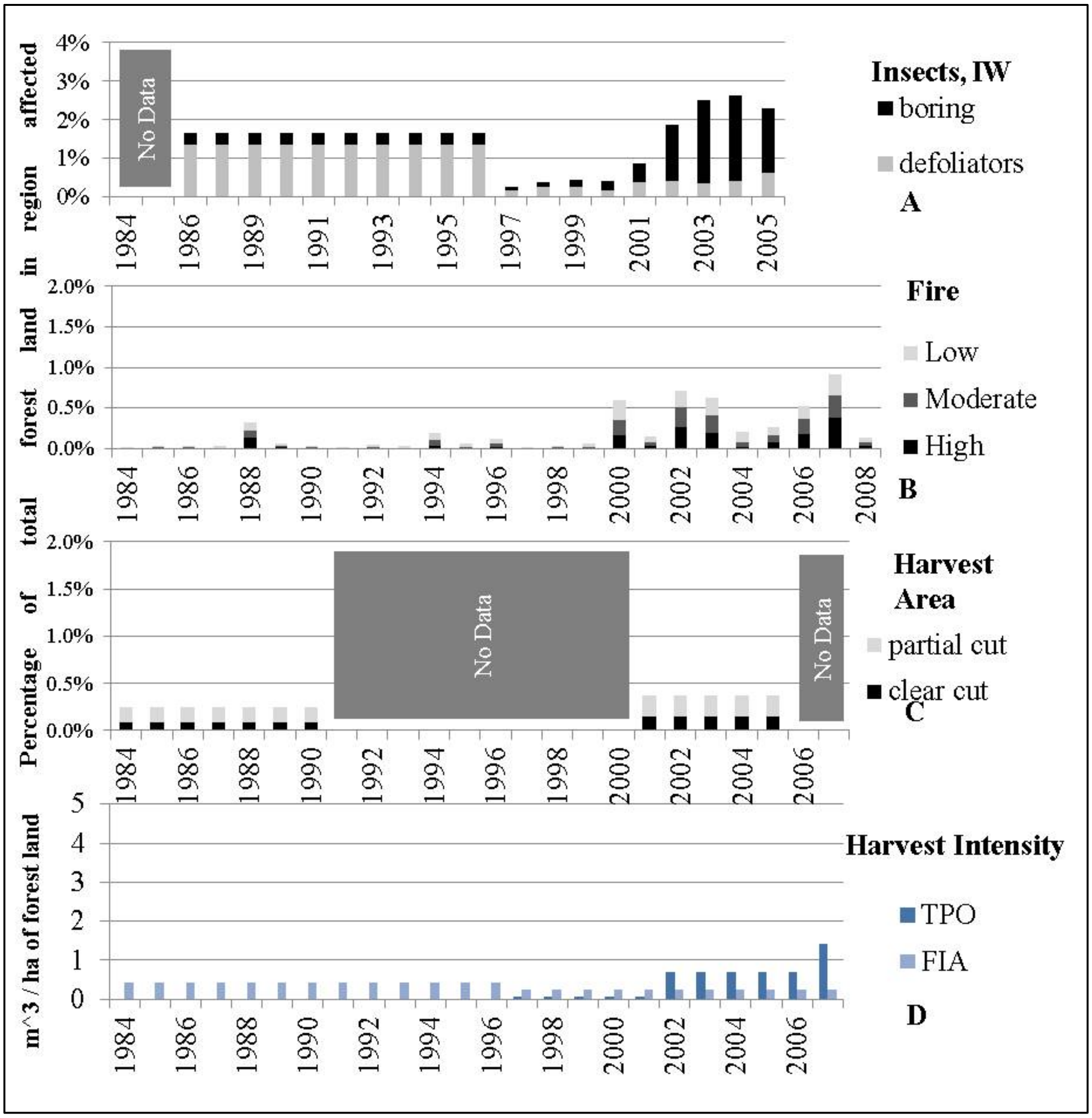


Figure 4-31: Graphs of the temporal patterns for forest change process in the NC region are punctuated by periods of missing data. Averaged rates across multiple years hide the true temporal patterns of each process. Graph A 1986-1997 data is from Birdsey et al. [2003], 1997-2007 data are from USFS reports. Graph B 1984-2008 fire data is generated from data produced by the MTBS project [*Eidenschenk et al.*, 2007]. Graph C 1984-1989 harvest data is from Birdsey et al. [2003] and 2001-2005 data is from Smith et al. [2009]. Graph D 1984-2007 volume of removal data is from Smith et al. [2009].

The IW region has the lowest amount of timberland of all regions and the lowest total volume of timber harvest removals across the last 30 years (Figure 2-12). The rate of harvest and average intensity of harvest increased through time. Clear-cut harvests, roughly 1/3 of all harvest, rose 54% affecting 0.37% annually by the early 2000's (Figure 4-31c). TPO and FIA volume per ha data show temporal trends that differ in their direction and magnitude (Figure 4-31d).

Mapped TPO data suggest that most of the sustained harvests are in the productive heavily forested NW part of the region (Figure 4-32). NAFD samples p42r29 and p42r28 have higher median rates of disturbance than most of the 13 samples in the region and overlay counties with the highest cumulative volume of TPO reported harvest removals. If these counties experienced the region wide trend of increasing average harvest intensity suggested by coarser data sources, than NAFD results, which detect clear-cut harvest better than partial harvest, would reflect those increases. Maps of the changes in TPO harvest volumes between reporting periods show mixed spatial trends across the region and in the counties in NAFD sample locations.

If the amount of forest land 'affected' by insects each year is reported in terms of decadal averages, then the rates appear fairly static, only increasing 10% to 1.81% (1.01 million ha yr^{-1}) according to FHP data (see section 2.5.1). However, annual rates show the rise of boring insect activity from small stable levels to the peak of a dramatic outbreak, an increase of 800% in only four years (Figure 4-31a). The distribution and health of tree host species in the region partially drives the spatial and temporal variability of the many mortality causing insects in the region. For example, forest area affected by Western Spruce Budworm, a defoliator that primarily affects pines in only southern Idaho, Montana and Colorado, decreased 300% between the 1986-1997 and 1997-2005 time periods [*(USDA)*, 2009]. Piñon Ips Bark Beetle, a boring insect that kills pines across the southern IW (AZ, UT, NV, NM and western CO states), reached epidemic levels for the first time in 2001, and has since been causing unprecedented levels of mortality since [*(USDA)*, 2009]. Mortality caused by Mountain pine beetle (MPB), a boring insect that primarily kills pines in the northern part of the region (ID, WY, MT, and CO), has been more cyclical. Rates peaked in 1980-81, and gradually dropped as MPB populations decreased to endemic levels through the 1990's. MPB damage is currently increasing to record high levels again, with 2.3 million ha affected in 2005 alone [*(USDA)*, 2009]. In general, NAFD biennial results do not pick up low to moderate severity/density or gradual disturbances (see section 2.3.1.4).

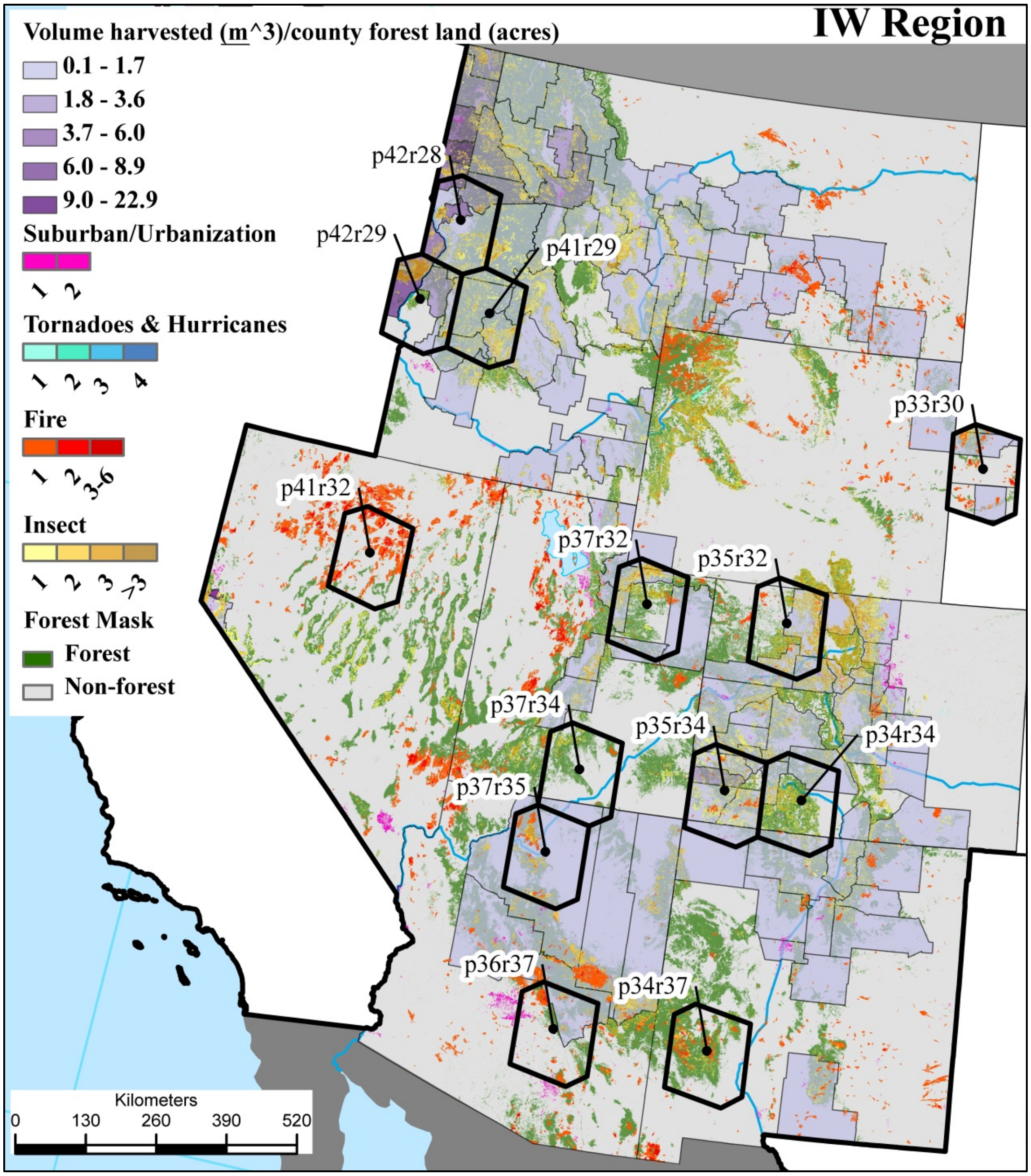


Figure 4-32 : A regional map of the forest land in the IW and the change processes affecting them through time. When the frequency and spatial overlap of forest change processes in the IW region are visualized, the processes appear clustered into hotspots. NAFD sample locations are outlined in black.

Forest fire rates in the IW region vary by source. Birdsey and Lewis [2003] report an average of 0.9% of total forest land burned annually from 1986-1997. MTBS data report an average of only 0.1% burnt forest area in the same time period, and an increase to 0.9% annual average from 1997-2005. Annual graphs of MTBS forest fires show an increase in fire occurrences and intensity beginning in 2001 (Figure 4-31b). The MTBS record used in the regional map of the frequency and overlap of forest change processes uses all MTBS records, not just those on forest lands.

Large peaks in the NAFD disturbance rates, for 9 of the 13 NAFD IW samples, fall between 1999 and 2002 suggesting that the causal process is a region wide phenomenon (Fig 4-33). Sharp peaks in the annual disturbance rates of many NAFD samples match well with the location and timing of many moderate to severe fires in the MTBs data set. 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. Convergence between NAFD maps and MTBS data suggest that the Eureka and Sadler fires caused a rate spike, in 1999, equal to 11% of the total forest area (3,540 ha), in NAFD sample p41r32 (NV). In the more forested north of the IW region, in 2000 and 2001, the high severity Diamond Peak, Flossie, Clear Creek, Salmon Challis and Snowshoe fires occurred within the boundaries of sample p41r29. The NAFD maps recorded a spike of canopy loss in 2000-2001 equal to 3.4% of the total forest area in the scene (33,220 ha).

Comparing NAFD disturbance locations and timing with known fire *and* insect damage that overlap in time, shows that the temporal signatures of NAFD disturbances are a tighter match with moderate to severe fire events, than with events in the insect layer. Not all of the NAFD disturbance dynamics for the IW samples can be explained with the ancillary reference data. For example, the high rates early in the series in p33r30.

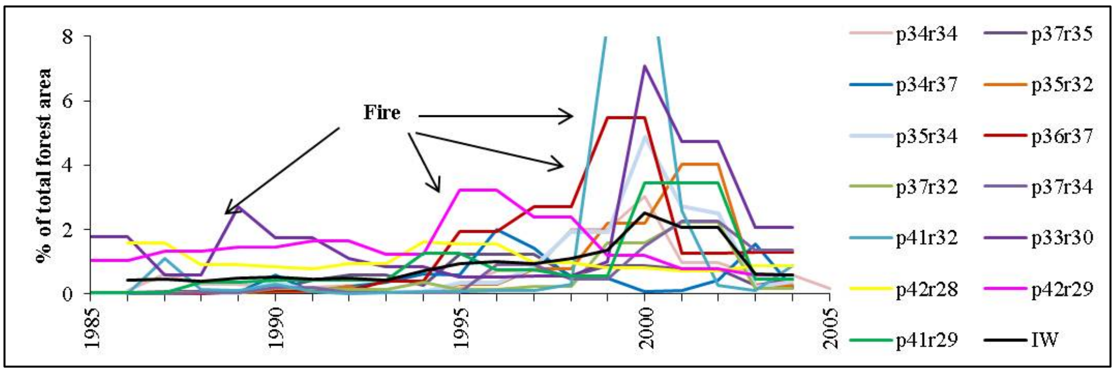


Figure 4-33: Many of the staccato spikes in NAFD disturbance rates can be attributed to fires by referencing the MTBS fire data set.

Overstocking, from land management decisions such as 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; *Samman and Logan*, 2000]. Mortality from insect epidemics can cause extreme fuel loads increasing the risk of catastrophic fires. Regionally, the forest area affected annually by fire increased along with mortality from boring insects, (Fig 4-31a and c). Fire and insect forest disturbance sometimes overlap in space and time (Figure 4-32). A direct aerial comparison of the two datasets would be confounded since MTBS data area not specific to forest land and ADS data only show some of the locations and times where insects strike and none of where they do not. Therefore, generalizations about the relationship between fire and insects must be built from a case by case basis, preferably in addition to local expert knowledge.

4.7. Pacific Coast (PAC)

The PAC region has high spatial variability in many factors that influence the management of forests such as the amount, ownership and type of forest land. In general, forest land along the Coastal and the Cascade Mountains are more heavily forested, productive and privately owned with dryer public timberland increasing towards the eastern and southern parts of the region (Figure 2-9).

Decadal volume inventories show a distinct decrease of 40% in harvest removal rates during the 1997 inventory cycle suggesting a change in regional harvest regimes some time during the period (Figure 4-34). Growth and natural mortality maintained the same direction (increases) through three inventories. NAFD estimates of forest area with canopy losses (temporary or permanent) are 70% higher than FIA estimates of forest area in the 0-19 year age class (Figure 4-35). Decadal averages of the annual NAFD disturbance rate for the PAC region were stable at 1.14% for the 1985-94 and 95-04 epochs (Fig 4-35).

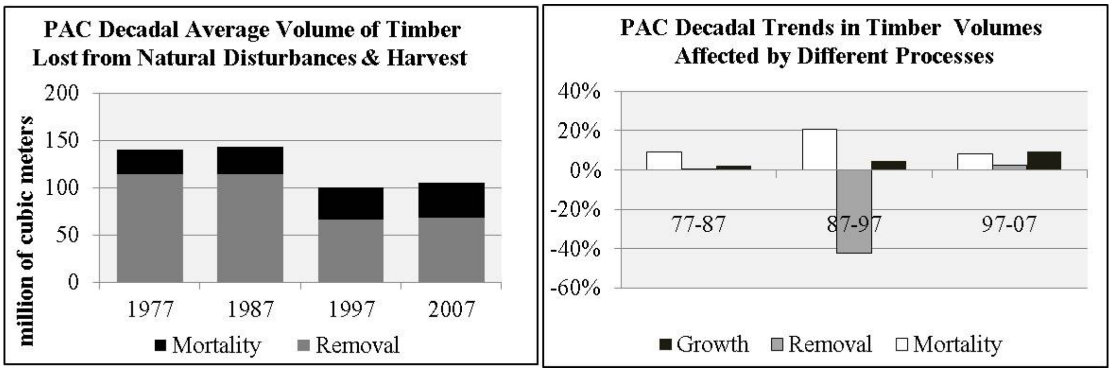


Figure 4-34 : FIA inventories capture a large decrease in PAC harvest removals (left graph), while volume increases from growth (a measure of productivity) increase at a low steady rate (right graph). Growth is the average growth in tree volume less the volume lost through mortality. Mortality is the average volume of timber dying due to natural causes. Removals are the volume removed during timber harvesting or other cultural treatments. Decadal change is calculated as the difference between volumes reported in the two inventories and given as a percentage of the volume from the previous inventory. Tabular inventory data and definitions from Smith et al. [2009].

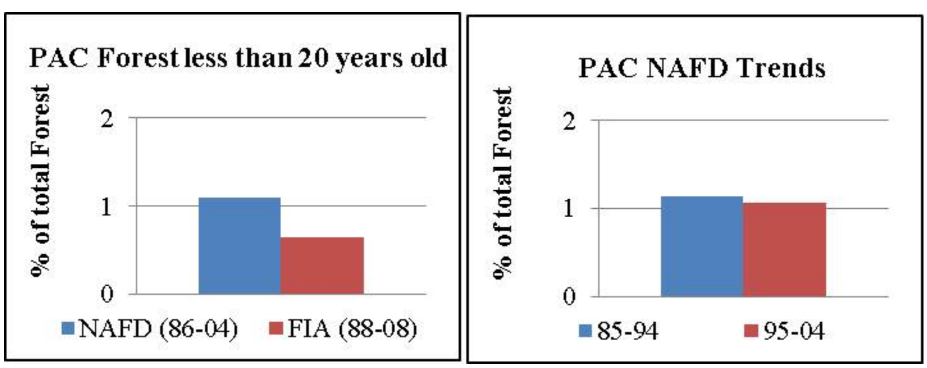


Figure 4-35 : NAFD forest history maps for the PAC samples estimate higher rates of disturbed forest area than FIA inventories.

The spatial variability in the arrangement of PAC forest land is captured in the 13 NAFD samples (Figure 4-36). Three samples with low forest area (p42r35, p40r37, and p48r27), either because they are on the coast or in the dryer less forested lands to the south, have maximum change rates that are dramatically higher than their median rates of change. The forest dynamics in samples with little forest area may appear more variable because they have a low denominator in the calculations of their annual rates (given in terms of total forest area in the sample). Because many of the PAC samples fall along the coast, the percentage of regional forest area sampled should not be taken for a measure of the density of forest area in the scene (Figure 4-37). For example, p48r27 has less than 2% of the regions forest area, but it overlays the tip of the very heavily forested Olympic peninsula.

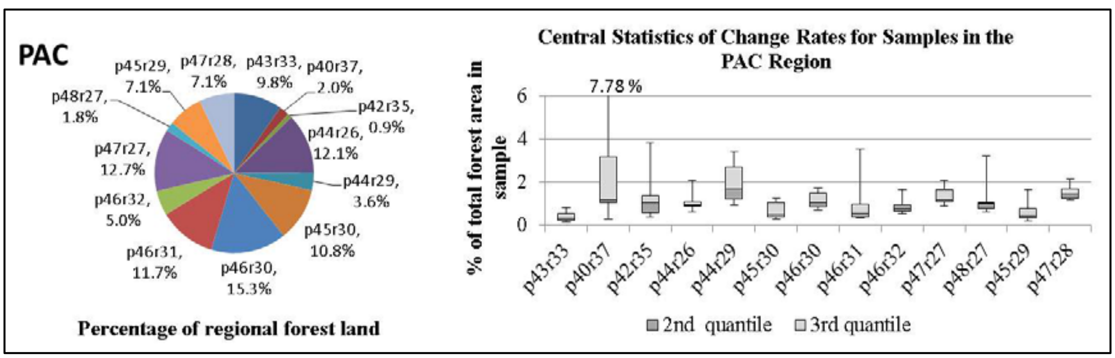


Figure 4-36 : The statistical distribution of total sampled forest area and of the annual change rates in individual samples show high variability.

To tease apart the relative influences of the multiple processes affecting forest canopy loss while decadal NAFD averages show little change, multiple data sets and landscape scale understanding of changing policy and disturbance regimes on forest land in the PAC region is necessary. Aggregated statistics can hide the rise and fall of the influence of individual canopy change processes. Separate graphs of the annual rates of forest area affected by different forest change processes in the region show how the importance of the processes changes through time (Figure 4-38). Forest land conversion to suburban/urban use is also minimal in the region and hotspots of conversion do not fall within the boundaries of NAFD samples. Wind storms also affect minimal amounts of PAC forests [*Barnes et al.*, 1998]. Neither process will be discussed further in this section.

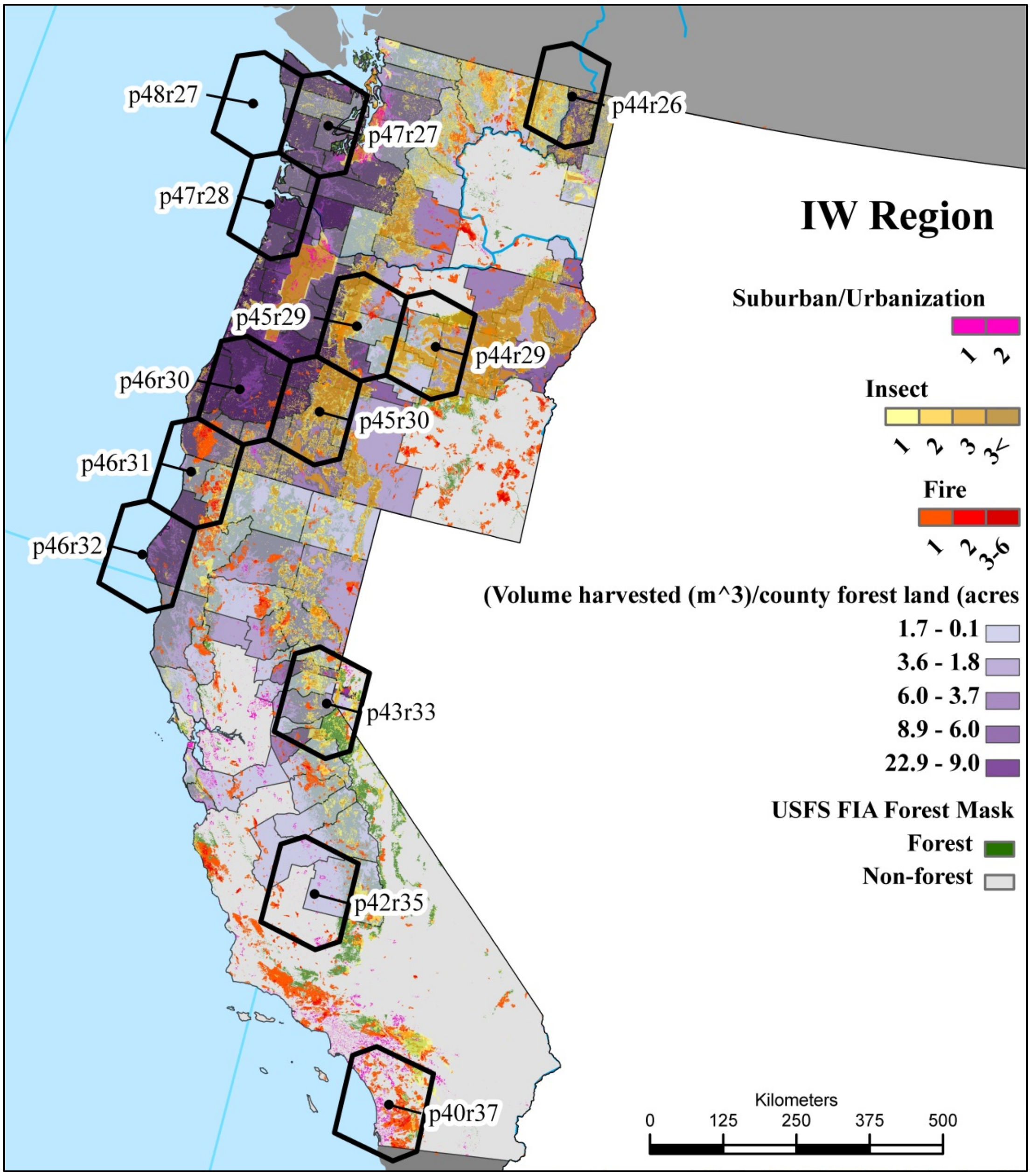


Figure 4-37 : Mapping the frequency and overlap of the multiple forest change processes in the region provides an integrated assessment of the hotspots of potential forest canopy loss and its underlying cause(s).

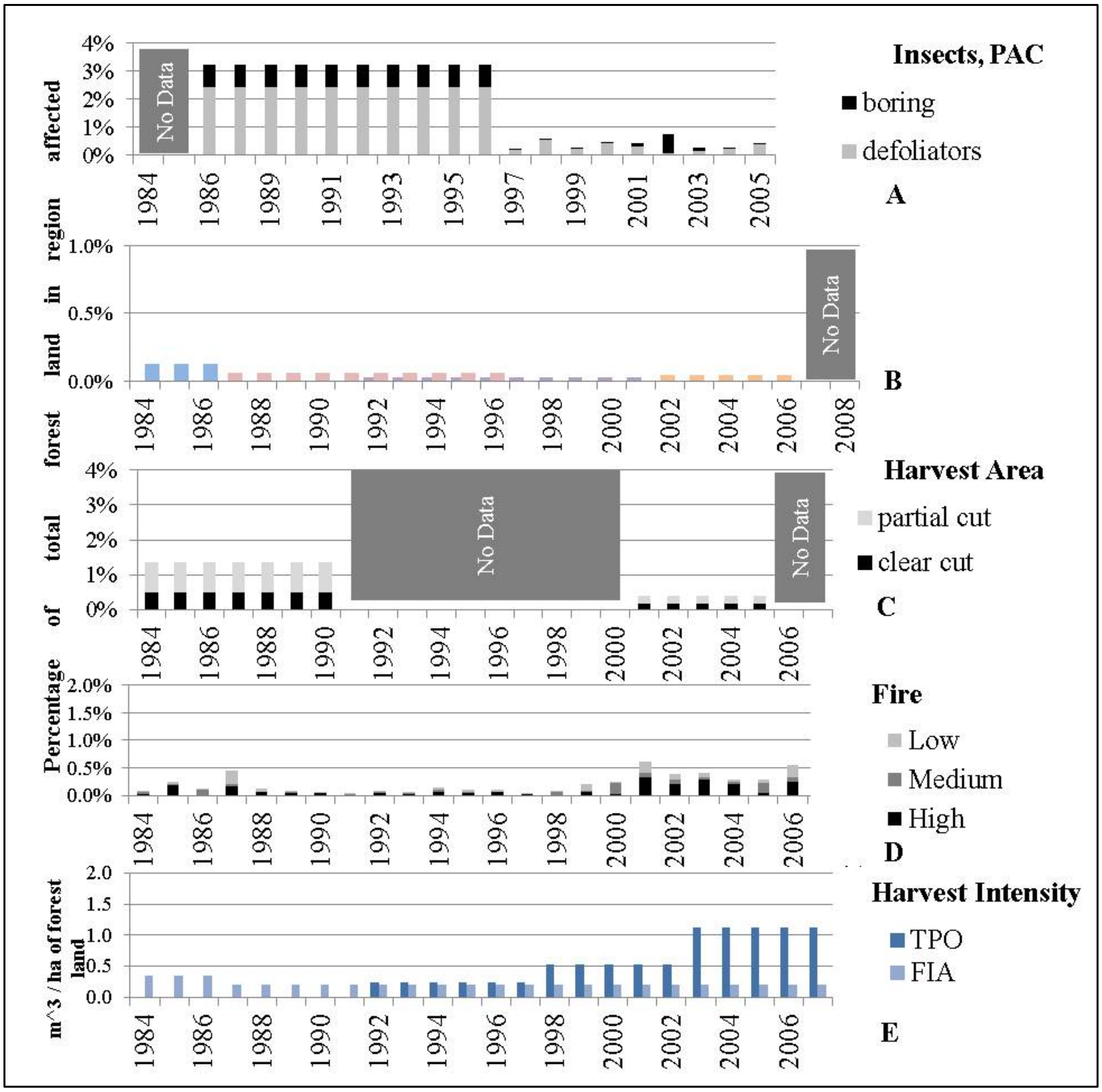


Figure 4-38: Graphs of the temporal patterns for forest change process in the NC region are punctuated by periods of missing data. Averaged rates across multiple years hide the true temporal patterns of each process. Graph A 1986-1997 data is from Birdsey et al. [2003], 1997-2007 data are from USFS reports. Graph B 1984-1996 and 1987-1996 data is from NRCS surveys in Birdsey et al. [2003], 1992-2001 and 2001-2006 data is from the NLCD change products [*Fry et al.*, 2009; *Xian et al.*, 2009]. Graph C 1984-1989 harvest data is from Birdsey et al. [2003] and 2001-2005 data is from Smith et al. [2009]. Graph D, 1984-2006 fire data is from the MTBS project [*Eidenschenk et al.*, 2007]. Graph E 1984-2007 volume of removal data is

from Smith et al. [2009].

The PAC region is the only region to show a decrease in the total area harvested through time. The rate of forest harvest dropped 73% to the average of 0.38% of PAC forest harvested annually between the 1980 and 2000's epoch (Figure 4-38c). Average harvest intensity, (the ratio of clear-cut to partial harvests) rose from 35% to 46%. FIA ground inventories across the 1987, 1997 and 2007 inventories show a 44% and 9.5% decrease in the rate of volume of harvest removals on timberland through time, respectively (Figure 4-38e). TPO data for the region show a steady increase in removals across the 1997, 2002 and 2007 surveys. Mapped county level TPO data show a general trend of decreasing harvest removals in counties bordering the coast and increasing harvest removals in counties further inland between the 1997 and 2002 reports (Figure 4-39).

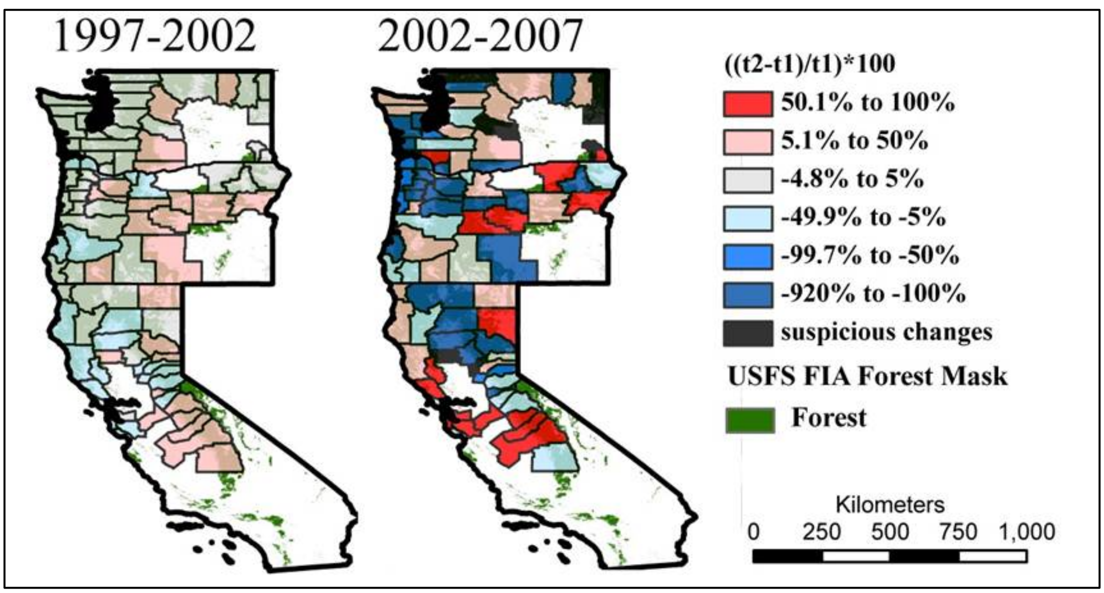


Figure 4-39 : The direction and magnitude of change between county harvest volumes reported

in the 1997 and 2002 TPO are on the left and the 2002 and 1997 TPO are on the right. Numbers are given as a percentage of the volume from the earlier survey.

Large shifts in the PAC regions human-managed disturbance regime can be attributed in part to changes in land management on federal lands (60% of all forest land), harvest regimes on private lands, and mill production capacity. Beginning in the late 80's to early 90's there were large management shifts on 9.7 million hectares of forest land, related to legislation to protect spotted owl habitat in western federal timberlands, beginning with temporary moratoriums blocking harvests on federal lands and culminating in the 1994 Northwest Forest Plan (NFP) [*Williams et al.*, 2007]. As part of the plan, former public timberland was reclassified to reserved and lower harvest limits were set on the remainder. Wear and Murray [2004] conclude that of the supply drop from public forest lands between 1990-1995, 43% was made-up for by increased supply from private pacific timber lands, 27% increase from Canadian imports, and 14% increase from private southern timber land. Finally, timber processing capacity fell 37% across the West between 1986-2003 further affecting local demand and supply [*Collins et al.*, 2008].

Localized remote sensing and inventory studies focusing on ownership and harvest rates in the region, show that harvests on private land in the region increased substantially, after the legal changes [*Huang et al.*, in press; *Pierce et al.*, 2005]. TPO data on the volume of removals for the PAC region are only available beginning in 1997 (actual data survey years are probably 1992-1995) so cannot reflect changes from the late 80's harvest regime.

FIA timberland inventories record increasing mortality due to natural disturbances across decadal surveys. FHP derived average rates of total area affected by insects decreased 44% to 1.81% of forest per year (Figure 4-38a). Specifically, the forest area affected Western Spruce Budworm (defoliator) and the Western Pine Beetle (borer) dropped more than 700% and 60%, respectively, between 1986-1997 and 1997-2004 [*(USDA)*, 2005]. Epidemic outbreaks of others bark beetles species are responsible for the large overall increase in boring insect damage across the regions forests [*(USDA)*, 2005]. Although NAFD sample locations overlay many of the areas of the spruce budworm epidemic, they do not systematically catch insect damage to tree canopies. Low severity and/or density insect damage from defoliators is not as readily captured in the NAFD results.

Prolonged stress from droughts in conjunction with densely stocked even-aged stands created prime conditions for both widespread bark beetle and fire related mortality in the dryer parts of the PAC region (inland OR, WA and CA). MTBS data on forest fire record an increase in the decadal averages of the annual rate of forest area burned from 0.1% to 0.22% (Fig 4-38d). Annual MTBS rates of the severity of forest fire show a sudden increase in the total area of forest fires and their severity with the rate slowly declining each year after until 2006 when they spike again.

Different direction trends in the harvest and fire regimes of the PAC forests likely negated each other across aggregated regional scales where NAFD rates appeared flat through time. NAFD disturbance results for the samples of the PAC region showed different temporal patterns across the region that seem to be related to the different disturbance harvest and fire regimes that they happen to overlap. Some anomalous events were explained by convergence with geospatial reference data. For example, MTBS data showed multiple large severe fires occur in 10 of the 13 PAC NAFD samples. Episodic peaks in NAFD forest change rates correspond to the timing and location of many 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 4-39). To understand the spatial and temporal characteristics of harvest and insects in the region and in relation to the NAFD disturbance rates, both ancillary data sets and published literature were necessary. Some of the canopy loss dynamics captured in NAFD samples cannot be explained or corroborated with the currently available reference data sources.

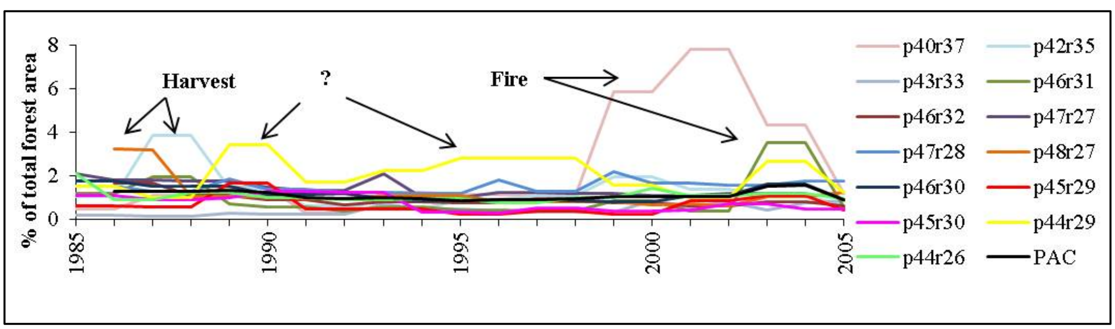


Figure 4-40 : In some cases the forest change processes underlying the base rates and staccato peaks evident in NAFD disturbance trajectories for sample locations in the PAC region were explicable using ancillary data sources, and in other cases they were not.

4.8. *Synthesis and Conclusions*

A different approach is needed to understand processes underlying historical forest disturbance and conversion where there is a lack of reference data (at local grains over large space and time extents). Statistically-based accuracy assessments using independent reference datasets are the standard procedure for assessing remote sensing based change detection products [*Congalton*, 1991; *Congalton and Greene*, 1999; *Stehman*, 2005; *Wulder et al.*, 2006]. Ground-based field studies use direct observations provide data on canopy dynamics and their underlying processes over limited space and time [*Amiro et al.*, 2010; *Busing and White*, 1997; *Clinton*, 2003; *Laiho et al.*, 2003; *Papaik and Canham*, 2006; *Peterson and Pickett*, 2000; *Sun et al.*, 2001; *Tarrega et al.*, 2006]. The focus of this chapter, was not to assess the error sources or 'validate' forest history products, but rather to use multiple sources of data to 'verify' observed canopy dynamics over decades and to establish the underlying causal processes where possible. It is necessary, to reiterate that there are many uncategorized errors, sources of uncertainty, and data gaps in each of the datasets used. As such, no one data set can be considered the 'truth'.

To gain new understanding of forest change processes and how we observe them, in this chapter, NAFD disturbance history maps, ancillary geospatial data, USFS inventories and published literature were combined across multiple scales of space and time evaluating areas of overlap, convergence and divergence. This approach cannot provide a quantitative measure of accuracy; however, it does provide new insights into the spatial and temporal characteristics of forest canopy loss from disturbance and conversion across six regions in the CONUS. Due to the local nature of forest canopy dynamics and their underlying processes, and to the distinct characteristics and data gaps in each dataset, the ability to 'verify' disturbance events and underlying causal processes varied within each region.

Local results can be grouped into the following categories, areas where data sources did not overlap, areas where data did overlap but did not converge on a similar result or on a specific process, and areas where data did overlap and converge. Areas that fell into the first category, where process data and NAFD maps did not overlap, still revealed how the distribution of events and the distribution of observations influence local and aggregated calculations of change rates. For example, in the NC region, landscape scale inspection of the data shows that NAFD samples do not overlap the clustered local areas of suburbanization. The NC NAFD locations under sampled this process and therefore regional rates may not reflect the proportion of canopies affected across the region by suburbanization. The random locations of NAFD samples in the NE and SE regions, possibly oversampled forest canopy losses from conversion to suburban/urban land uses. Because high population densities have an inverse relationship with harvest activities, the under or oversampling of suburbanization by NAFD locations may have implications for how well NAFD locations captured harvest processes in different regions.

In many areas, the wind storm data and NAFD maps did not overlap, because of the limited locations of NAFD samples and also because the wind dataset missed some storm events. The NAFD sampling scheme missed the majority of severe tornadoes and hurricanes that occur across the NE, NC, SE, and SC regions. However, NAFD results captured a severe Derecho event in Minnesota that was documented only in the FHP insect data, exposing data gaps in the national wind storm database. NAFD results in the exact year and spatial neighborhood (< 1 m radius) of tornadoes paths in Pennsylvania converged suggesting that the scene level spike in NAFD change rates was storm related and highlighted the spatial imprecision of the tornado paths. Spikes in NAFD rates in two SE samples converged in space and time with the severe hurricane data set suggesting the extreme levels of canopy damage were related to hurricane Hugo. Lack of geospatial harvest data makes it difficult to attribute all of the change to wind damage since salvage logging also occurred in the area.

Spatially explicit fire data was more challenging to use for verification of NAFD results, in part due to uncertainties regarding the land cover where MTBS fires are detected. In the SE and SC regions, the available fire data almost completely fell outside of the spatial boundaries of the NAFD results. It is plausible, that NAFD picked up forest fire events in these regions that were missed by MTBS, due to its large minimum fire size restrictions (see section 3.3.1). In the IW and PAC regions, where MTBS fire and NAFD sample locations intersected, in many instances the location and timing of forest fires and NAFD detected canopy changes converged. Fire explained many of the ‘staccato’ peaks in the NAFD change trajectories in the IW and PAC. There are many fire locations in these two regions that overlap with NAFD samples were the year and location do not converge with NAFD detected canopy loss. Again NAFD may have detected fires smaller than the MTBS minimum fire mapping size in these areas (1000 acres).

The cyclical nature of the life cycle of many forest insects suggests that epidemic outbreaks and the related forest increase in forest canopy damage would be captured in NAFD change trajectories as episodic increases in change rates that last for 3-5 years, not as consistent ‘base’ rates, nor ‘staccato’ peaks of forest disturbance. However, it was impossible to test this assumption since the insect data was difficult to use to verify the underlying cause of NAFD change for reasons related to scale and magnitude. County level assessments of Southern Pine Beetle infestations (the finest scale available) did not converge temporally or spatially with increases in NAFD disturbance rates. In the NE, some known insect outbreaks intersected spatially with NAFD sample boundaries, but not temporally (the ADS data did not go back far enough in time). In the NC region, there were many areas where NAFD samples and ADS insect records did and did not intersect spatially. Where they did overlap spatially, the specific years and locations of insect infestations did not converge with NAFD disturbance events, most likely because the disturbance was from defoliators with lower severity and density disturbances. The same held for areas in the IW and PAC region where documented insect outbreak locations intersected NAFD disturbance maps, but did not converge at the same space and time. In general, low severity or low density disturbance events are not detected as well in NAFD biennial maps [*Thomas et al.*, 2011]. It also must be restated that the ADS data has many spatial and temporal gaps so the amount of insect disturbance captured in NAFD results cannot be determines solely by comparing the two datasets.

The approach of this study offers a novel contribution to the poorly understood spatial and temporal dynamics of causal processes and canopy loss across multiple scales. Discussions of the temporal dynamics of forestry products and markets, and their related associated harvest implications, appear in economic and forestry literature [*Collins et al.*, 2008; *Johnson*, 2001]. Yet, there has been little work linking these economic drivers to empirical evidence of local spatial and temporal harvest pattern, in part, because there is very little fine scale spatio-temporal data on harvest events. This work was able to link changes in local harvest regimes with sustained increases in NAFD disturbance rates (across 5 years) for two sample locations and with related increase the aggregated rates for the SC regional and rates for the nation.

In the NE, NC, SE, SC, and PAC regions the 'base' rates of change for NAFD samples were attributed to harvest, because published data suggest that harvest activities affect more forest volume and area than natural disturbances [*Smith et al.*, 2009]. The coarse scale of the harvest data made it difficult to assess how the random spatial location of NAFD samples affect the ability of NAFD results to capture regional level harvest dynamics. Often, the temporal patterns in county level TPO data did not coincide with disturbance patterns in NAFD results. Evidence of inconsistencies in the TPO reported data suggest that the error and uncertainty in TPO accounting methods need to be better characterized. The increase in partial harvests is likely to have been missed in the NAFD maps.

The 'base' rates for each region were extremely hard to verify, for multiple reasons. Principally, the forest change process datasets have too many spatial and temporal data gaps, or are too coarse in scale to verify such broad scale disturbance regimes. Also, it was shown that the spottiness of the NAFD locations may over or under sample specific processes. The implication of this result is that the base rates for the NAFD regional aggregates may not be representative of rate of the most dominant or common forest change processes in the region. A wall to wall effort may be the only way to truly asses the multiple disturbance regimes affecting forests in the CONUS through time.

Many of the 'staccato' peaks in NAFD canopy loss rates converged with the spatial location and timing of wind and fire events. These highly localized rare events have been the topic of much discussion and theory in disturbance ecology ( ); however, few forest canopy monitoring efforts have been able to capture these events across broad extents of land and time. A longer time series of data is needed to determine if the staccato peaks are simply infrequent episodic events or part of a periodic/cyclical disturbance pattern. Other localized peaks in the NAFD change rates were unexplainable with available ancillary data.

Local sustained increases in canopy loss are documented in several NAFD samples in different regions. In the SC and PAC regions, evidence was found to suggest that this temporal signature is evidence of changes in local harvest regimes. Other locations of sustained increase in NAFD rates in the NC, SC, and PAC regions were not verifiable with existing data. Insect canopy damage is likely to have a similar signature (though of lower magnitude); the signature was not captured by the NAFD disturbance maps.

Characterizing how NAFD results relate to the patterns of underlying forest change processes is of benefit to a wide science community. For example, the NAFD approach has already been adopted for use in a wide range of USFS forest change detection applications [*Nelson et al.*, 2009; *Schroeder et al.*, 2011; *Vogelmann et al.*, 2011]. Also, attributing the cause of forest canopy changes is necessary to disaggregate the geographic patterns of carbon sources and sinks in forested landscapes ([*Pacala et al.*, 2007] and avoid confusion over long term trends and implications of forest canopy loss observed over relatively short periods of time [*Hansen et al.*, 2010b; *Reams et al.*, 2010].

Chapter 5: Summary and Conclusions

5.1. Introduction

The objective of this research was to synthesize 20 + years of inventory, remotely sensed, and geospatial data to reach a more integrated understanding of the many forest change processes that underlie observed canopy losses across the contiguous US. This study interpreted patterns of forest canopy loss and of forest change processes together and separately across multiple scales. Data gaps and resolution constraints in canopy change observations and reference geospatial data sets were constant barriers to quantitative analyses. The study points to multiple examples of where and why better estimates of the spatial, temporal, and severity related errors and uncertainties of the data are necessary. Suggestions were made for future studies that focus on how to address these issues. The use of many data sets over multiple scales provided novel insights into how the unique characteristics of each underlying causal process may affect observations of historical forest disturbance and conversion. Overall, the study improves the geographic understanding of major forest change processes and provides new capacity and knowledge for incorporating the complexities of forest land dynamics into Earth systems science.

5.2. Study Implications

Monitoring and quantifying forest canopy changes are essential to characterize how forests influence other earth systems. Forest canopy change dynamics interact with energy, hydrologic, nutrient, atmospheric and biotic systems across a range of scales.

Though the underlying causal processes operate across a range of spatial and temporal scales, canopy loss is a localized phenomenon. Yet, there have been few integrated studies to distinguish the spatial and temporal characteristics of the multiple change processes underlying forest canopy dynamics at cogent scales across large land areas in the U.S. In its entirety, this study offers a unique multi-scale contribution to the body of knowledge on forest disturbance and conversion processes that affect the majority of forest land in the CONUS.

The approach used here of integrating local knowledge, geospatial technologies, and historic datasets across a range of scales establishes a new baseline for integrated research on forest change processes. The approach also provides a more complete geographic model of each of the major forest change processes and their overlap across the CONUS. The work helps categorize the various sources of error and uncertainty inherent in each of the datasets incorporated into the geodatabase of change processes. Future researchers can build on the knowledge framework and the geodatabase developed herein to quantitatively evaluate the spatial and temporal relationships of forest change processes and their chosen phenomenon of interest. Finally, the study points to multiple future research opportunities such as the need for 1) new approaches to studies of forest canopy change that focus more on systematically characterizing the severity of events in terms of the biophysical properties of forest stands and 2) better geospatial data on forest harvest and insects in the U.S.

This approach was novel because of the scales of the datasets incorporated and the linkages to local georeferenced data on change processes. This work interprets NAFD results in the context of USFS inventories, the oldest and richest dataset of forest dynamics across the country and in relation to the different processes acting on forested landscapes, serving a wider scientific community. NAFD has been successful in transitioning the lessons and technology developed over the course of the project to the USFS. The USFS has in turn conducted applied research on forest disturbance dynamics using the NAFD methodology ranging from small local application [*Nelson et al.*, 2009] , large regional initiatives [*Stueve et al.*] , to national modeling fore fire ecology support [*Vogelmann et al.*, 2011] so the interaction with scientists and NAFD data has grown rapidly.

Phase I of the NAFD project (NASA Grant NNG05GE55G) was designed to estimate national disturbance rates for the contiguous U.S. and a major goal of phase II (NASA Grant NNX08AI26G) was to reduce the error bounds on the estimates. This work, which focused on the patterns of disturbance processes, revealed how the sampling method used by the NAFD project missed catastrophic change events. Furthermore, this work suggested that any sampling scheme to estimate canopy change rates across the CONUS would have difficulty capturing the range of patterns and shifting dynamics that are evidenced in the geographic model of forest change processes created in this thesis. This new understanding was used to support the proposal of a wall to wall national Landsat study of forest dynamics in NAFD phase

III (NASA NACP proposal NNX11AJ78G S 01).

5.3. Summary of Research

This dissertation grew out of my associated work with the North American Forest Dynamics (NAFD) project which was funded to estimate the rates of forest dynamics across the contiguous U.S. in support of the North American Carbon Project. While analyzing the patterns of canopy loss across discrete noncontiguous random sample locations it became apparent that there were few comprehensive assessments of forest disturbance and conversion processes through time. Such assessments are necessary to understand how NAFD and other observations of forest canopy loss observe the result of various underlying forest change processes. To answer the question: "How has the amount of forest area affected by major disturbance and conversion processes changed through recent time across 6 US regions?", I undertook a national assessment (divided into 6 regions) of the state of knowledge on the geographic and temporal characteristics of fire, wind, insect, harvest and suburbanization processes and of how NAFD and FIA estimates of canopy change related to data on these processes. Findings from this work included:

- How the amount of forest area affected by major disturbance and conversion processes varied across regions and time in the CONUS.
- NAFD and USFS FIA estimates of forest canopy change over the last two decades have a similar spatial distribution across the six USFS regions though NAFD estimates were higher.

- A better geographic model is needed to disaggregate the relative effects of each of the overlapping forest change processes operating across the forested landscape with implications for different sampling methodologies (and their error variances) and whether aggregated estimates of forest canopy changes are representative of the multiple dynamic processes occurring within a region.

The second research question was "what are the geographic patterns of forest change processes (wind, fire, insects, harvest, and conversion to suburban urban lands) through time across the CONUS?". To answer this question I created a novel data environment, assembled data on forest change processes into a geodatabase and used it to reveal a more detailed geographic model of forest change processes. Using a time-series approach with each of the change processes datasets; I generated synoptic temporal metrics and severity/confidence measures that offer a new perspective on the total area affected by individual processes and multiple overlapping processes. This integrated knowledge framework of individual change processes and their overlap is a first step towards linking the complex patterns of forest canopy dynamics to both their underlying causal processes and their interactions with other earth systems across broad scales. Findings from this work included:

- Large ranges in the estimated area of forest land affected by fire and wind which reveal the need for better geospatial characterization on the distribution of forest lands through time.
- Six major areas of uncertainty/error for the process datasets that should be taken into account when they are used for geospatial analysis and recommendations for

future research in this area.

- A time-series approach to severity of insect infestations showed that the area of moderate to high confidence/severity events is extremely low across mapped regions, in contrast to the amount mapped in the raw ADS data.
- The geographic distribution of wind, fire, insect, and harvest processes have large local spatial variability and the physical distribution of the variability changes largely between short time periods.
- Limitations from data gaps and coarse resolution prohibit precise calculations of the amount of forest land affected by multiple processes through time.

Building on the work of the previous two chapters, I could address the question "can the causal processes responsible for observed canopy dynamics in NAFD forest history maps be verified by synthesizing multiple data sources to look for convergent 'truths' ?". Focusing within the six historic USFS regions at local scales, I examined whether the temporal trends in coarse scale data did or did not agree with NAFD aggregated trends. I then explored fine scale geospatial process data and NAFD forest history maps to 'verify' observations of forest change and their underlying causes, and to understand how the local observations affected coarser aggregated estimates. Thought the chapter concentrated on within region analysis, it is useful to draw more comprehensive findings from the chapter including:

- The use of multiple ancillary data sets for the same process was useful for qualitatively filling in data gaps.

- The ability to ‘verify’ NAFD disturbance trends varied by region because the scale and reliability of the ancillary geospatial data varied spatially.
- Temporal trends in aggregated (regional/decadal) rates did not always agree in magnitude or direction with NAFD results. Local analysis exposed multiple reasons including that the location of NAFD samples in the region may not have adequately captured the spatial distribution of one or more individual change processes, that one or more of the data sets is in error, or that the rates of multiple processes are cancelling each other out (i.e. one is increasing and the other decreasing through time).
- ‘Staccato’ peaks in NAFD disturbance rates (lasting 1-2 years) were often attributable to large localized natural disturbance events (fire and wind) while sustained increases and decreases in NAFD rates (3-5 years) were attributable to changes in human-managed disturbance regimes (harvest).
- The hypothesis that harvest events are responsible for the ‘base’ or consistent rates of change across regions cannot be tested using existing geospatial data, because of their spatial and temporal resolution and data gaps.
- The causal processes underlying some peaks, episodic trends, and base rates in the NAFD results were unexplainable with this approach and merit closer scrutiny.
- Canopy damage caused by fire, wind, and harvest events were reflected in NAFD rates for individual samples, aggregated regional and national rates suggesting that to accurately estimate CONUS canopy change rates the sampling scheme used must take into consideration the patterns of these processes.

Select results of chapter 2, 3 and 4 have been summarized into a manuscript that has been accepted by the Journal of Geophysical Research.

5.4. Future Applications

In this study, integrated analysis of multiple data sources, with local to regional scales over 20+ years, on forest change processes and forest canopy observations provided a better understanding of forest change processes and their patterns across the contiguous U.S. The data and knowledge base created expose the opportunity for future studies.

It must be acknowledged that this work only scratches the surface of local understanding of forest change processes across the CONUS. Analysis of the VCT results related to specific change processes was limited to locations of NAFD phase I and phase II sample locations. With this geographic restriction lifted, applications to quantitatively estimate forest area affected by specific processes could be conducted, such as an assessment of the hurricane related damage captured using the VCT algorithm across the entire SE. Also, using more geographically succinct areas and results from the attribution work in phase III, the synergistic relationship between multiple change types could be better analyzed. For example, such applications could include the interaction of insect damage and fire in the dry forestlands of the interior mountain region in the west, hurricane damage and fires in the South, or changes in harvest regimes related to catastrophic disturbances, changing local market dynamics or population density pressure.

This study highlighted many sources of uncertainty and error in the various data sets on forest change processes. Future applications could focus on how to quantitatively characterize the spatial and temporal uncertainty and error in the data and how they might affect downstream applications such as biomass fluxes from forest ecosystem and carbon modeling. The tools and knowledge created in this thesis will be useful for continually identifying and testing the numerous assumptions that we are forced to make about forest change processes due to the currently incomplete empirical understanding of forest dynamics.

During this thesis I have developed a solid foundation of the geospatial techniques, technical capacities, and knowledge framework of the geographic and ecological patterns of forest disturbances processes. This foundation will be applied in a USFS postdoc position under a component of the successful phase III grant tasked to use the geodatabase of forest change processes, developed in this thesis, to attribute, with an empirical model, the type of causal process to each observed canopy loss event mapped in NAFD III across the U.S. My work will focus on creating proximity neighborhoods (in space and time) based on the locations and timing of data in the geodatabase for predictor variables, using the severity of change events as a predictor variable, exploring and mapping sources of uncertainty and how they affect the empirical models, and how to capture rare, episodic and consistent processes in the empirical model. At the minimum, this work will help address the current lack of spatially and temporally explicit information of forest harvest regimes across the

CONUS.

Appendix

A. The specific USFS inventory used for each state in harvest analysis of stand ages.

Inventory ALABAMA 2001-2010: CURRENT AREA, CURRENT VOLUME

Inventory Arizona, cycle 3, 2001-2009: area/vol/gro/mort

Inventory ARKANSAS 2000-2009: CURRENT AREA, CURRENT VOLUME

Inventory California 2001-2009 Sampled plots annual P2 inventory

Inventory CONNECTICUT 2006-2010: CURRENT AREA, CURRENT VOLUME

Inventory DELAWARE 2006-2010: CURRENT AREA, CURRENT VOLUME

Inventory FLORIDA 2002-2010: CURRENT AREA, CURRENT VOLUME

Inventory GEORGIA 2005-2010: CURRENT AREA, CURRENT VOLUME

Inventory Idaho, cycle 2, 2004-2009: area/vol/gro/mort

Inventory ILLINOIS 2006-2010: CURRENT AREA, CURRENT VOLUME

Inventory INDIANA 2006-2010: CURRENT AREA, CURRENT VOLUME

Inventory IOWA 2006-2010: CURRENT AREA, CURRENT VOLUME

Inventory Kansas 2005-2009: area/volume

Inventory KENTUCKY 2005-2010:CURRENTAREA,CURRENTVOLUME

Inventory LOUISIANA 2001-2009:CURRENTAREA,CURRENTVOLUME

Inventory MAINE 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory Maryland 2005-2009:area/volume

Inventory MASSACHUSETTS 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory MICHIGAN 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory MINNESOTA 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory MISSISSIPPI 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory MISSOURI 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory Montana,cycle2,2003-2009:area/vol/gro/mort

Inventory NEBRASKA 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory Nevada,cycle2,2004-2005:area/vol/gro/mort

Inventory NEWHAMPSHIRE 2005-2010:CURRENTAREA,CURRENTVOLUME

Inventory NewJersey 2005-2009:area/volume

Inventory NewMexico:1999area

Inventory NewYork 2005-2009:area/volume

Inventory NORTHCAROLINA 2003-2010:CURRENTAREA,CURRENTVOLUME

Inventory NORTHDAKOTA 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory Ohio 2005-2009: area/volume

Inventory OKLAHOMA 2008-2010:CURRENTAREA,CURRENTVOLUME

Inventory Oregon 2001-2009 Sampled plots annual P2

Inventory PENNSYLVANIA 2006:2010: CURRENT AREA, CURRENT VOLUME

Inventory RHODEISLAND 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory SOUTHCAROLINA 2002-2010:CURRENTAREA,CURRENTVOLUME

Inventory SOUTHDAKOTA 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory TENNESSEE 2005-2010:CURRENTAREA,CURRENTVOLUME

Inventory TEXAS_EAST 2004-2010:CURRENTAREA,CURRENTVOLUME

Inventory Utah,cycle2,2000-2009:area/vol/gro/mort

Inventory VERMONT 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory VIRGINIA 2002-2010:CURRENTAREA,CURRENTVOLUME

Inventory Washington 2002-2009SampledplotsannualP2inventory

Inventory WestVirginia 2005-2009:area/volume

Inventory WISCONSIN 2006-2010:CURRENTAREA,CURRENTVOLUME

Inventory Wyoming:2000area

B. The dates, projections, and resolution of the Landsat Surface Reflectance images used to produce NAFD products

Site Name	Image Date(s)	Image Projection	Phase	Spatial Resolution
p12r27	8/22/2007 7/12/2004 9/12/2003 5/25/2001 8/26/2000 8/24/1999 8/21/1995 6/15/1994 6/7/1991 9/8/1990 8/1/1988 7/27/1986 8/9/1985	WGS84, UTM, Zone 19N	Phase I	28.5 m
p12r31	9/20/2006 8/29/2004 6/24/2003 9/6/2001 9/27/2000 6/10/1998 7/6/1996 8/21/1995 8/15/1993 6/7/1991 7/27/1989 9/16/1987	WGS84, UTM, Zone 19N	Phase I	28.5 m

	8/9/1985			
p14r32	7/16/2006 7/26/2004 9/7/2002 7/2/2001 9/23/1999 6/21/1997 8/19/1995 8/29/1993 6/21/1991 6/28/1988 6/10/1987 8/23/1985	WGS84, UTM, Zone 18N	Phase I	28.5 m
p15r33	9/19/2004 9/6/2002 7/6/2000 8/2/1998 7/11/1996 8/23/1994 9/16/1991 8/12/1990 8/22/1988 5/16/1987 5/29/1986 8/27/1984	WGS84, UTM, Zone 18N	Phase I	28.5 m
p15r34	8/21/2005 8/5/2002 10/10/2000 5/14/1998 10/15/1996 8/23/1994 10/20/1992 10/15/1990 9/23/1988	WGS84, UTM, Zone 18N	Phase I	28.5 m

	10/20/1986 8/27/1984			
p16r36	7/27/2005 9/24/2003 5/24/2002 8/14/2000 9/26/1998 7/2/1996 9/15/1994 9/28/1993 5/2/1991 10/6/1990 9/14/1988 9/25/1986 7/1/1984	WGS84, UTM, Zone 17N	Phase I	28.5 m
p16r37	10/15/2005 7/19/2002 10/9/2000 10/23/1999 10/12/1998 10/22/1996 9/15/1994 10/27/1992 10/6/1990 10/3/1989 9/14/1988 9/25/1986 9/3/1984	WGS84, UTM, Zone 17N	Phase I	28.5 m
p17r31	8/6/2006 7/2/2005 8/16/2004 8/3/2002 9/6/2000 9/12/1999	WGS84, UTM, Zone 17N	Phase I	28.5 m

	7/12/1997 8/26/1996 6/21/1995 10/8/1994 5/30/1993 6/28/1992 7/25/1990 7/3/1988 7/17/1987 8/31/1986 6/22/1984			
p18r35	8/7/2004 6/2/2003 6/9/2000 9/11/1999 9/5/1997 9/13/1994 7/21/1992 6/11/1989 8/27/1988 6/6/1987 9/20/1985 9/1/1984	WGS84, UTM, Zone 17N	Phase I	28.5 m
p19r39	4/27/2005 4/22/2003 7/16/2002 10/14/2000 6/27/1998 5/20/1996 10/9/1995 7/31/1993 6/8/1991 4/18/1990 6/15/1988 4/26/1987 4/23/1986	WGS84, UTM, Zone 16N	Phase I	28.5 m

	6/4/1984			
p21r37	10/18/2005 6/23/2003 9/29/2001 9/16/1999 8/25/1997 6/17/1995 10/1/1993 9/26/1991 9/7/1990 6/13/1988 6/27/1987 9/6/1984	WGS84, UTM, Zone 16N	Phase I	28.5 m
p21r39	10/15/2004 10/18/2002 10/15/2001 8/15/1999 8/25/1997 10/7/1995 10/1/1993 9/26/1991 10/22/1989 6/27/1987 6/24/1986 9/6/1984	WGS84, UTM, Zone 16N	Phase I	28.5 m
p22r28	8/6/2005 7/16/2003 8/3/2001 9/7/1999 7/18/1998 8/13/1996 6/8/1995 8/21/1993 7/12/1990	WGS84, UTM, Zone 16N	Phase I	28.5 m

	8/7/1988 8/18/1986 7/11/1984			
p25r29	7/10/2005 8/22/2003 8/8/2001 8/29/2000 10/6/1999 8/5/1997 9/19/1996 8/29/1994 9/8/1992 9/16/1989 9/13/1988 7/22/1986 9/18/1984	WGS84, UTM, Zone 15N	Phase I	28.5 m
p26r36	8/31/2004 9/11/2002 9/29/2000 8/18/1999 9/29/1997 9/10/1996 7/19/1994 7/13/1992 7/8/1990 6/19/1989 8/1/1987 7/29/1986	WGS84, UTM, Zone 15N	Phase I	28.5 m
p27r27	9/13/2006 8/6/2004 9/5/2003 7/5/2001 7/24/1999 8/6/1998	WGS84, UTM, Zone 15N	Phase I	28.5 m

	9/4/1997 8/14/1995 8/24/1993 8/19/1991 7/31/1990 9/14/1989 8/21/1986 6/28/1984			
p27r38	9/13/2006 9/7/2004 8/1/2002 7/21/2001 7/24/1999 7/18/1997 9/28/1994 7/23/1993 8/3/1991 10/19/1990 9/11/1988 9/25/1987 8/18/1985	WGS84, UTM, Zone 14N	Phase I	28.5 m
p34r37	9/30/2006 5/22/2005 9/8/2004 7/4/2003 6/23/2002 6/12/2001 5/8/2000 6/7/1999 6/20/1998 6/1/1997 5/29/1996 5/27/1995 6/25/1994 6/22/1993 7/5/1992	WGS84, UTM, Zone 13N	Phase I	28.5 m

	5/16/1991 5/13/1990 6/11/1989 6/8/1988 6/22/1987 5/18/1986 6/16/1985 6/13/1984			
p35r32	9/5/2006 9/15/2004 9/2/2002 9/12/2000 8/30/1998 7/7/1996 6/16/1994 9/30/1992 8/11/1991 7/4/1989 9/3/1988 7/28/1986 7/6/1984	WGS84, UTM, Zone 13N	Phase I	28.5 m
p35r34	9/8/2007 6/14/2005 6/25/2003 8/17/2002 6/11/2001 9/12/2000 9/26/1999 6/24/1997 6/5/1996 6/16/1994 6/18/1992 6/21/1990 7/4/1989 9/19/1988 7/28/1986	WGS84, UTM, Zone 12N	Phase I	28.5 m

	7/6/1984			
p36r37	9/28/2006 9/6/2004 8/24/2002 6/15/2000 6/18/1998 8/31/1996 6/23/1994 8/4/1992 7/1/1991 9/13/1989 9/26/1988 8/20/1986 6/14/1985	WGS84, UTM, Zone 12N	Phase I	28.5 m
p37r32	9/3/2006 8/28/2004 8/15/2002 6/6/2000 8/28/1998 7/21/1996 8/17/1994 9/15/1993 9/26/1991 7/2/1989 8/30/1987 8/8/1985	WGS84, UTM, Zone 12N	Phase I	28.5 m
p37r34	9/19/2006 8/28/2004 8/15/2002 6/6/2000 9/8/1999 6/22/1997 9/21/1995 6/27/1993	WGS84, UTM, Zone 12N	Phase I	28.5 m

	6/22/1991 8/27/1989 9/15/1987 8/24/1985			
p37r35	9/3/2006 8/31/2005 7/9/2003 6/12/2002 6/14/2000 6/25/1998 6/22/1997 6/14/1994 6/27/1993 6/22/1991 6/19/1990 7/2/1989 7/26/1986 6/21/1985	WGS84, UTM, Zone 12N	Phase I	28.5 m
p41r29	8/8/2004 7/10/2002 10/8/2000 7/26/1999 7/4/1997 7/31/1995 8/10/1993 10/8/1991 7/14/1989 9/11/1987 7/16/1984	WGS84, UTM, Zone 11N	Phase I	28.5 m
p41r32	8/17/2007 7/13/2006 7/26/2005 6/21/2004 6/3/2003	WGS84, UTM, Zone 11N	Phase I	28.5 m

	6/16/2002 6/21/2001 6/2/2000 7/2/1999 8/8/1998 7/4/1997 9/3/1996 7/15/1995 6/26/1994 8/26/1993 6/20/1992 8/21/1991 9/3/1990 6/28/1989 6/9/1988 6/23/1987 6/20/1986 7/3/1985			
p43r33	7/24/2005 8/6/2004 8/20/2003 7/16/2002 7/21/2001 7/18/2000 7/24/1999 8/3/1997 9/1/1996 8/14/1995 8/8/1993 8/5/1992 7/28/1989 7/9/1988 7/23/1987 8/5/1986 7/17/1985 6/28/1984	WGS84, UTM, Zone 10N	Phase I	28.5 m

p45r29	8/26/2006 8/20/2004 8/31/2002 9/18/2000 8/4/1998 7/13/1996 8/25/1994 8/3/1992 8/14/1990 7/23/1988 8/19/1986 8/13/1984	WGS84, UTM, Zone 10N	Phase I	28.5 m
p47r28	7/20/2005 9/1/2003 7/1/2001 10/16/1999 8/2/1998 8/12/1996 6/23/1995 9/21/1993 9/16/1991 9/10/1989 7/21/1988 8/1/1986 7/13/1985	WGS84, UTM, Zone 10N	Phase I	28.5 m
p14r31	8/4/2007 7/16/2006 6/24/2004 6/19/2002 8/16/2000 7/26/1998 7/23/1997 8/19/1995 6/26/1993 7/4/1990 7/30/1988	WGS84, UTM, Zone 18N	Phase II	30 m

	8/26/1986 8/20/1984			
p15r31	7/15/2009 7/10/2007 6/21/2006 9/6/2005 7/15/2003 7/9/2001 7/28/1999 6/28/1997 7/11/1996 8/23/1994 6/14/1992 7/27/1990 8/22/1988 6/25/1987 7/29/1985 8/27/1984	WGS84, UTM, Zone 18N	Phase II	30 m
p16r35	7/3/2008 8/18/2007 7/27/2005 9/10/2004 8/20/2002 8/14/2000 7/24/1998 8/19/1996 9/15/1994 7/10/1993 7/21/1991 8/3/1990 9/14/1988 6/21/1986 7/1/1984	WGS84, UTM, Zone 17N	Phase II	30 m
p16r41	7/19/2008	WGS84,	Phase	30 m

	7/17/2007 6/28/2006 7/8/2004 8/20/2002 8/25/2001 8/30/2000 6/22/1998 7/2/1996 8/30/1994 7/10/1993 8/6/1991 6/16/1990 8/16/1989 7/10/1987 8/24/1986 8/18/1984	UTM, Zone 17N	II	
p19r36	7/24/2008 7/3/2006 7/13/2004 8/1/2002 7/2/2000 6/27/1998 7/10/1997 7/5/1995 7/31/1993 7/12/1992 7/7/1990 8/18/1988 6/26/1986 9/8/1984	WGS84, UTM, Zone 16N	Phase II	30 m
p20r33	8/24/2005 9/6/2004 7/31/2002 6/26/2001 7/7/1999 7/17/1997	WGS84, UTM, Zone 16N	Phase II	30 m

	7/12/1995 8/23/1993 8/2/1991 6/28/1990 8/25/1988 8/4/1986 7/13/1984			
p21r30	7/20/2007 7/30/2005 6/23/2003 8/4/2001 7/30/1999 7/11/1998 7/5/1996 7/3/1995 8/14/1993 8/25/1991 6/19/1990 7/29/1987 7/23/1985 8/21/1984	WGS84, UTM, Zone 16N	Phase II	30 m
p23r28	8/3/2007 7/15/2006 7/25/2004 7/23/2003 7/20/2002 7/12/1999 8/10/1998 7/3/1996 8/15/1994 7/24/1992 8/20/1990 9/2/1989 7/29/1988 8/9/1986 6/3/1985	WGS84, UTM, Zone 16N	Phase II	30 m

p23r35	8/5/2008 8/3/2007 7/31/2006 8/10/2004 6/21/2003 8/2/2001 8/29/1999 8/23/1997 8/18/1995 7/27/1993 8/23/1991 7/3/1990 8/30/1988 7/24/1986 7/18/1984	WGS84, UTM, Zone 15N	Phase II	30 m
p24r37	8/28/2008 8/10/2007 9/5/2005 8/17/2004 9/16/2003 8/9/2001 8/6/2000 8/12/1999 8/30/1997 7/8/1995 7/5/1994 8/16/1992 8/27/1990 8/5/1988 7/31/1986 6/23/1984	WGS84, UTM, Zone 15N	Phase II	30 m
p26r34	8/8/2007 8/5/2006 8/15/2004	WGS84, UTM, Zone 15N	Phase II	30 m

	7/9/2002 8/12/2000 7/25/1999 8/28/1997 8/23/1995 7/16/1993 7/13/1992 7/8/1990 8/3/1988 7/29/1986 7/23/1984			
p26r37	7/7/2007 8/18/2005 7/28/2003 7/30/2001 8/28/2000 8/26/1999 8/28/1997 9/10/1996 7/19/1994 8/17/1993 6/25/1991 7/8/1990 7/18/1988 7/29/1986 6/21/1984	WGS84, UTM, Zone 15N	Phase II	30 m
p27r27	8/15/2007 7/11/2006 7/21/2004 9/5/2003 7/5/2001 7/24/1999 8/6/1998 7/31/1996 7/29/1995 8/24/1993	WGS84, UTM, Zone 15N	Phase II	30 m

	9/6/1992 7/31/1990 9/14/1989 8/8/1987 8/21/1986 6/28/1984			
p33r30	7/24/2007 7/2/2005 9/1/2004 7/10/2002 7/12/2000 8/19/1999 9/1/1998 8/10/1996 8/21/1994 8/15/1992 7/28/1991 8/23/1989 7/3/1988 8/15/1986 8/9/1984	WGS84, UTM, Zone 13N	Phase II	30 m
p34r34	7/15/2007 7/12/2006 7/6/2004 8/10/2002 7/19/2000 7/1/1999 7/3/1997 8/15/1995 6/25/1994 7/5/1992 7/3/1991 7/5/1989 6/22/1987 8/6/1986 8/19/1985	WGS84, UTM, Zone 13N	Phase II	30 m

p40r37	9/16/2009 7/27/2008 7/6/2006 9/2/2004 8/28/2002 8/22/2000 8/1/1998 8/27/1996 7/21/1994 8/16/1992 8/27/1990 7/20/1988 7/31/1986 6/23/1984	WGS84, UTM, Zone 11N	Phase II	30 m
p42r28	7/25/2008 7/20/2006 7/30/2004 7/9/2002 7/27/2000 8/15/1998 8/9/1996 7/19/1994 8/1/1993 7/27/1991 7/8/1990 8/6/1989 8/1/1987 6/24/1985	WGS84, UTM, Zone 11N	Phase II	30 m
p42r29	8/24/2007 7/20/2006 7/30/2004 8/2/2002 8/28/2000 8/31/1998	WGS84, UTM, Zone 11N	Phase II	30 m

	8/9/1996 7/19/1994 7/29/1992 7/8/1990 8/19/1988 7/13/1986 7/7/1984			
p42r35	8/10/2008 8/5/2006 8/31/2004 8/18/2002 8/12/2000 7/14/1998 9/10/1996 8/4/1994 7/29/1992 8/25/1990 8/19/1988 7/29/1986 7/7/1984	WGS84, UTM, Zone 11N	Phase II	30 m
p44r26	7/7/2008 8/19/2006 7/28/2004 7/15/2002 8/2/2000 9/9/1999 8/10/1997 8/21/1995 9/16/1993 7/1/1991 7/27/1989 7/14/1987 8/25/1985 9/7/1984	WGS84, UTM, Zone 11N	Phase II	30 m

p44r29	7/5/2007 7/18/2006 7/28/2004 9/9/2002 7/25/2000 8/13/1998 7/22/1996 8/18/1994 8/28/1992 9/8/1990 7/16/1988 8/12/1986 7/5/1984	WGS84, UTM, Zone 11N	Phase II	30 m
p45r30	8/15/2008 7/25/2006 8/23/2005 8/18/2003 8/20/2001 8/17/2000 8/4/1998 7/13/1996 6/25/1995 7/5/1993 8/1/1991 8/11/1989 7/7/1988 8/19/1986 8/13/1984	WGS84, UTM, Zone 10N	Phase II	30 m
p46r30	7/3/2007 8/17/2006 7/26/2004 7/21/2002 7/23/2000 8/27/1998 8/8/1997 8/3/1995	WGS84, UTM, Zone 10N	Phase II	30 m

	8/29/1993 8/10/1992 8/8/1991 9/3/1989 7/30/1988 8/10/1986 8/4/1984			
p46r31	7/3/2007 7/13/2005 8/27/2004 7/5/2002 8/16/2000 7/26/1998 7/20/1996 8/16/1994 7/9/1992 8/8/1991 9/3/1989 8/31/1988 9/11/1986 8/4/1984	WGS84, UTM, Zone 10N	Phase II	30 m
p46r32	9/5/2007 8/17/2006 8/27/2004 8/6/2002 9/9/2000 8/27/1998 7/20/1996 8/16/1994 7/9/1992 8/8/1991 9/3/1989 7/28/1987 6/20/1985	WGS84, UTM, Zone 10N	Phase II	30 m

p47r27	7/10/2007 8/5/2005 9/1/2003 8/13/2002 7/30/2000 9/3/1998 8/12/1996 7/22/1994 8/4/1993 8/15/1991 7/11/1990 7/21/1988 8/1/1986 7/13/1985	WGS84, UTM, Zone 10N	Phase II	30 m
p48r27	9/19/2007 7/27/2005 8/9/2004 8/12/2002 9/10/2001 8/22/2000 9/21/1999 9/2/1995 9/9/1992 7/5/1991 9/20/1990 8/27/1987 8/8/1986 7/4/1985	WGS84, UTM, Zone 10N	Phase II	30 m

C. Characteristics of conversion and disturbance regimes

Process	type	temporal	spatial	severity

		duration	seasonality (most characteristic)	rate (on a daily basis)	predictability	extent	configuration	predictability	level	affected by
Fire										
	Crown-fire	minutes-days	dry season	fast	moderate	varies	varies	moderate	high	vegetation structure, fuel availability
	mixed fire	days	vary	slow-fast	moderate	varies	varies	moderate	mixed	topology, vegetation structure, fuel availability
	ground-fire	days	dry season	slow	moderate	varies	varies	moderate	low	topology, vegetation structure, fuel availability
Wind										
	Hurricane	hours-days	june-nov (heaviest in sept.)	fast	low	warm coasts	damage worse on easterly side of storm	low	low-high	climatic variables, distance from coast
	Tornado	minutes	march-august	fast	low	inland	compact; west to east damage tracks	low	low-high	vegetation structure
	Derechos	minutes	all-year (heaviest in May-July)	fast	low	great plains and eastern US	highly localized	low	low-high	vegetation structure
	Blowdowns	minutes	x	fast	low	inland	highly localized	low	low-high	vegetation structure
Flood		days-weeks	wet season	fast	low	x	compact	high	low-high	nearness to coast, river, wetlands
Pollution		years	no	slow	low	x	x	moderate	low-high	
Drought		years	no	slow	moderate	x	highly localized	moderate	low-high	climatic variables
Disease		days to years	x	slow to fast	moderate	vector-host specific	non-contiguous	moderate	low-high	climatic variables
Insects										
	boring	days to years	specific to life cycle of insect	slow to fast	moderate	vector-host specific	non-contiguous	moderate	med-high	vegetation type and configuration, climatic variables
	defoliator	weeks to years	specific to life cycle of insect	slow to fast	moderate	vector -host specific	non-contiguous	moderate	low-high	vegetation type and configuration, climatic variables
Harvest										

	salvage	days	no snow	fast	low	not on reserve land or near large population centers, close to roads	non-contiguous	low	low-med	accessibility, vegetation type and configuration
	Partial	days	no snow	fast	low	not on reserve land or near large population centers, close to roads	compact regular forms	low	low - med	topology, local policy, distance to mills
	Clear-cut	days	no snow	fast	low	not on reserve land or near large population centers, close to roads	compact regular forms	low	high	topology, local policy, distance to mills, ownership
	treatments	days	no snow	fast	low	not on reserve land or near large population centers, close to roads	x	x	low-med	topology, local policy, distance to mills
Conversion										
	mining	years	warm months	fast	low	close to roads	non-contiguous	moderate	high	land ownership, local policy
	housing/developed	years	warm months	fast	low	close to roads	compact irregular forms	moderate	high	topology, land ownership, local policy
	reservoir	years	warm months	fast	low	close to population center	compact, irregular forms	moderate	high	land ownership, local policy
	ag/pastureland	years	?	fast	low	?		moderate	high	land ownership, local policy

D. Logic used to rank the severity confidence metric of different Forest Health Program regions

R1, R2, R3, R4,R5		TPA			severity		pattern			
		Low = 1/4 - 4 trees/acre	Medium = 5-15 trees/acre	High = 16-30 trees/acre	low	high	host species relatively contiguous, damage >50%	host species relatively contiguous, damage >50%	host species relatively contiguous, damage >50%	host species relatively contiguous, damage >50%
damage type	damage	Low	Low	Moderate	Low	L	X	X	X	X
	defoliation	X	X	X	Low	Mod	mod	low	mod	low
	mortality	Low	Mod	High	Low	high	X	X	X	X

R9		TPA			severity		pattern			
		Low = 1/4 - 4 trees/acre	Medium = 5-15 trees/acre	High = 16-30 trees/acre	low	high	host species relatively contiguous, damage >50%	host species relatively contiguous, damage >50%	host species relatively contiguous, damage >50%	host species relatively contiguous, damage >50%
damage type	damage	x	x	x	Low	L	low	low	low	low
	defoliation	x	x	x	Low	Mod	mod	low	mod	low
	mortality	Low	Low	Moderate	low	high	high	mod	high	mod

The trees per acre thresholds used here are from the piñon juniper pine special surveys conducted by the USFS in California.

E. The specific USFS inventory used for the area of forest land per county pre 1997.

Inventory -- Arkansas: 1995 area

Inventory -- Florida: 1995 area

Inventory -- Maine, 1995: area (periodic)

Inventory -- North Dakota, 1995: area (periodic)

Inventory -- South Dakota, 1995: area (periodic)

Inventory -- Alabama: 1990 area

Inventory -- Idaho: 1991 area

Inventory -- Kansas, 1994: area (periodic)

Inventory -- Louisiana: 1991 area

Inventory -- Michigan, 1993: area (periodic)

Inventory -- Minnesota, 1990: area (periodic)

Inventory -- Mississippi: 1994 area

Inventory -- Nebraska, 1994: area (periodic)

Inventory -- New York, 1993: area (periodic)

Inventory -- North Carolina: 1990 area

Inventory -- North Carolina: 1990 area

Inventory -- Ohio, 1991: area (periodic)

Inventory -- Oklahoma: 1993 area

Inventory -- Oregon: 1992 area

Inventory -- South Carolina: 1993 area

Inventory -- Texas: 1992 area

Inventory -- Utah: 1993 area

Inventory -- Virginia: 1992 area

Inventory -- Washington: 1991 area

Inventory -- Wisconsin, 1996: area (periodic)

Inventory -- Arizona: 1985 area

Inventory -- California: 1994 area

Inventory -- Colorado: 1984 area

Inventory -- Connecticut, 1985: area (periodic)

Inventory -- Delaware, 1986: area (periodic)

Inventory -- Georgia: 1989 area

Inventory -- Illinois, 1985: area (periodic)

Inventory -- Indiana, 1986: area (periodic)

Inventory -- Kentucky: 1988 area

Inventory -- Maryland, 1986: area (periodic)

Inventory -- Massachusetts, 1985: area (periodic)

Inventory -- Missouri, 1989: area (periodic)

Inventory -- Montana: 1989 area

Inventory -- Nevada: 1989 area

Inventory -- New Hampshire, 1983: area (periodic)

Inventory -- New Jersey, 1987: area (periodic)

Inventory -- New Mexico: 1987 area

Inventory -- Pennsylvania, 1989: area (periodic)

Inventory -- Rhode Island, 1985: area (periodic)

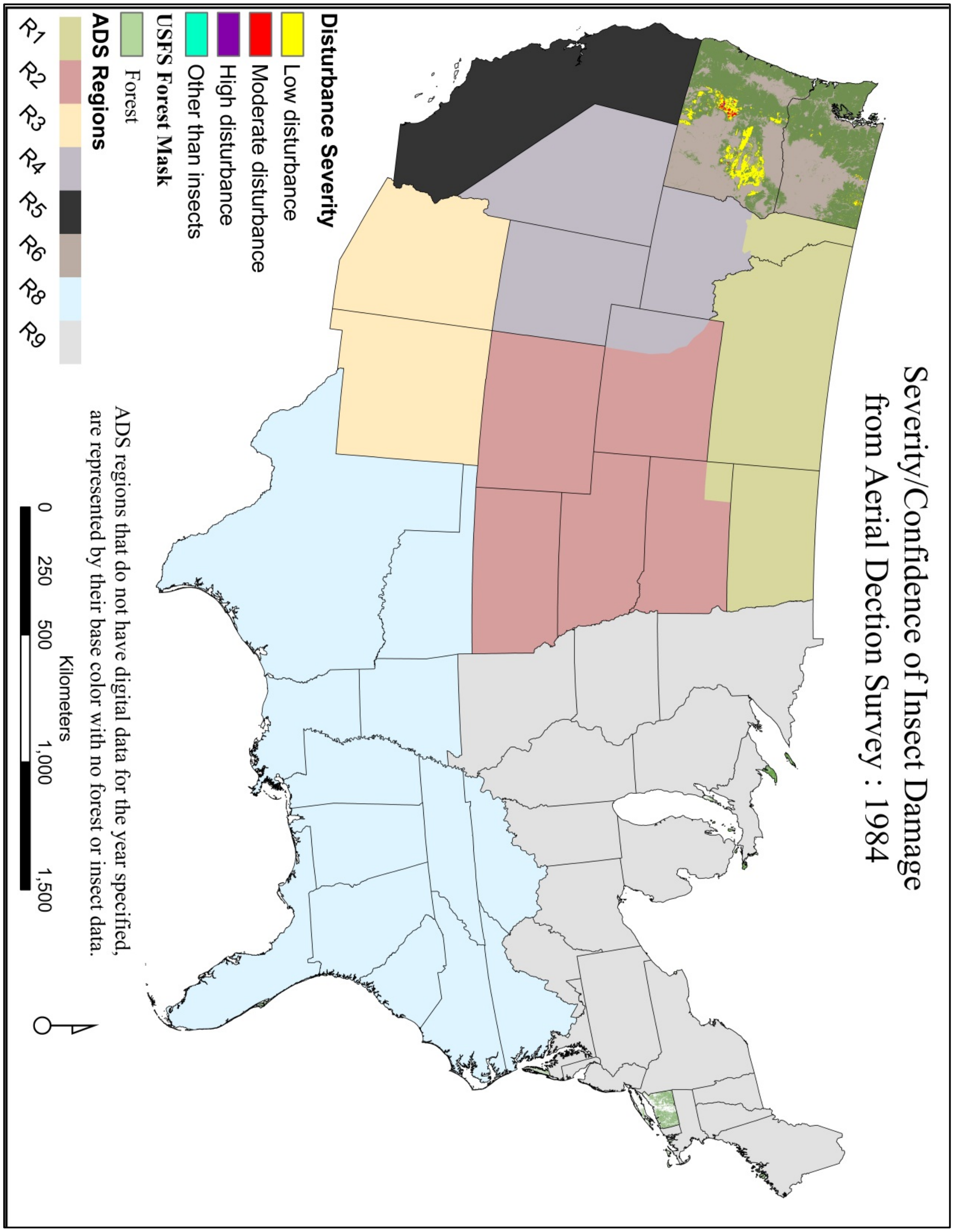
Inventory -- Tennessee: 1989 area

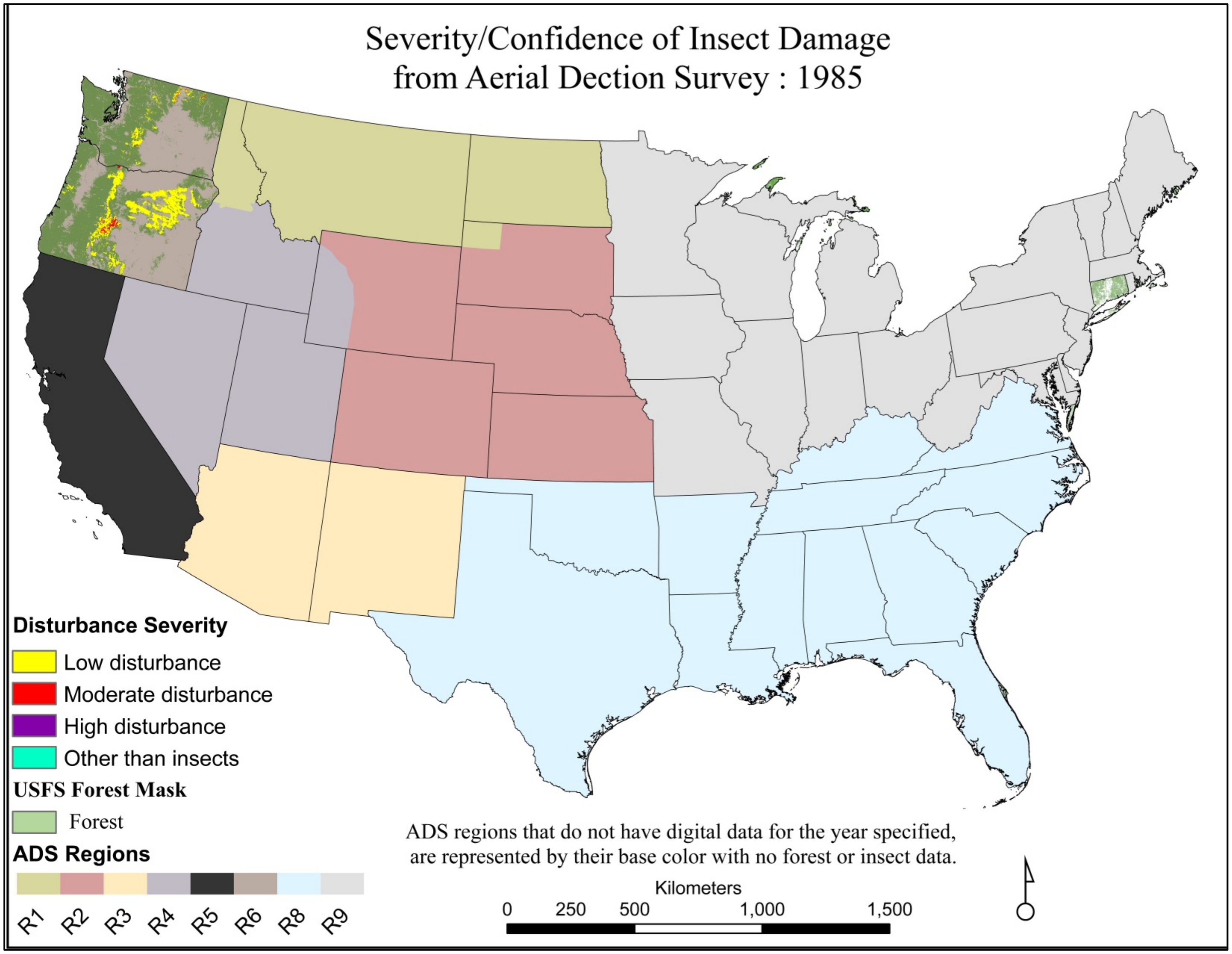
Inventory -- Vermont, 1983: area (periodic)

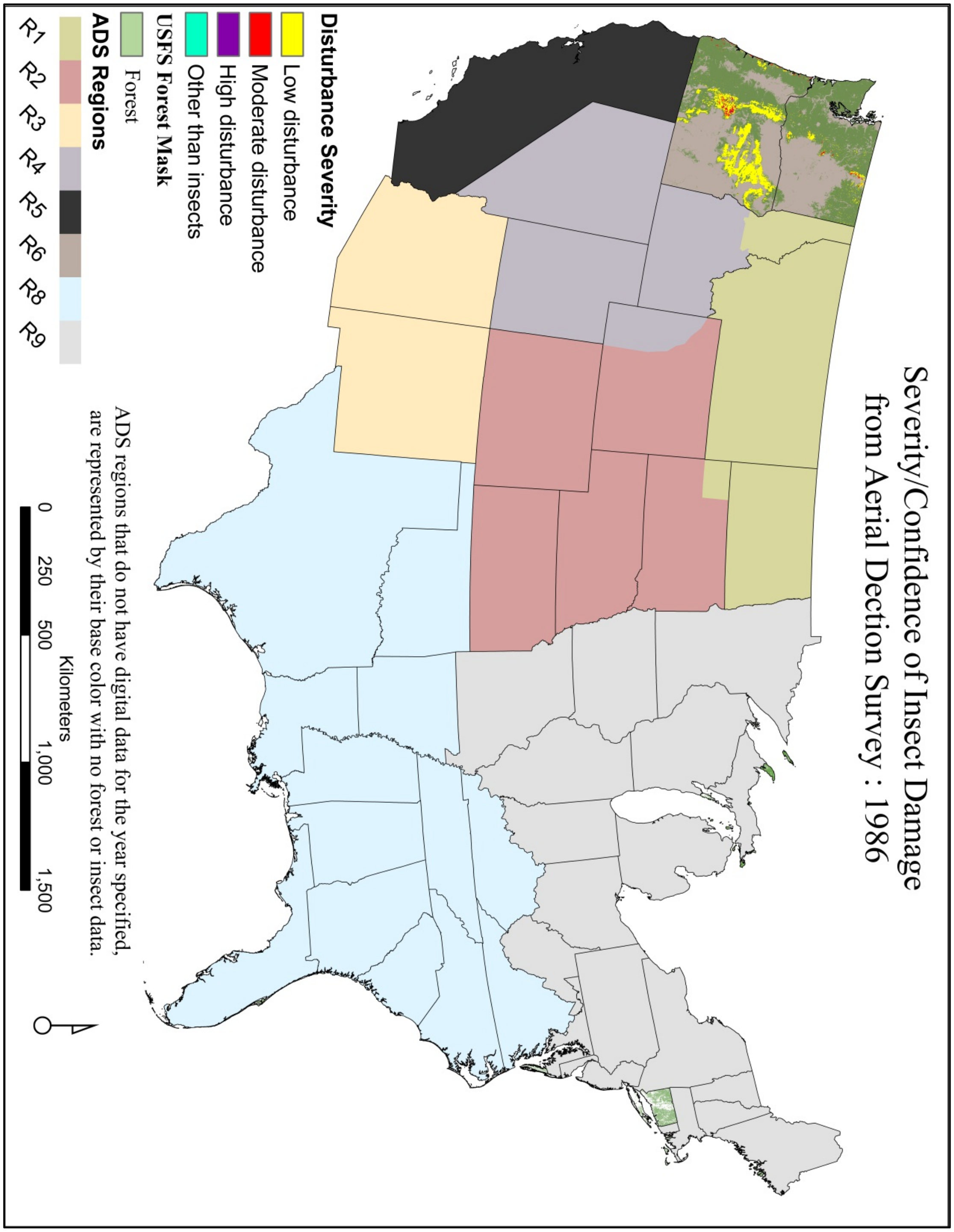
Inventory -- West Virginia, 1989: area (periodic)

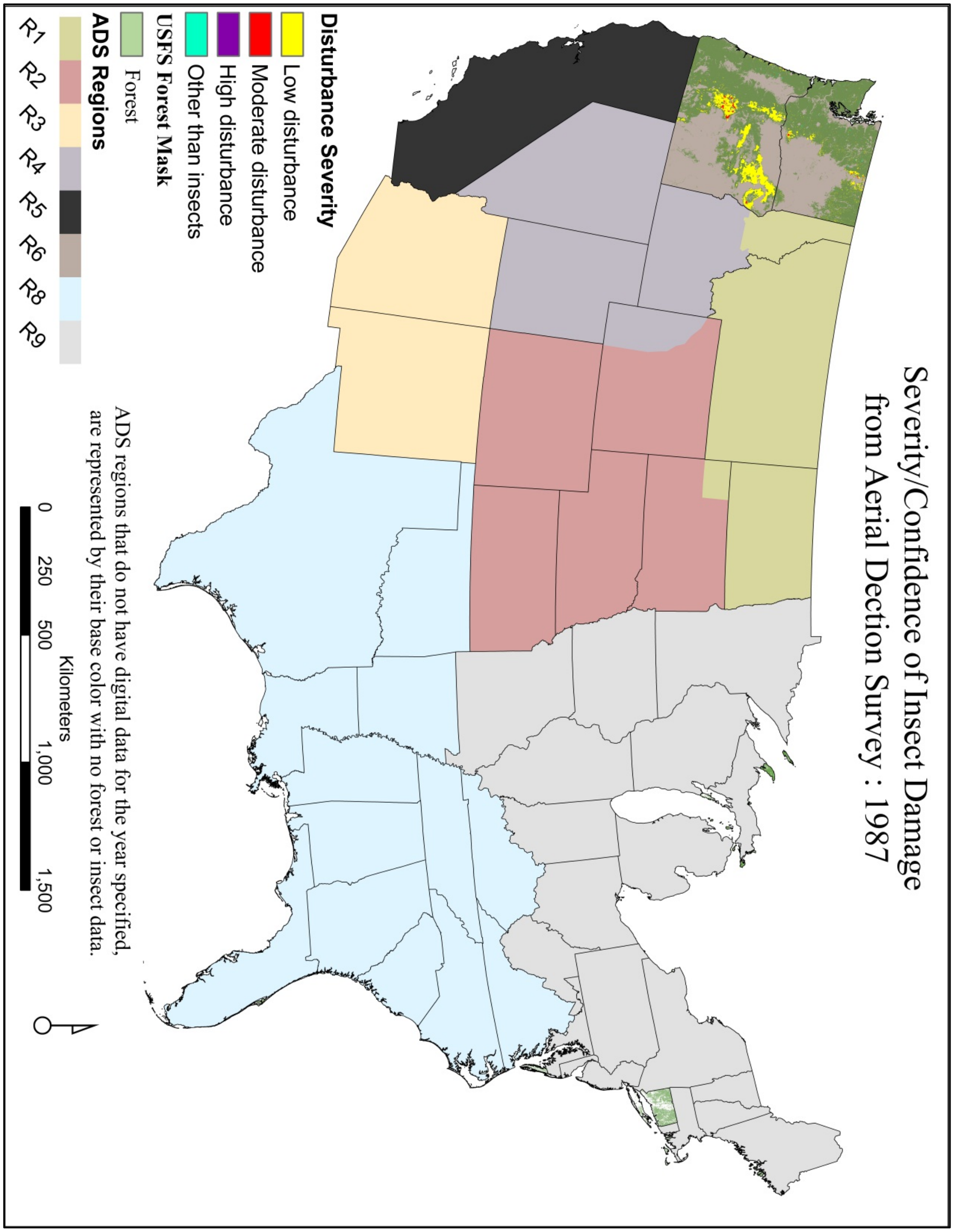
Inventory -- Wyoming: 1984 area

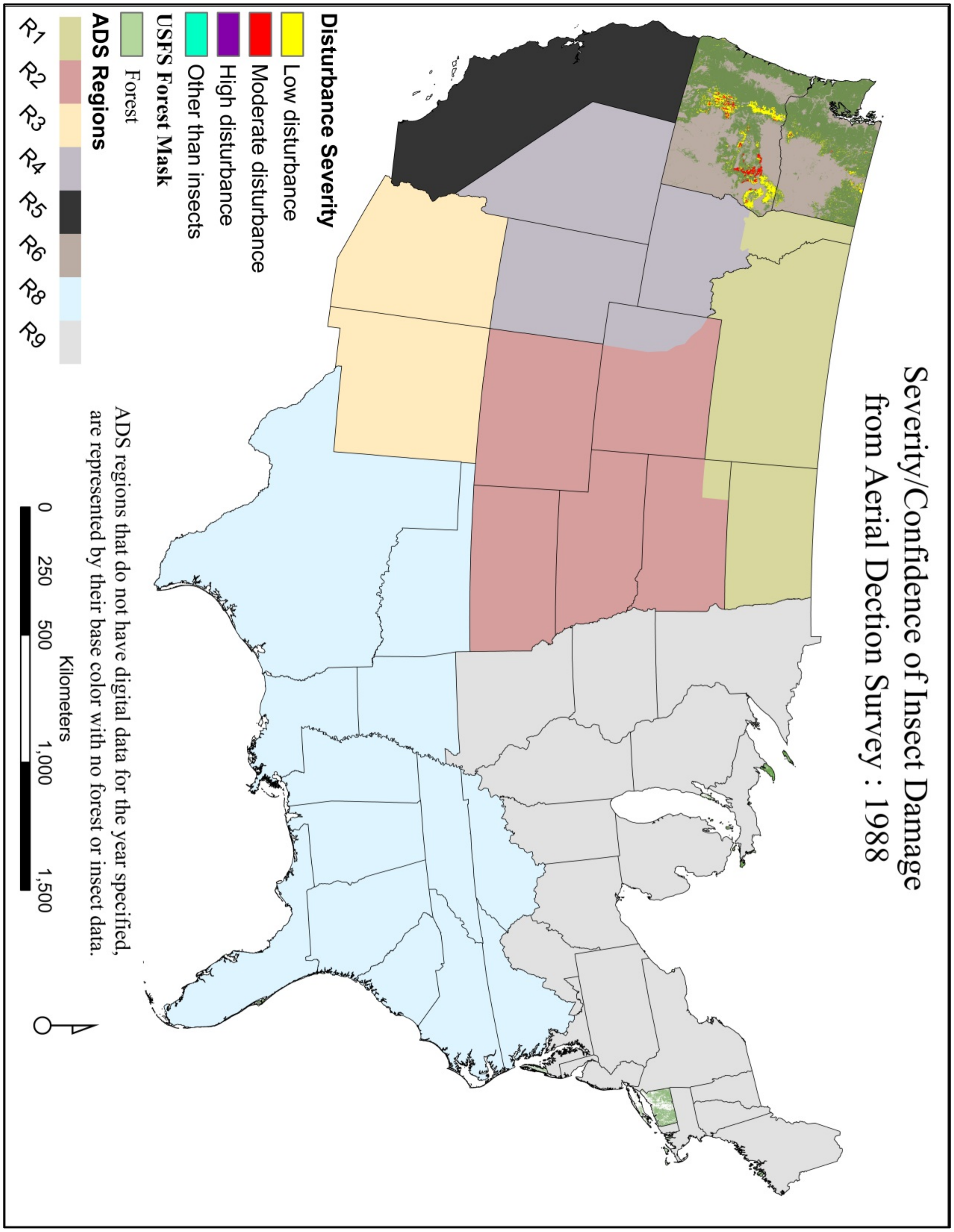
F. Maps of Insect Severity/Confidence Disturbance for Individual Years

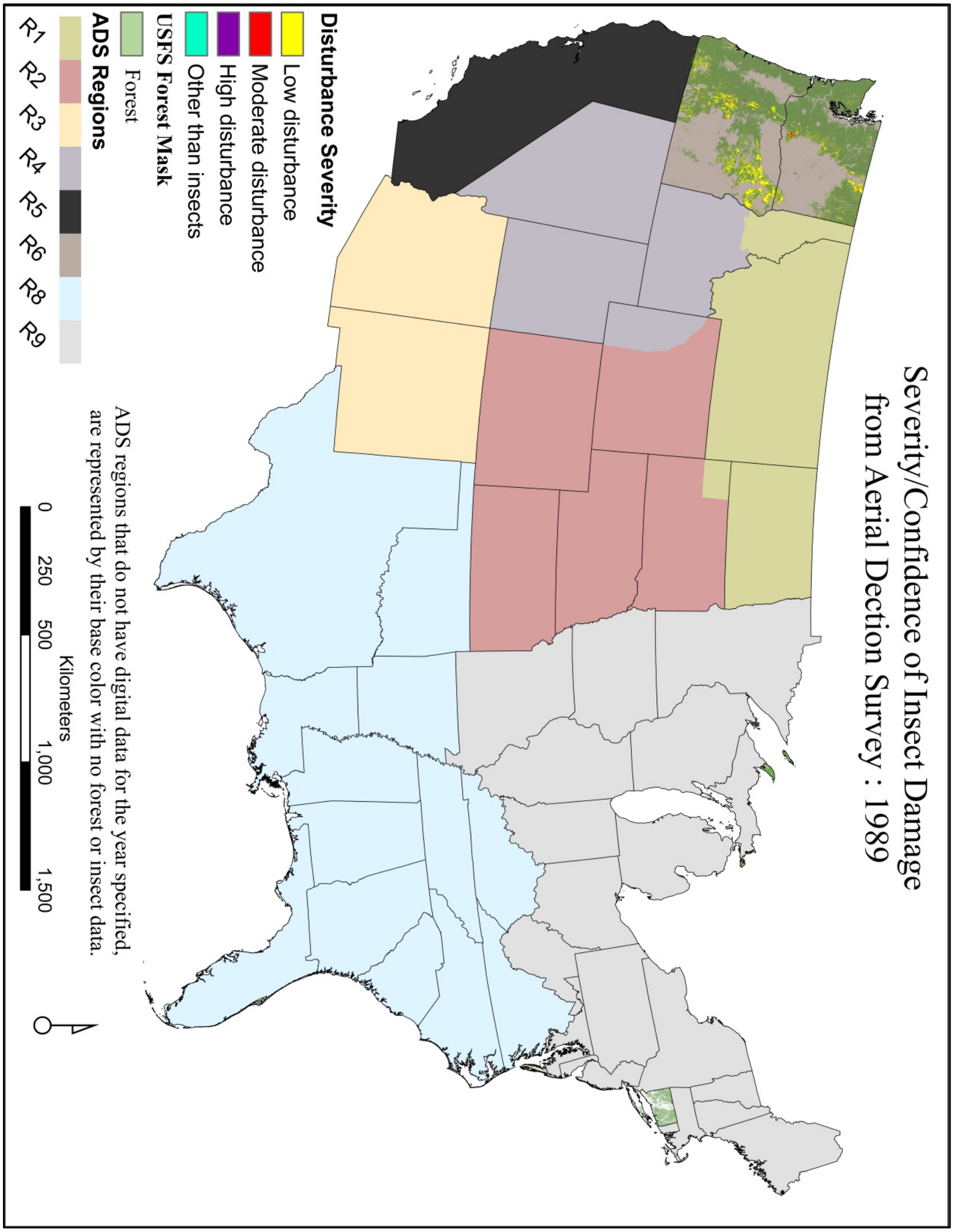

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1984
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
USFS Forest Mask
Forest
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
0
250
500
1,000
1,500
Kilometers

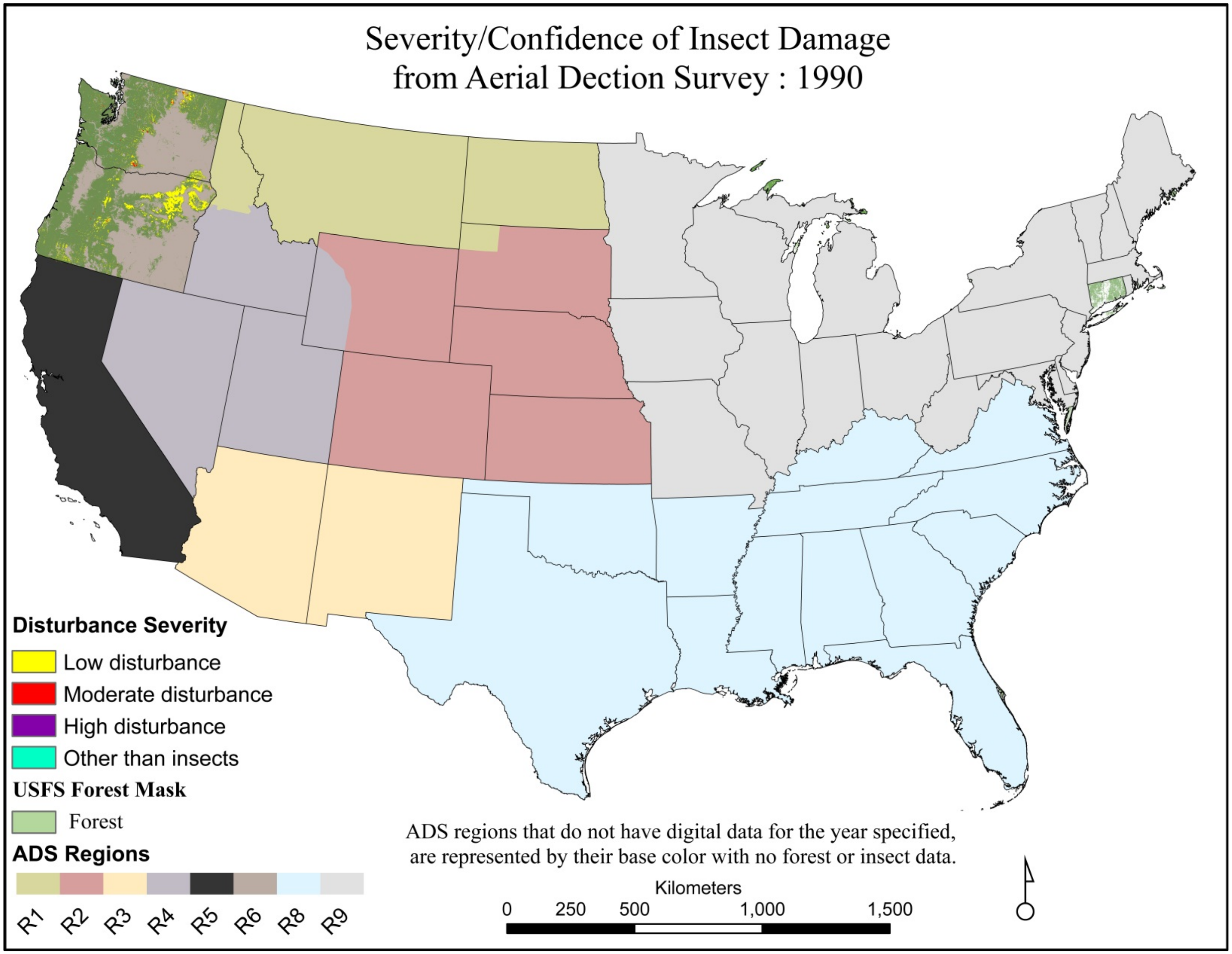

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1985
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
USFS Forest Mask
Forest
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500


Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1986
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
USFS Forest Mask
Forest
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
0
250
500
1,000
1,500
Kilometers

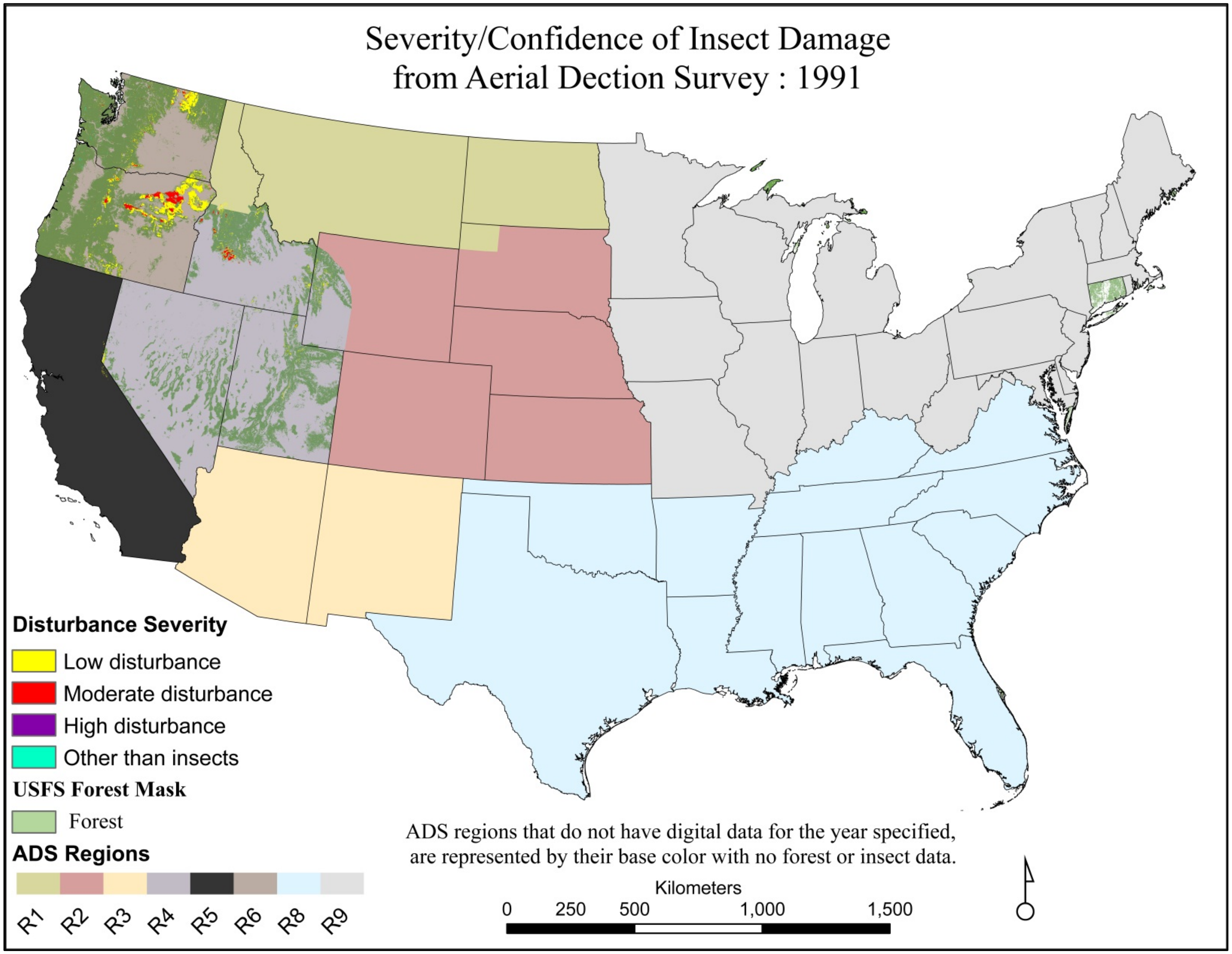

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1987
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
USFS Forest Mask
Forest
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
0
250
500
1,000
1,500
Kilometers

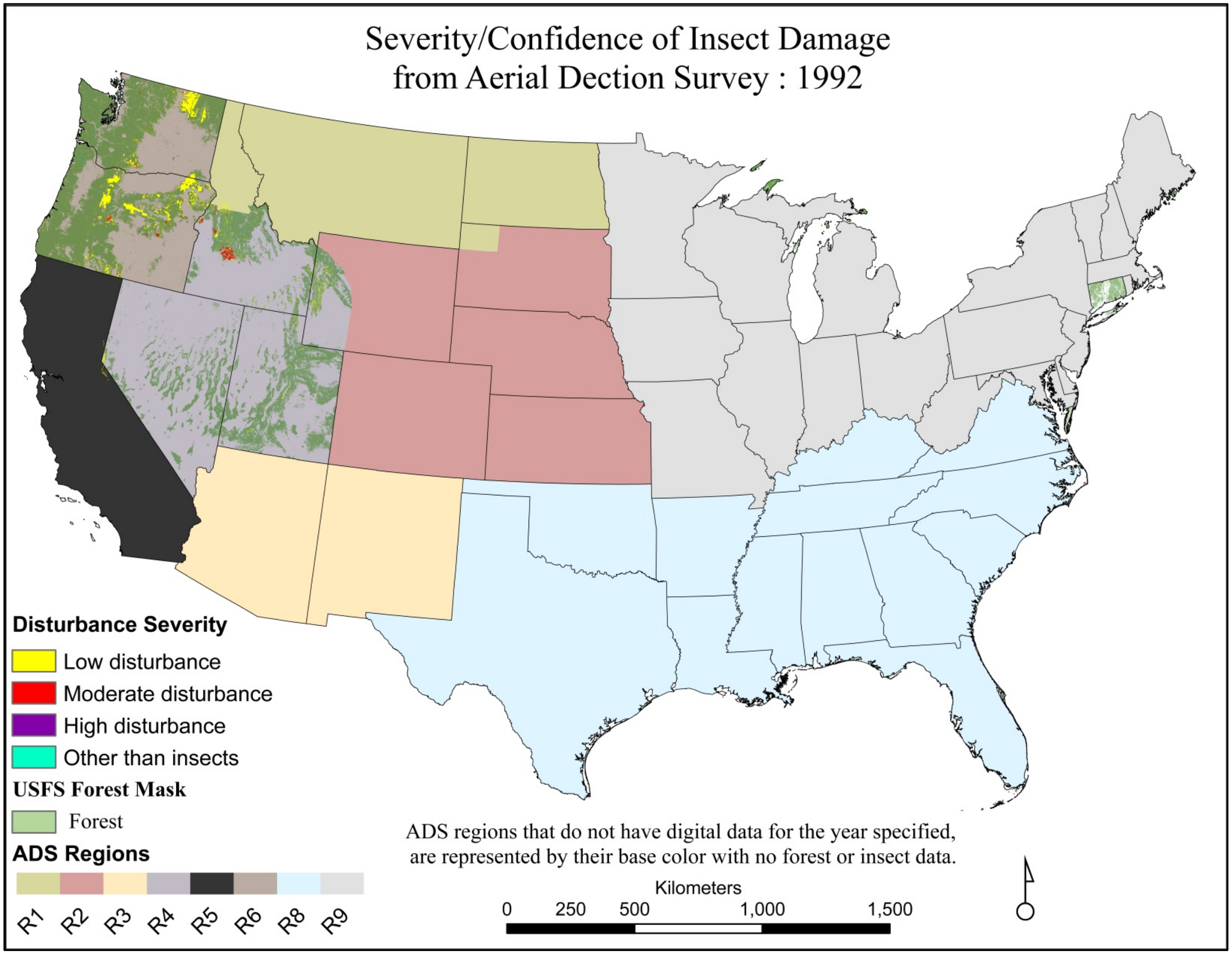

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1988
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
USFS Forest Mask
Forest
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
0
250
500
1,000
1,500
Kilometers

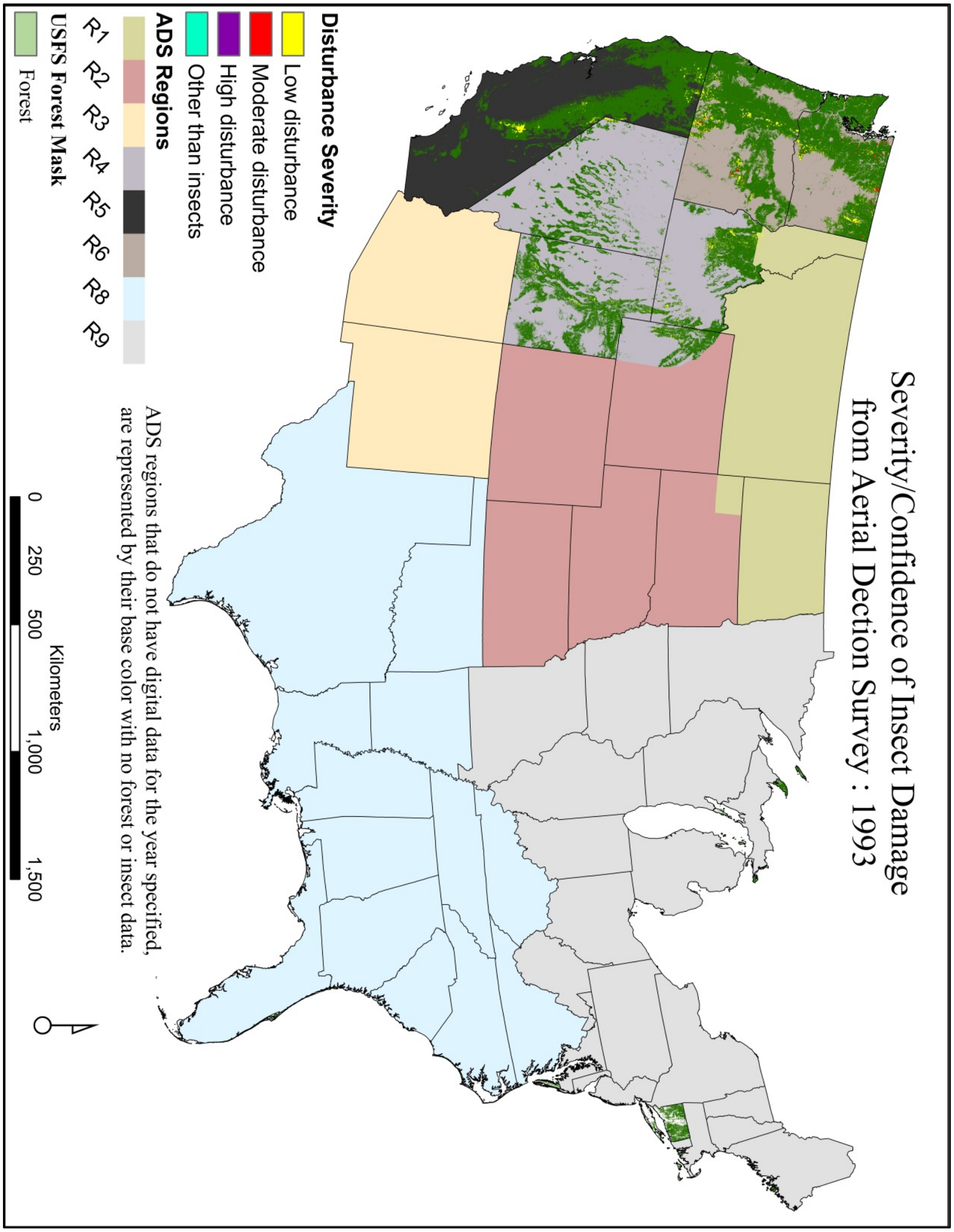

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1989
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
USFS Forest Mask
Forest
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
0
250
500
1,000
1,500
Kilometers

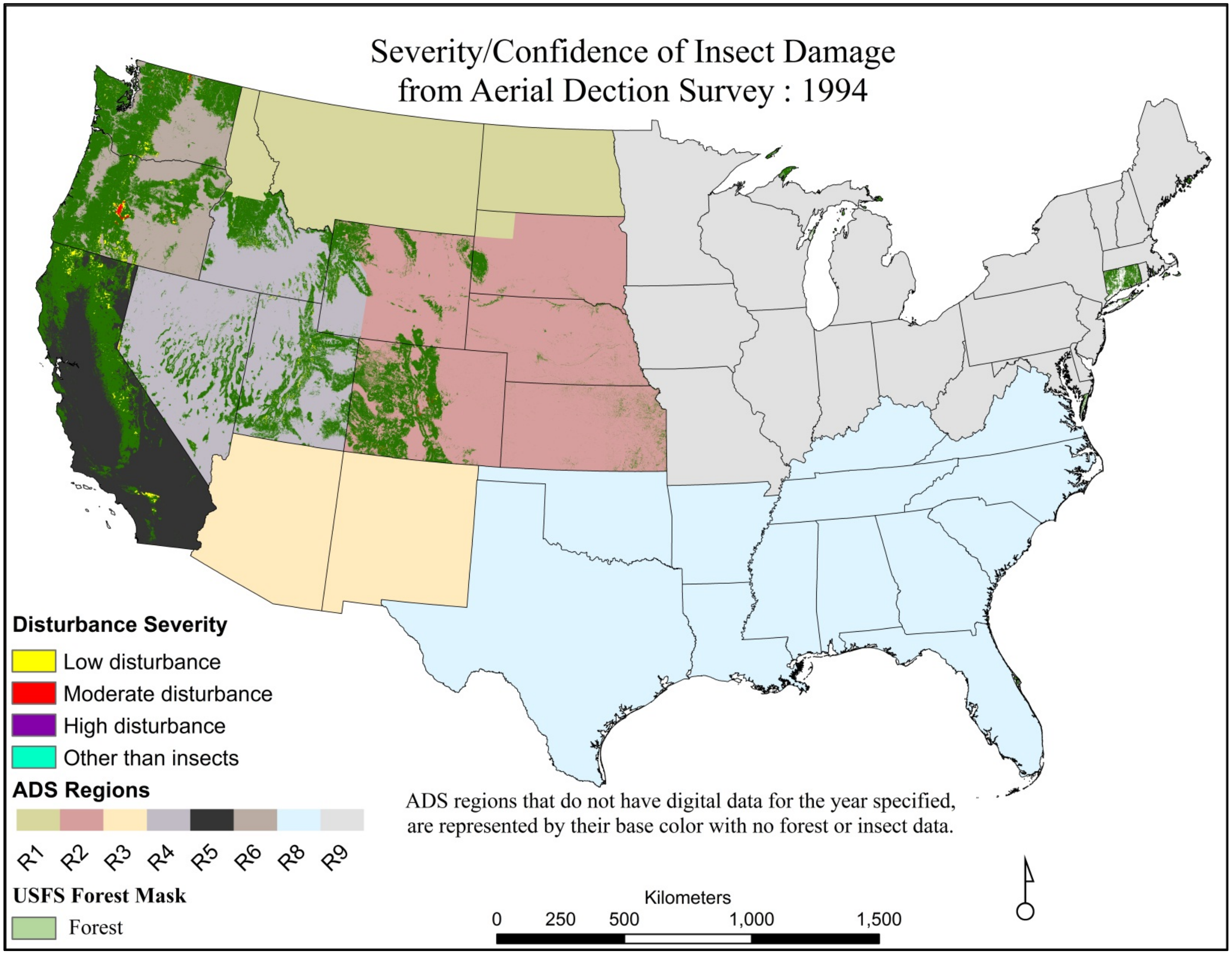


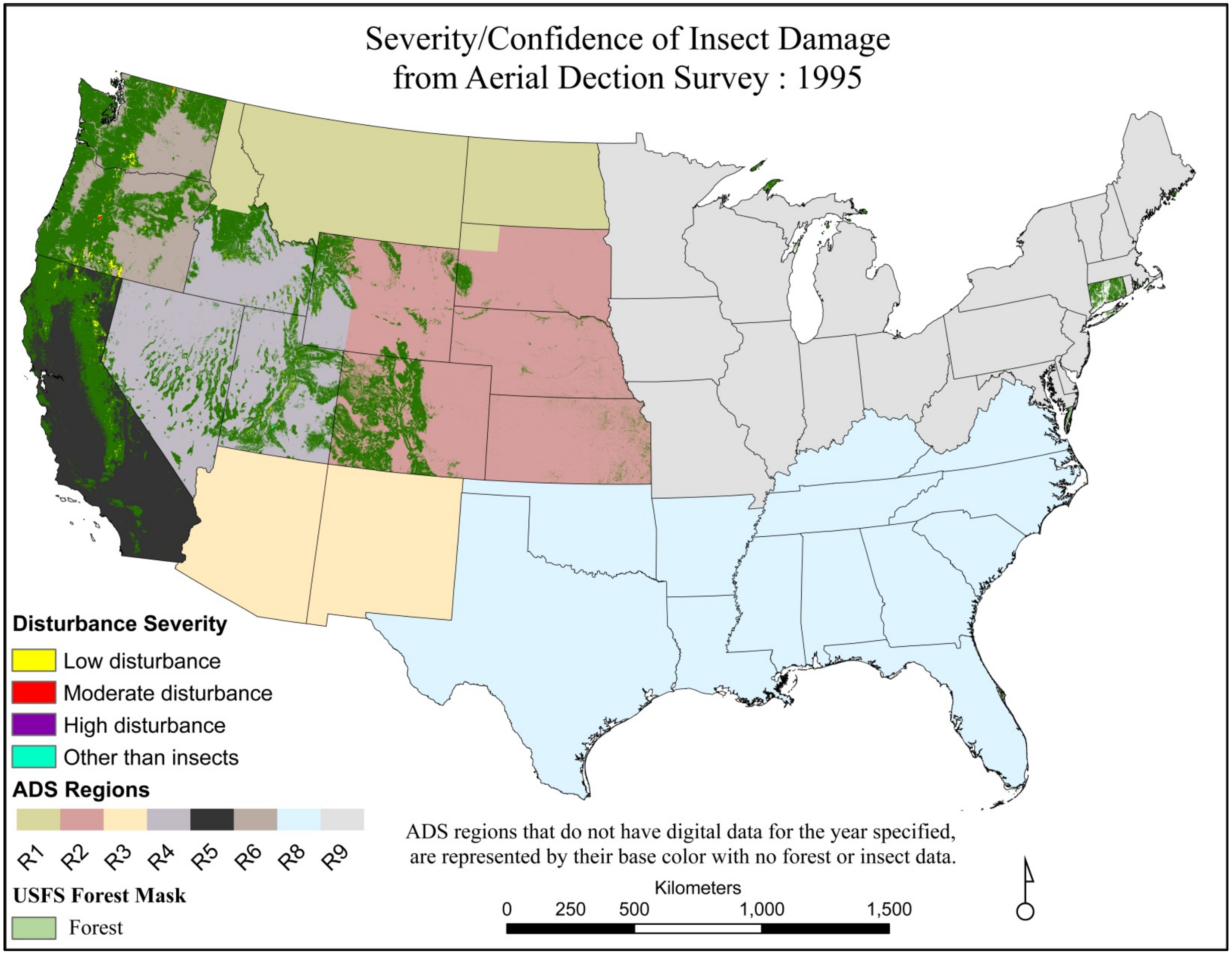
Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1990
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
USFS Forest Mask
Forest
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500


Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1991
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
USFS Forest Mask
Forest
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500

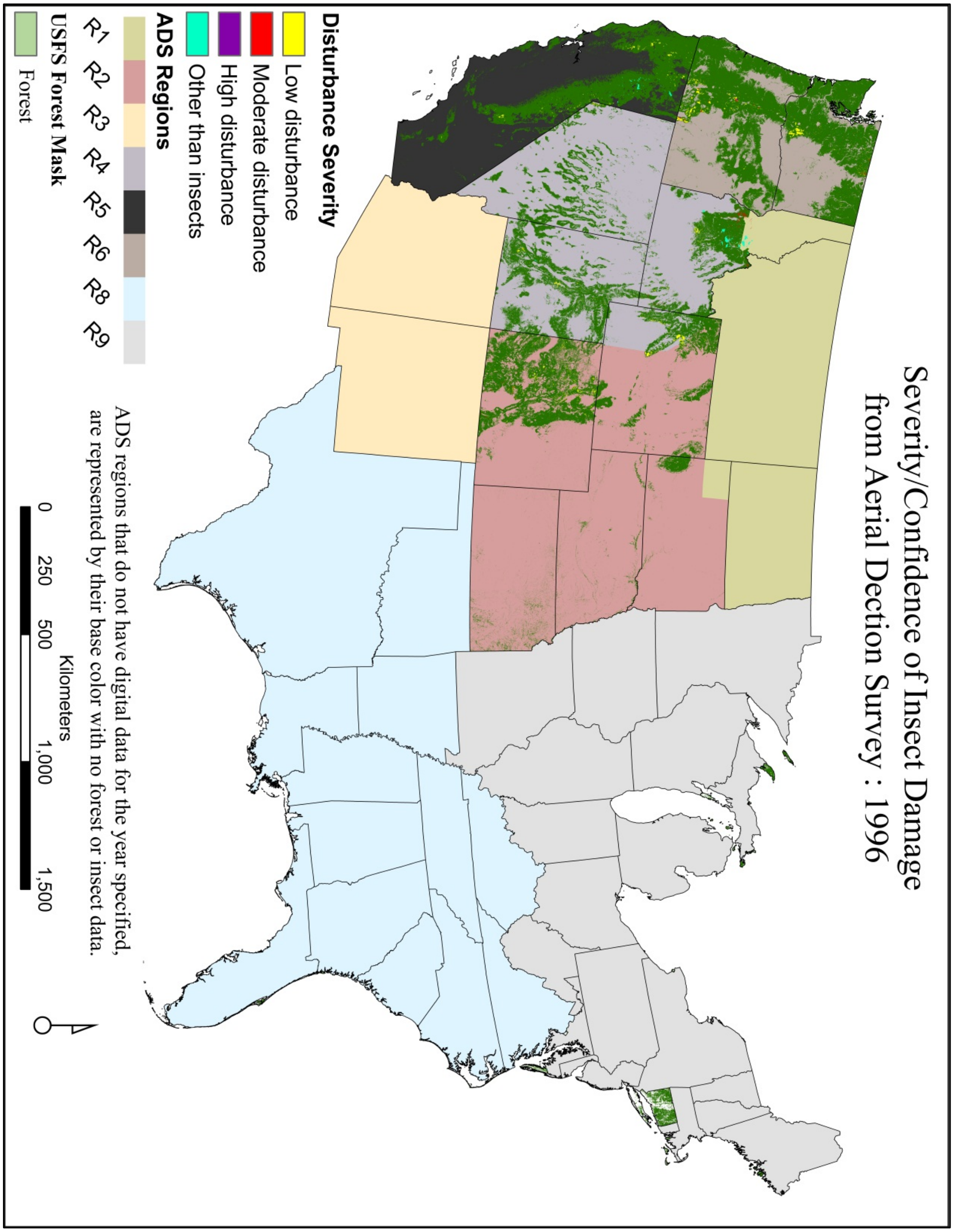

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1992
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
USFS Forest Mask
Forest
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500

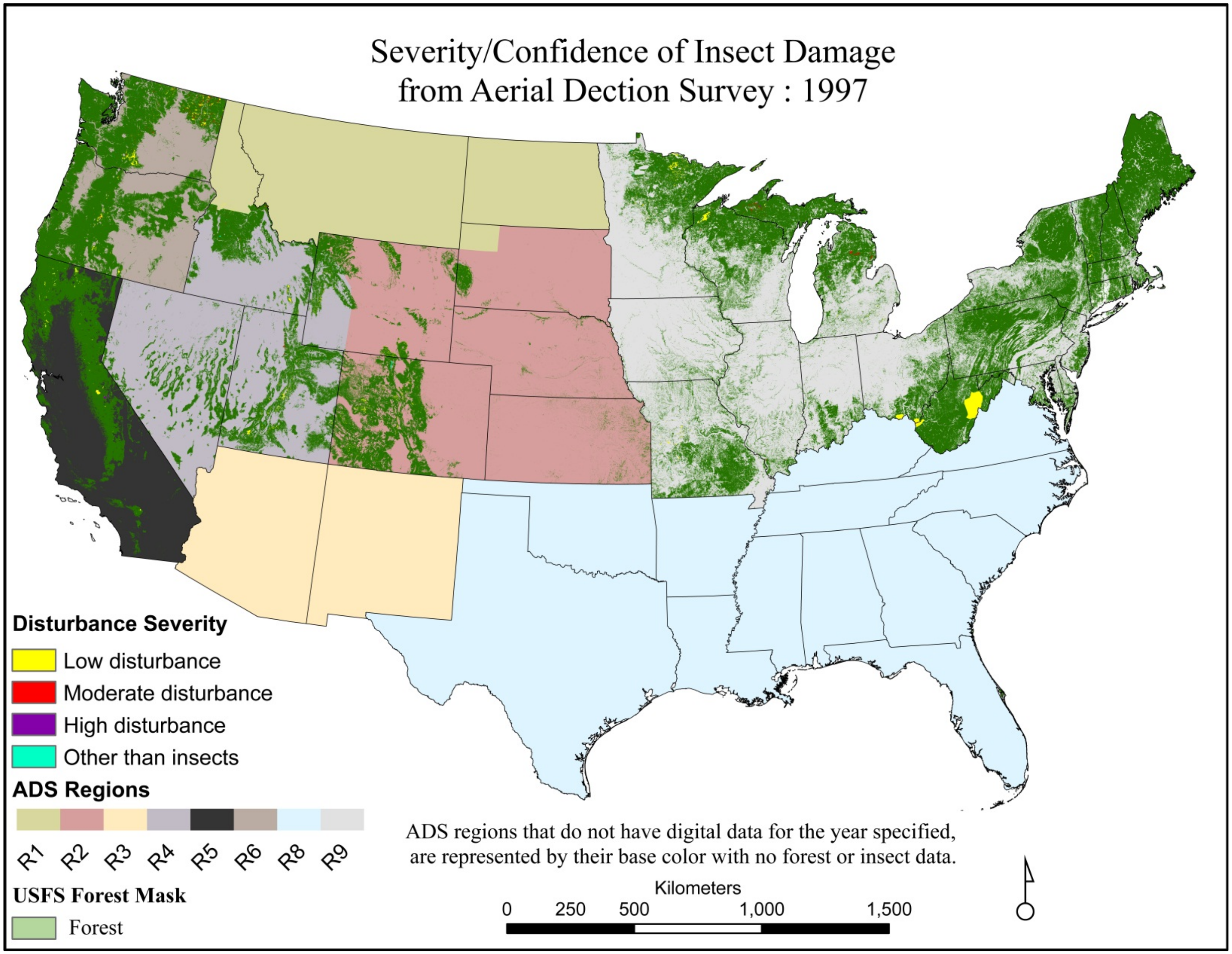

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1993
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
0
250
500
1,000
1,500
Kilometers

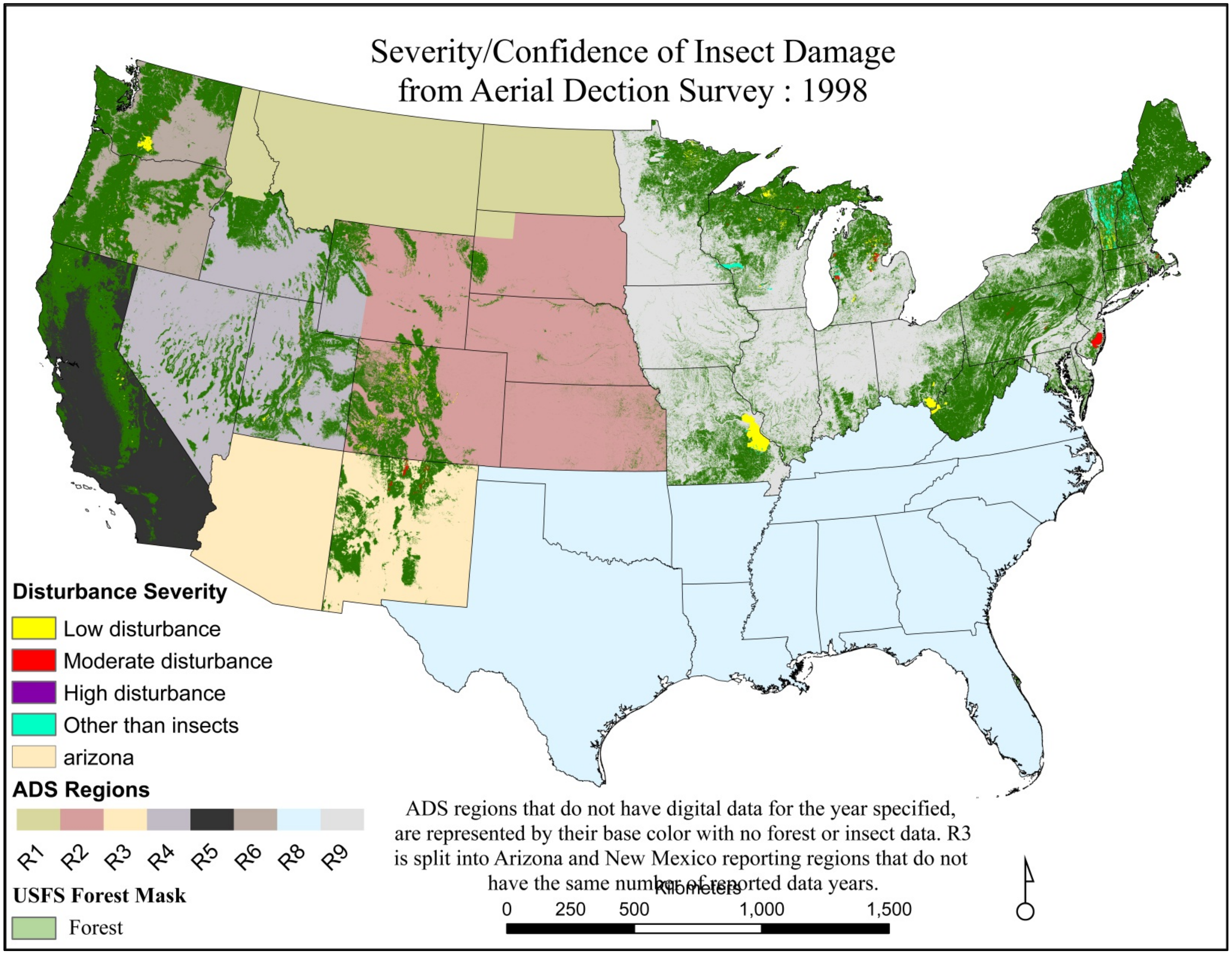

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1994
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500



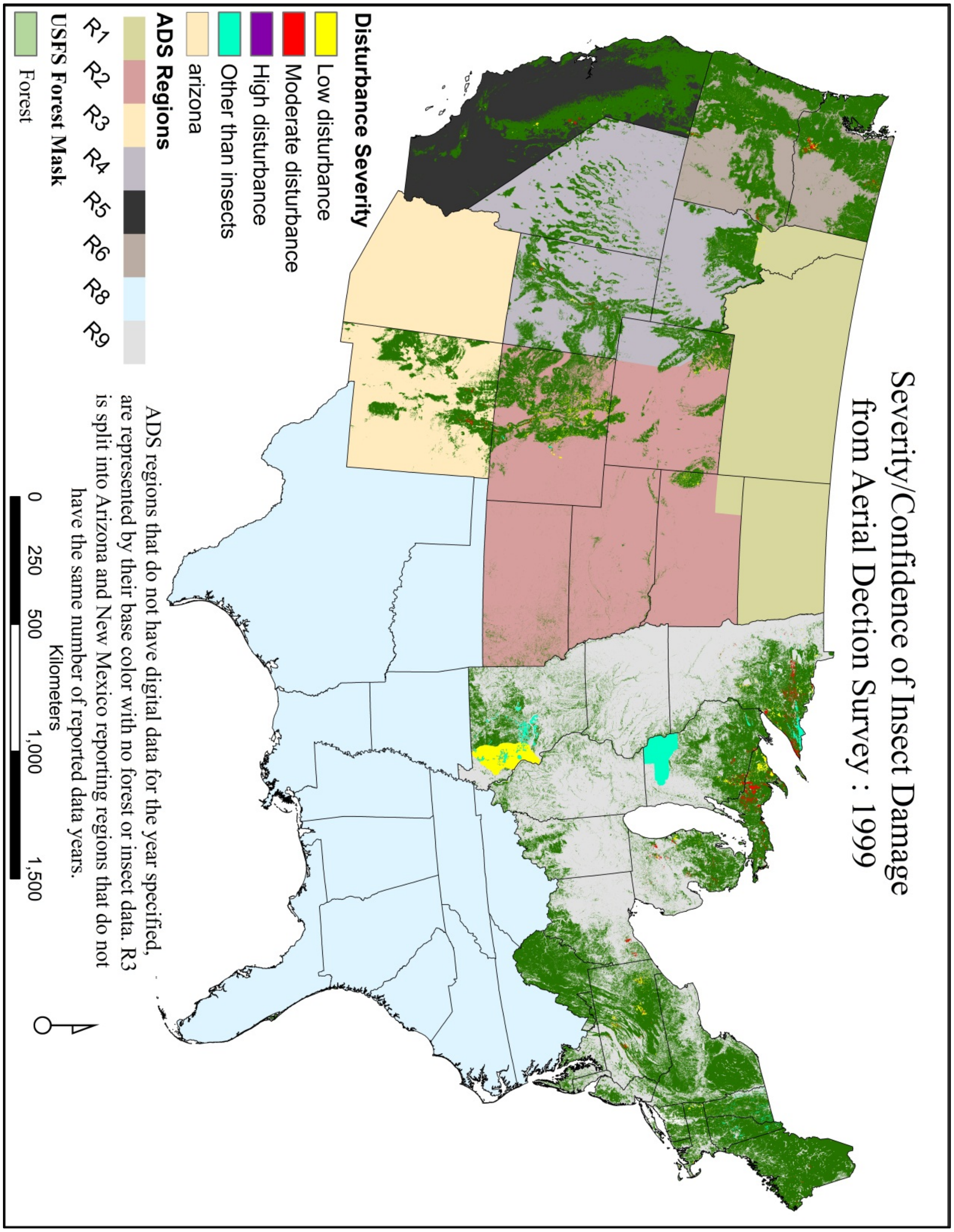
Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1995
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500


Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1996
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
0
250
500
1,000
1,500
Kilometers

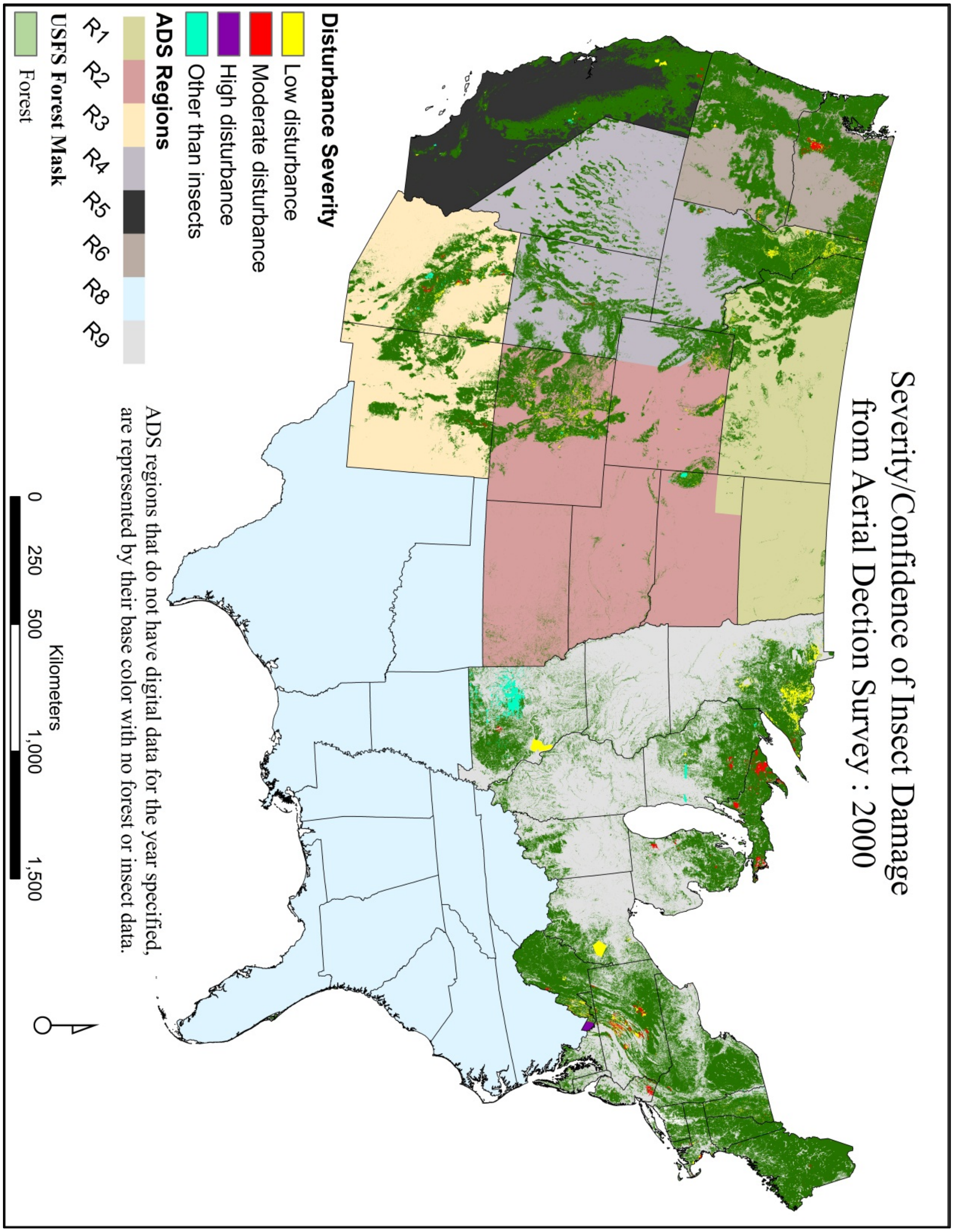

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1997
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500

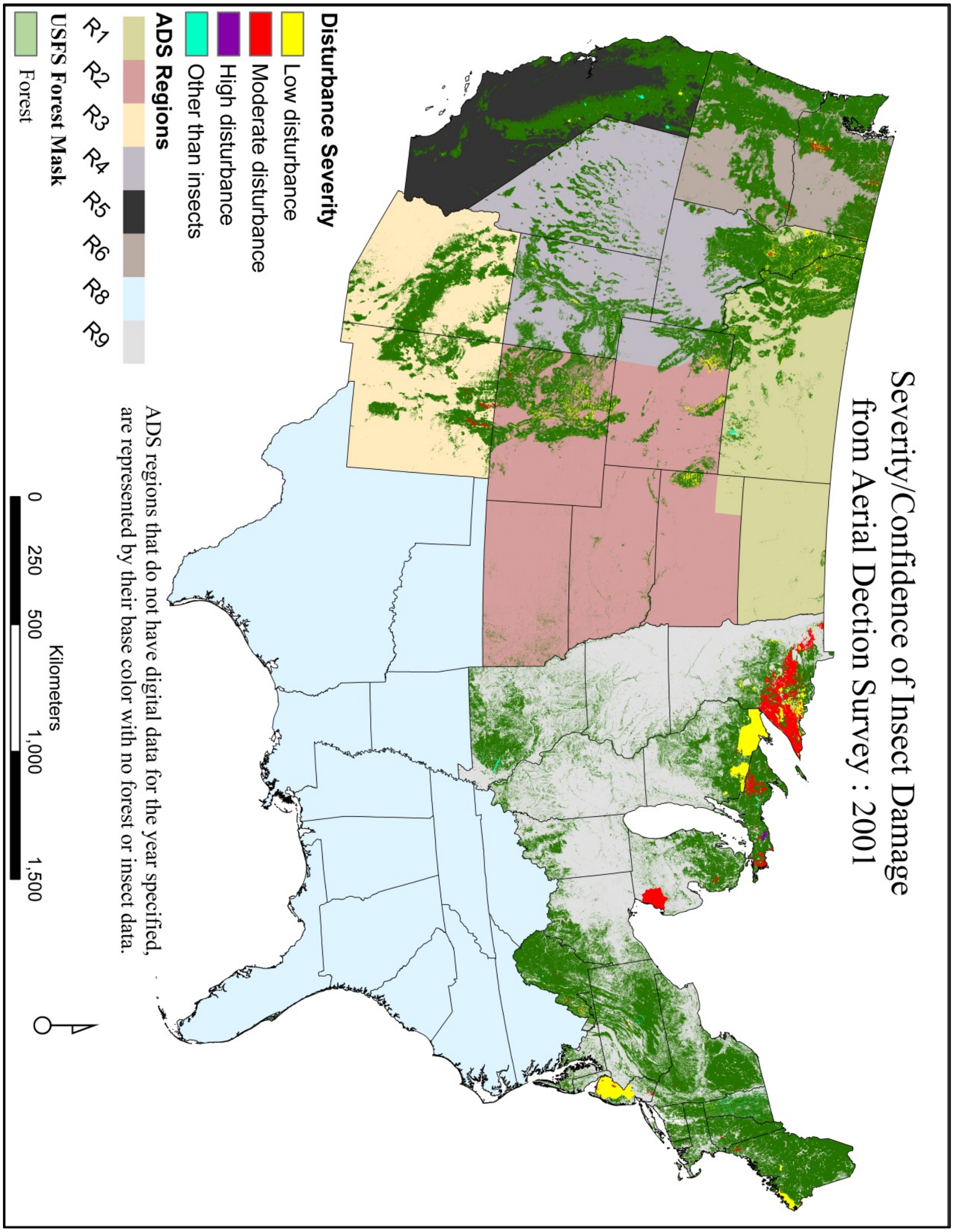


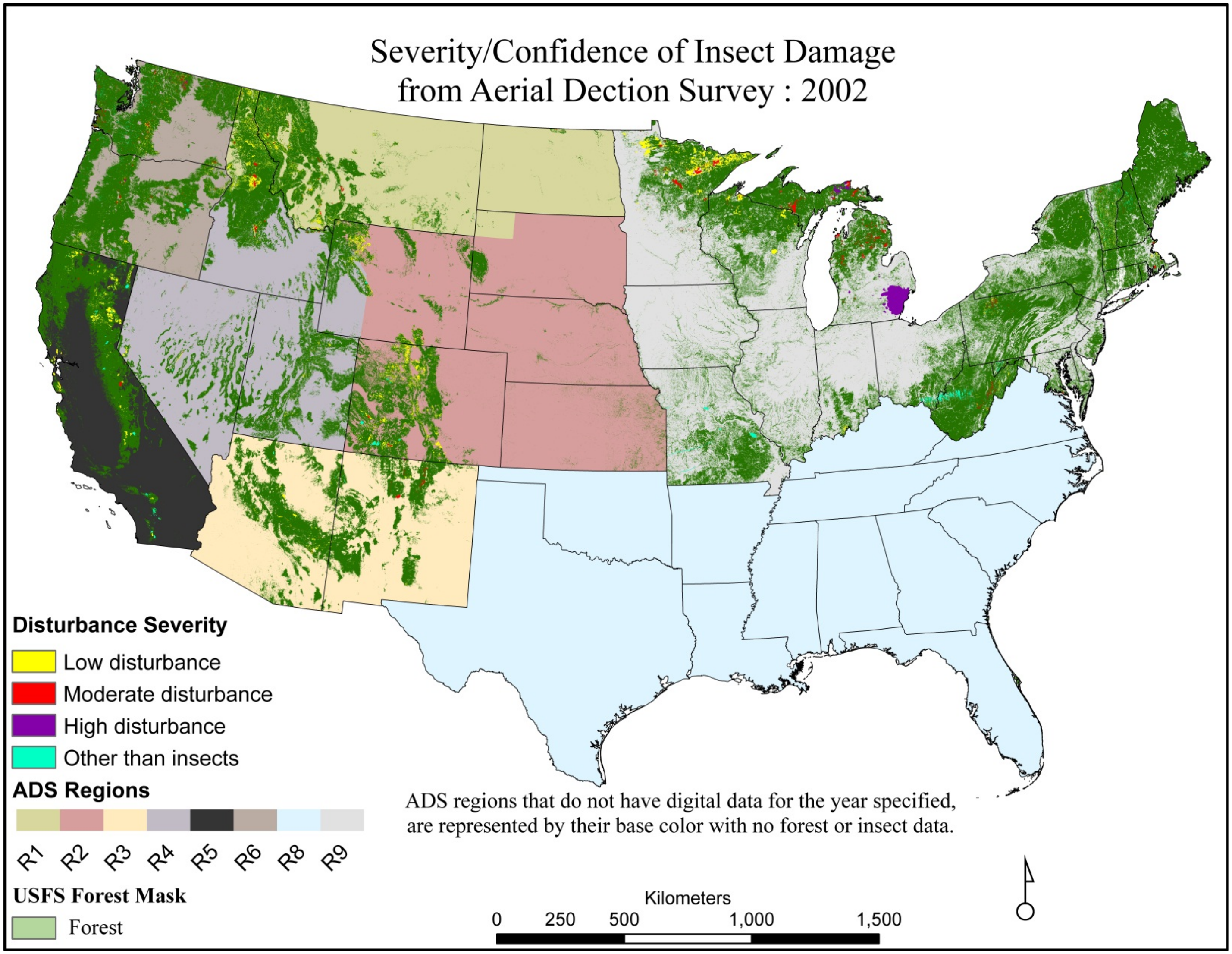
Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1998
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
arizona
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified, are represented by their base color with no forest or insect data. R3 is split into Arizona and New Mexico reporting regions that do not have the same number of reported data years.
Kilometers
0
250
500
1,000
1,500



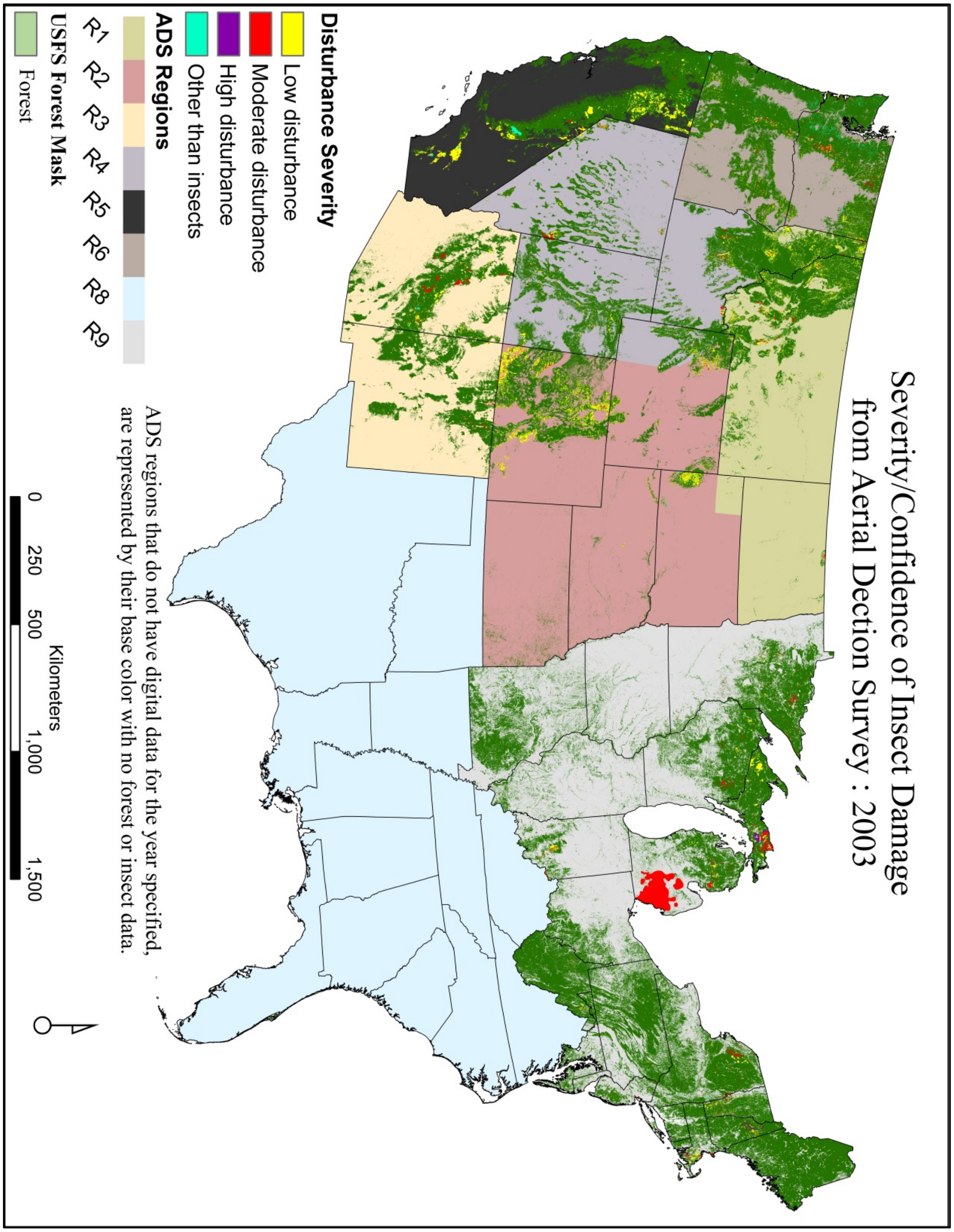
Severity/Confidence of Insect Damage
from Aerial Dection Survey : 1999
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
arizona
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified, are represented by their base color with no forest or insect data. R3 is split into Arizona and New Mexico reporting regions that do not have the same number of reported data years.
0
250
500
1,000
1,500
Kilometers


Severity/Confidence of Insect Damage
from Aerial Dection Survey : 2000
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
0
250
500
1,000
1,500
Kilometers

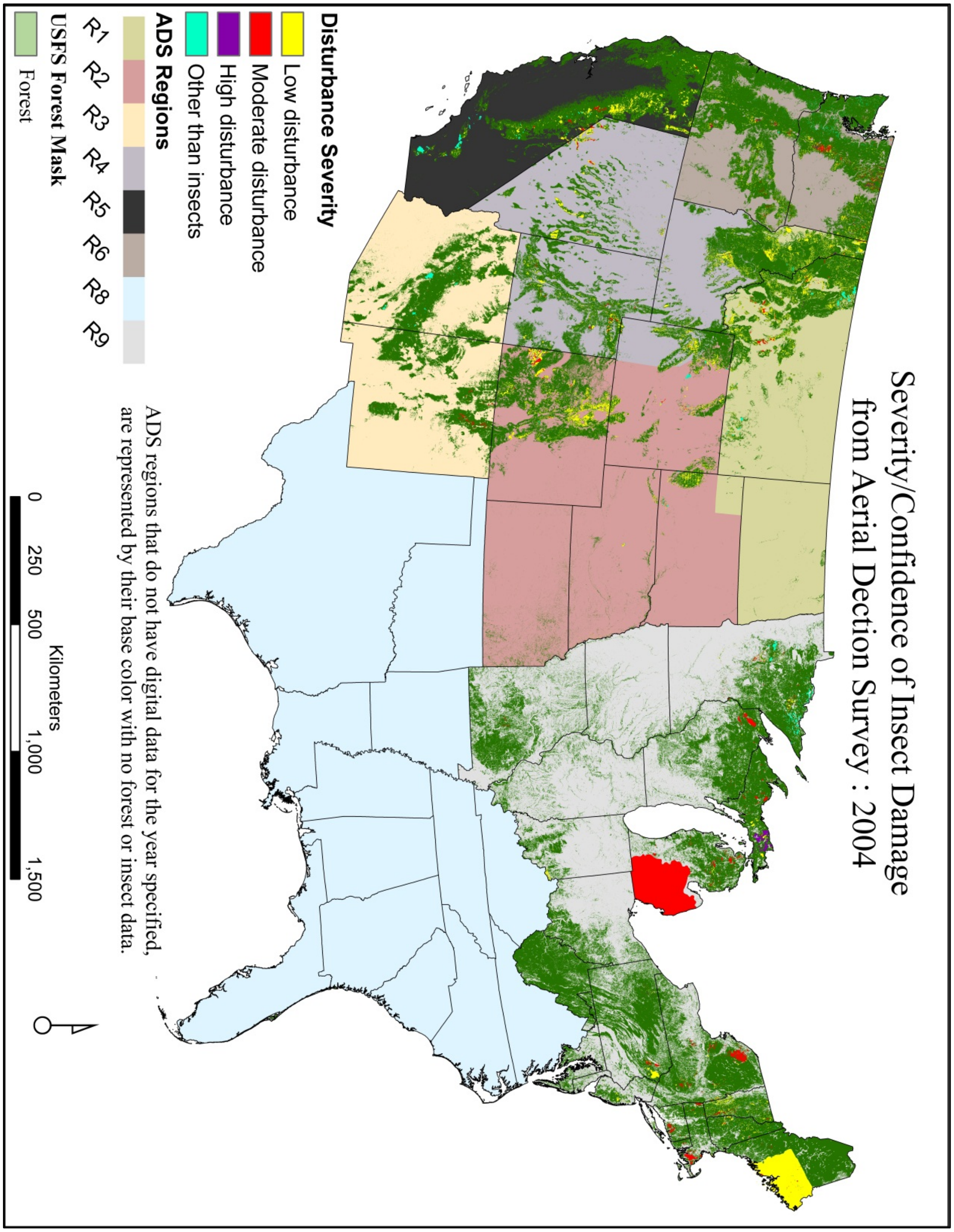

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 2001
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1 R2 R3 R4 R5 R6 R8 R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0 250 500 1,000 1,500

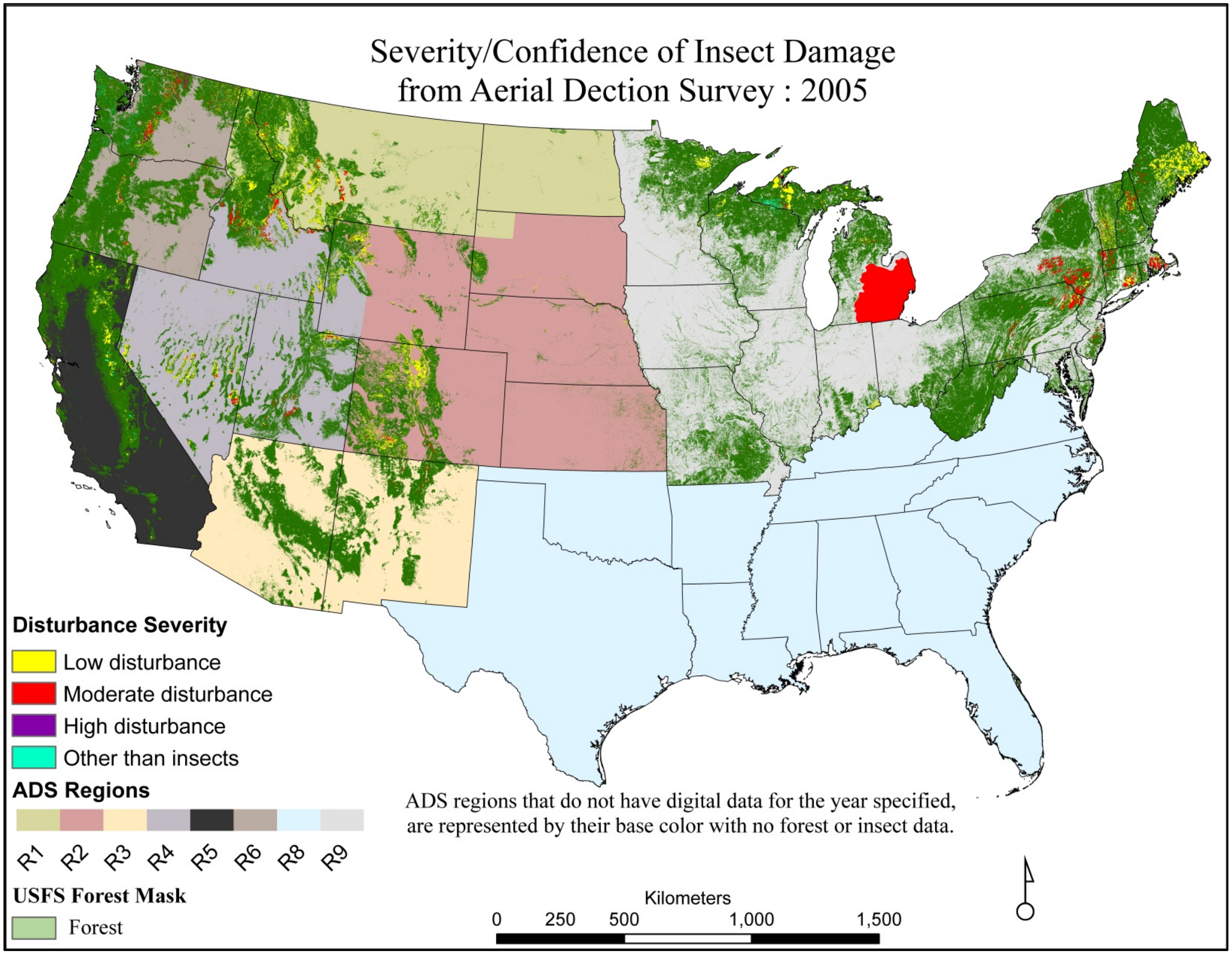


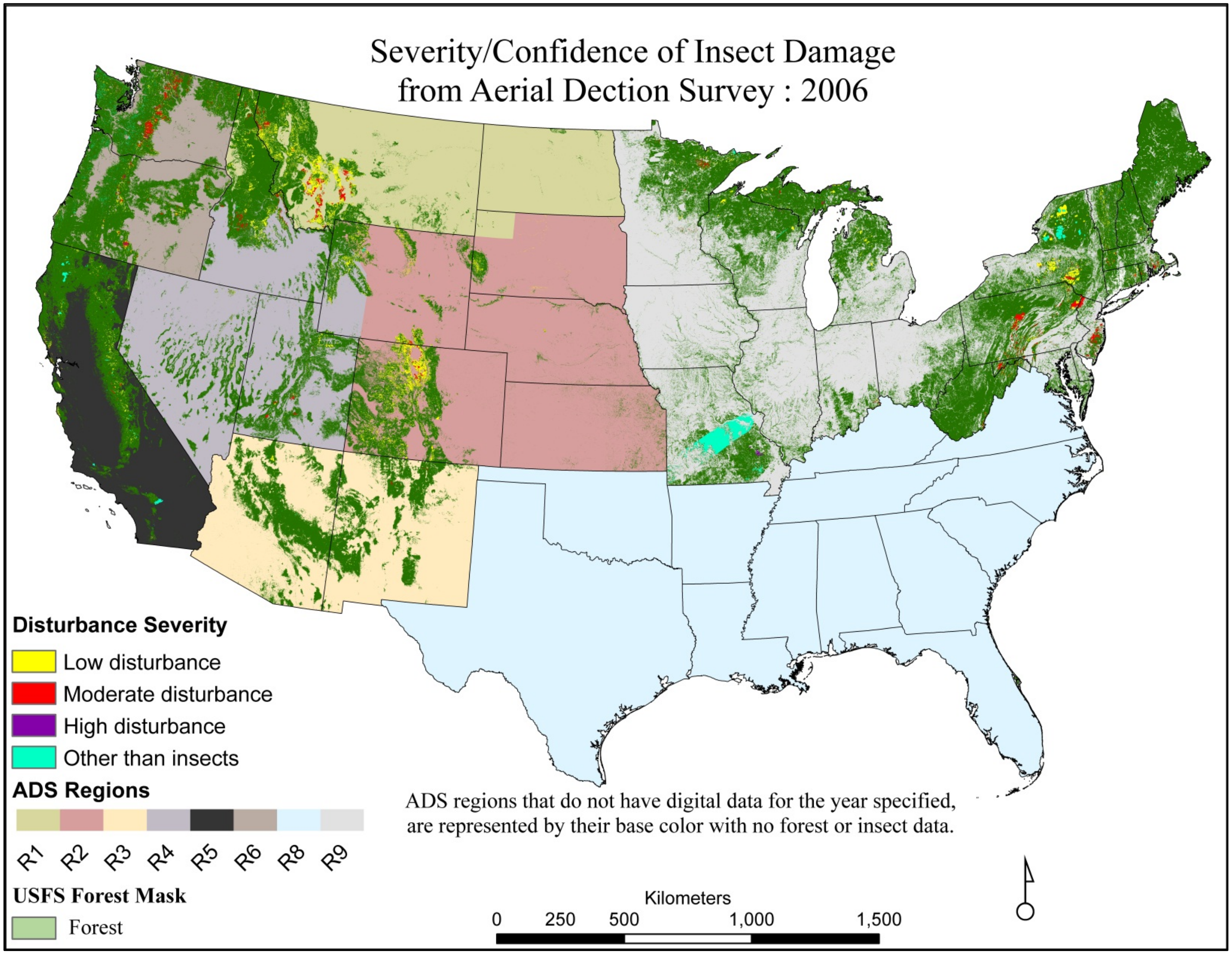
Severity/Confidence of Insect Damage
from Aerial Dection Survey : 2002
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500

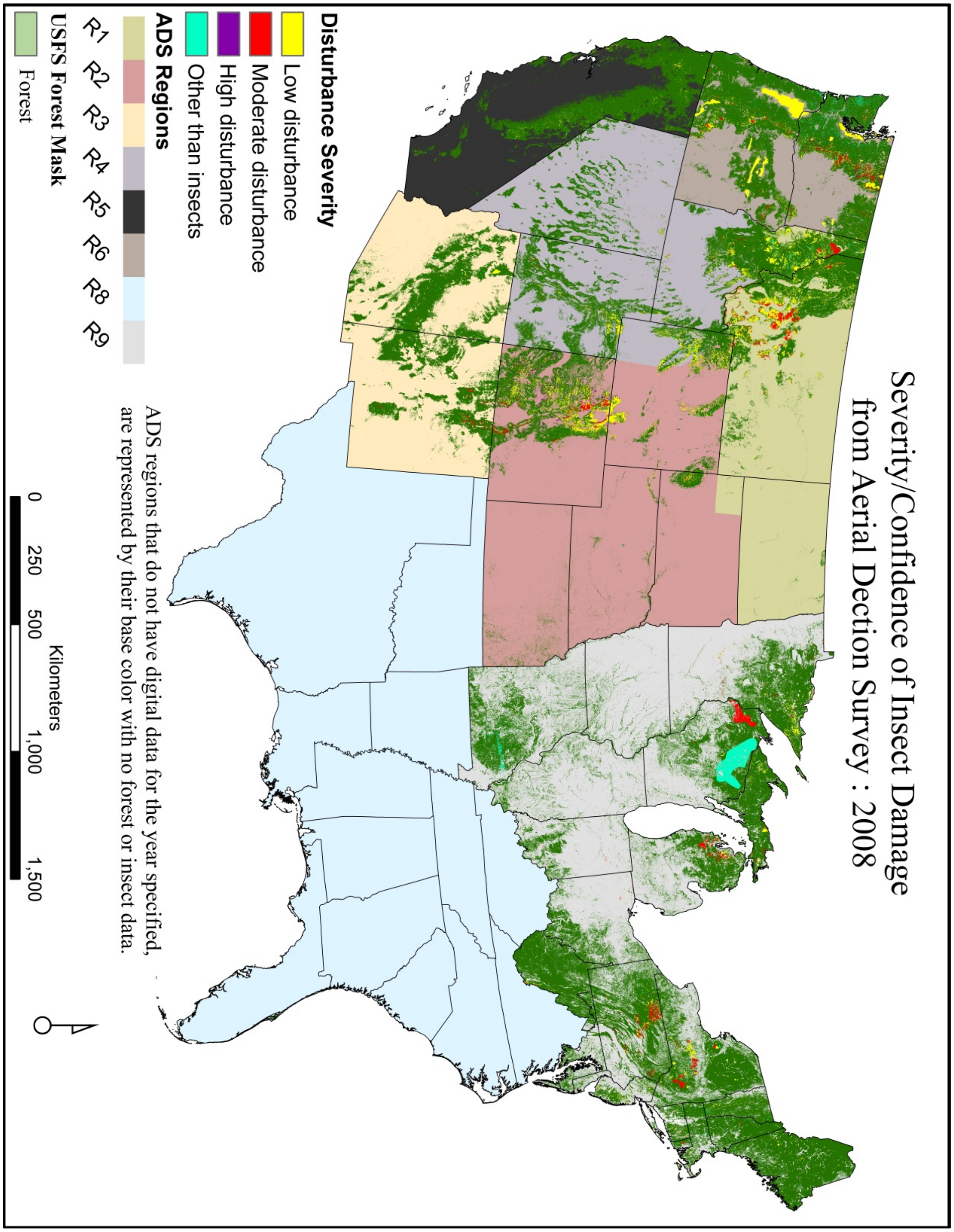


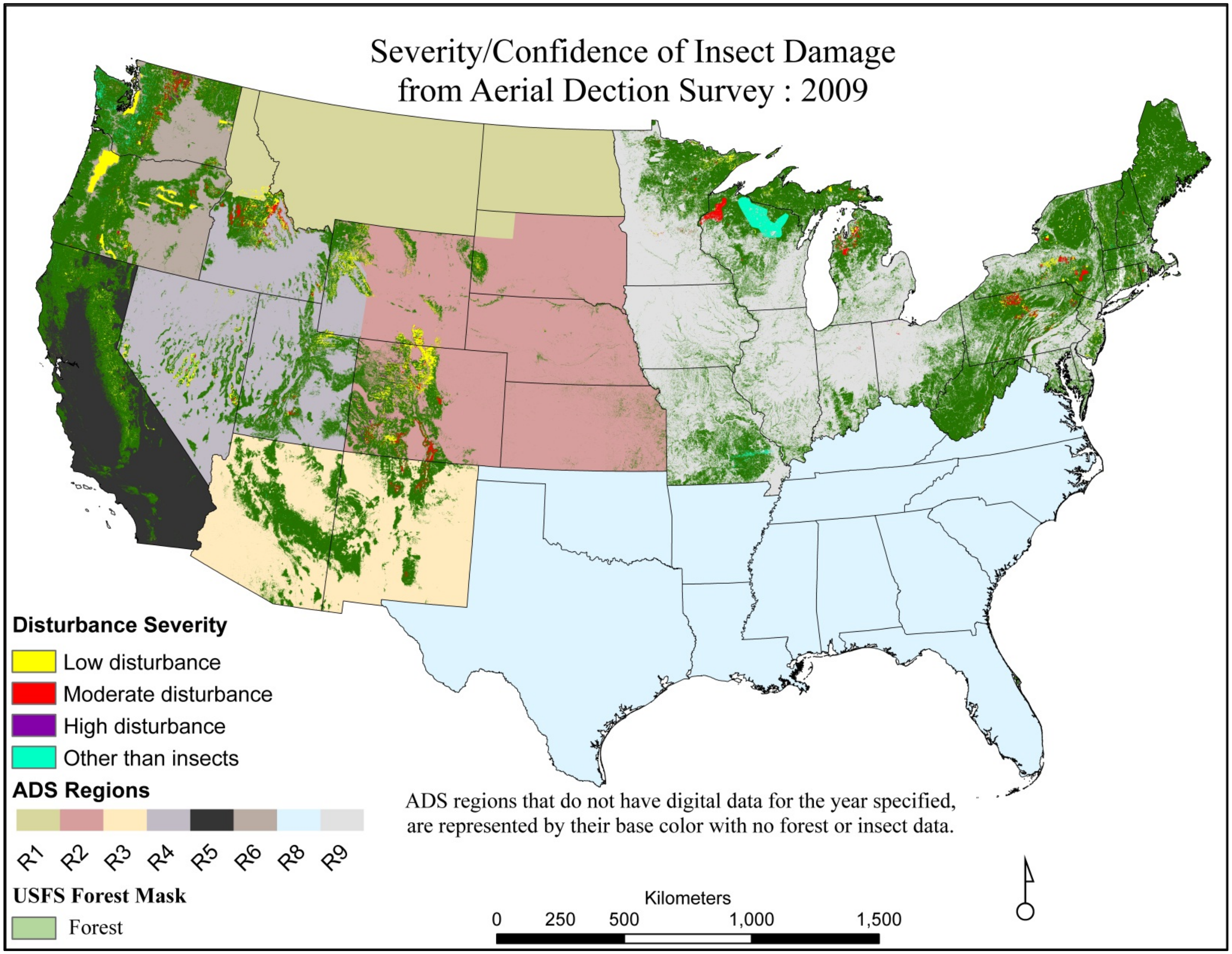
Severity/Confidence of Insect Damage
from Aerial Dection Survey : 2003
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1 R2 R3 R4 R5 R6 R8 R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
0 250 500 1,000 1,500
Kilometers

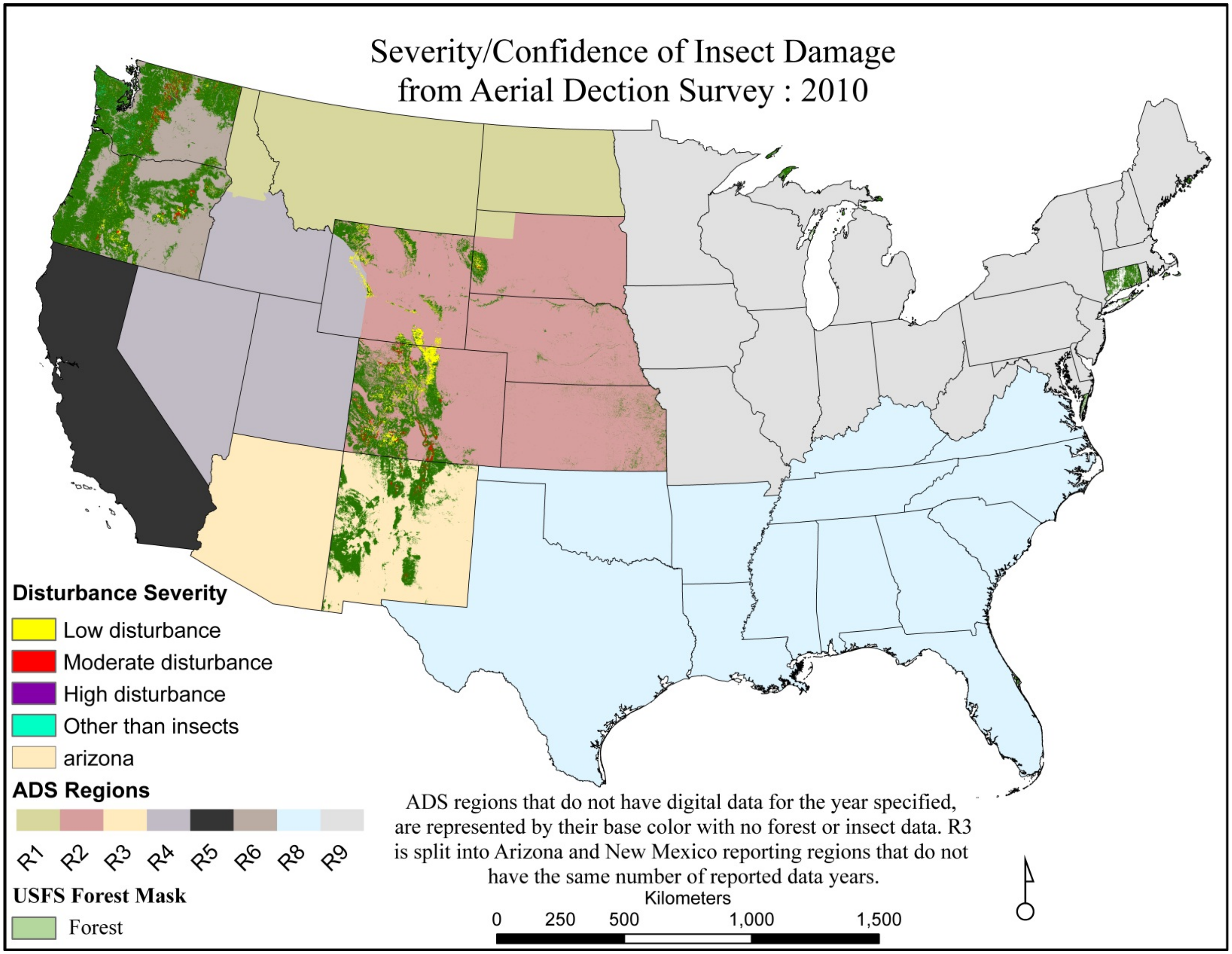

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 2004
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500


Severity/Confidence of Insect Damage
from Aerial Dection Survey : 2005
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1 R2 R3 R4 R5 R6 R8 R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0 250 500 1,000 1,500

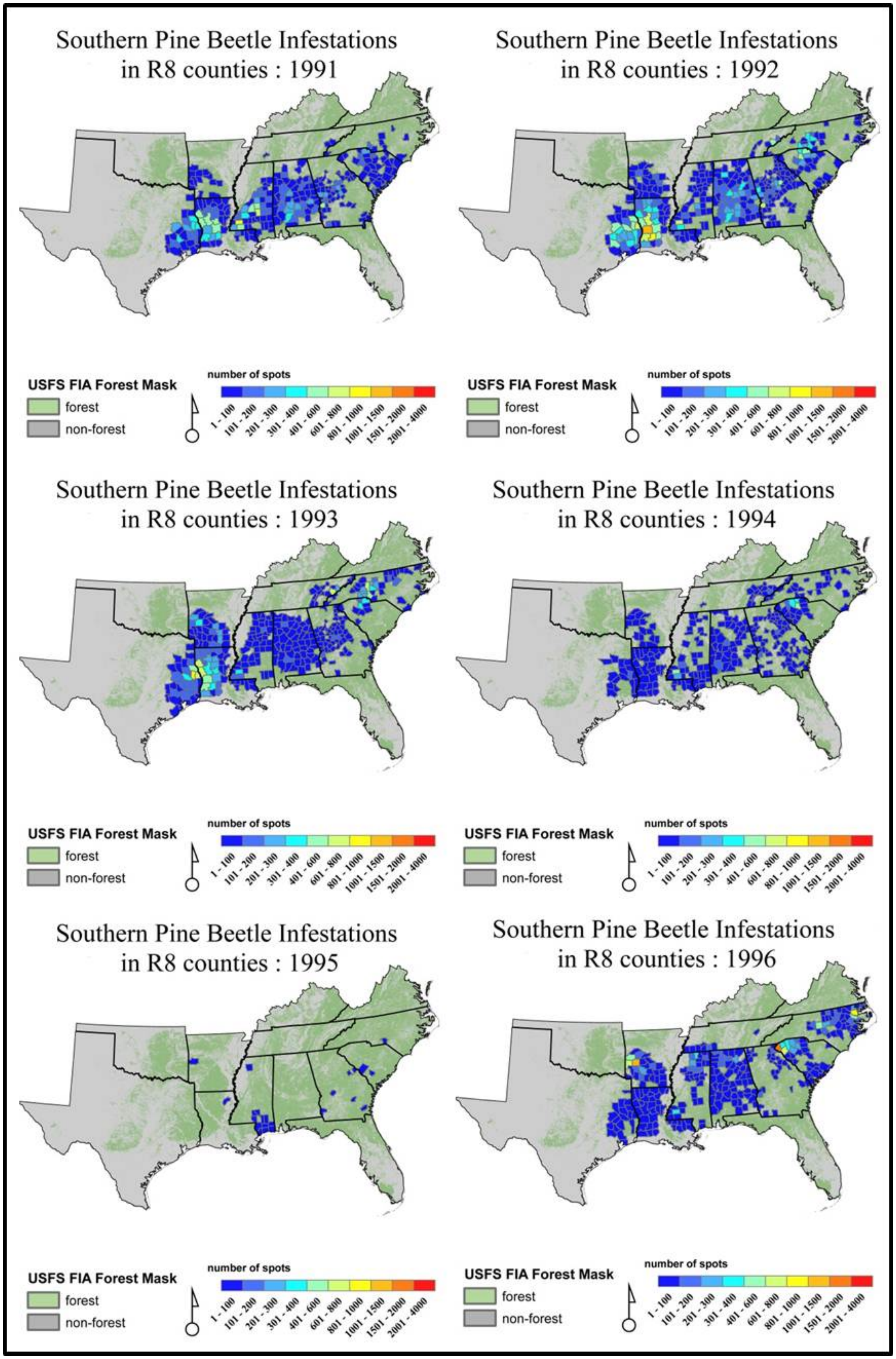

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 2006
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500

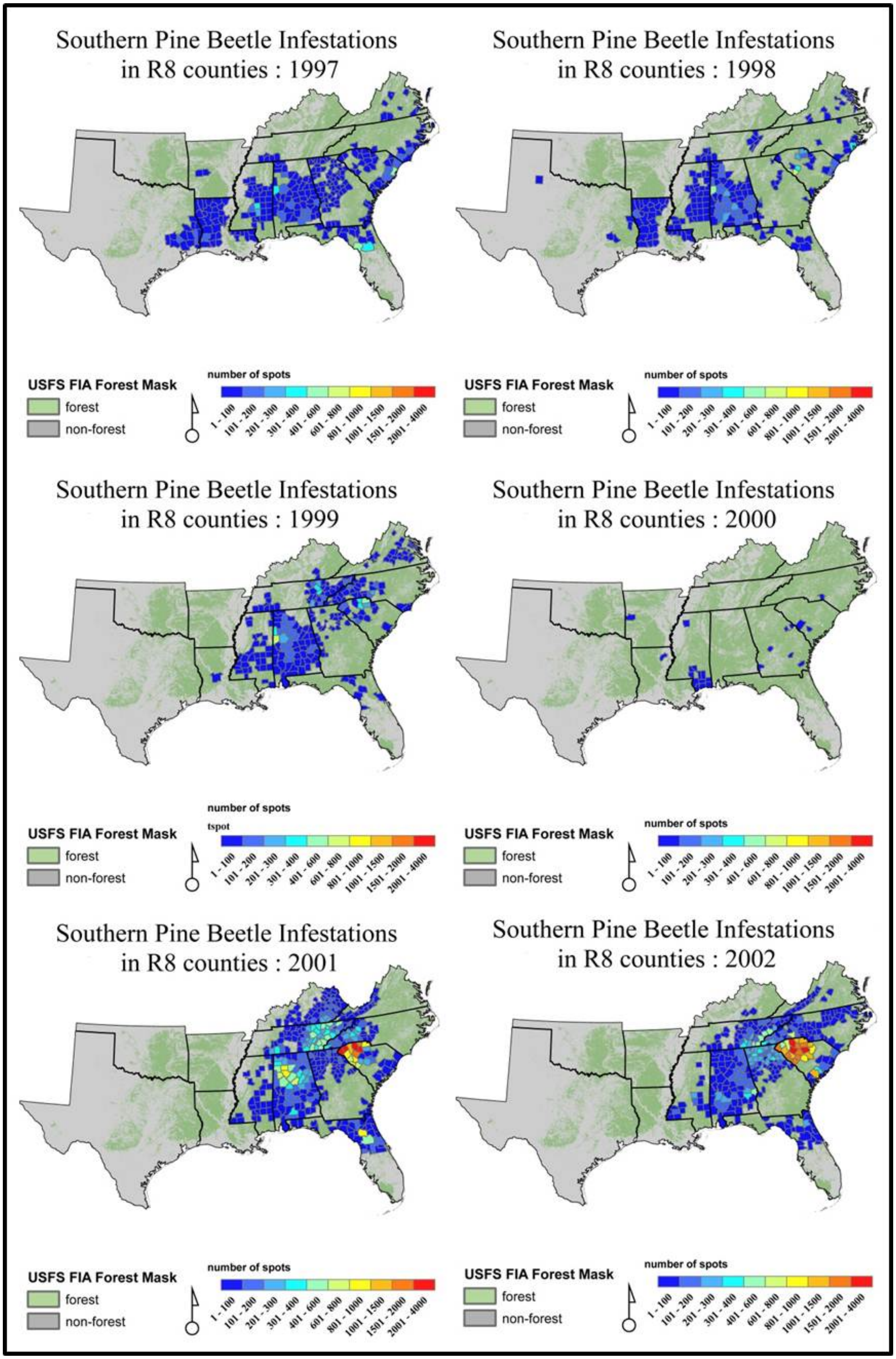

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 2008
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1 R2 R3 R4 R5 R6 R8 R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified,
are represented by their base color with no forest or insect data.
0 250 500 1,000 1,500
Kilometers

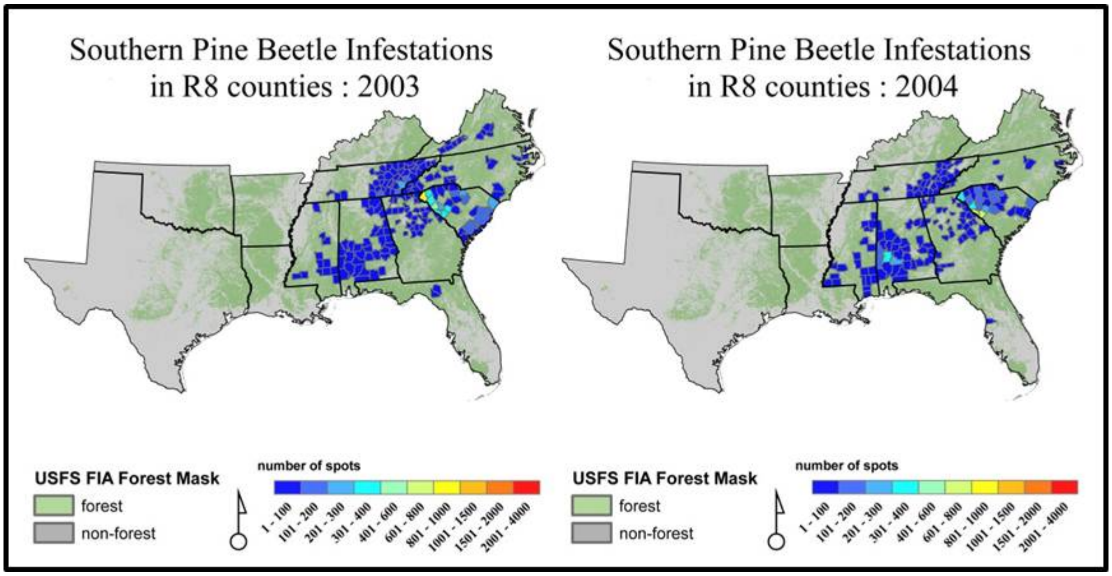

Severity/Confidence of Insect Damage
from Aerial Dection Survey : 2009
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified, are represented by their base color with no forest or insect data.
Kilometers
0
250
500
1,000
1,500


Severity/Confidence of Insect Damage
from Aerial Dection Survey : 2010
Disturbance Severity
Low disturbance
Moderate disturbance
High disturbance
Other than insects
arizona
ADS Regions
R1
R2
R3
R4
R5
R6
R8
R9
USFS Forest Mask
Forest
ADS regions that do not have digital data for the year specified, are represented by their base color with no forest or insect data. R3 is split into Arizona and New Mexico reporting regions that do not have the same number of reported data years.
Kilometers
0
250
500
1,000
1,500

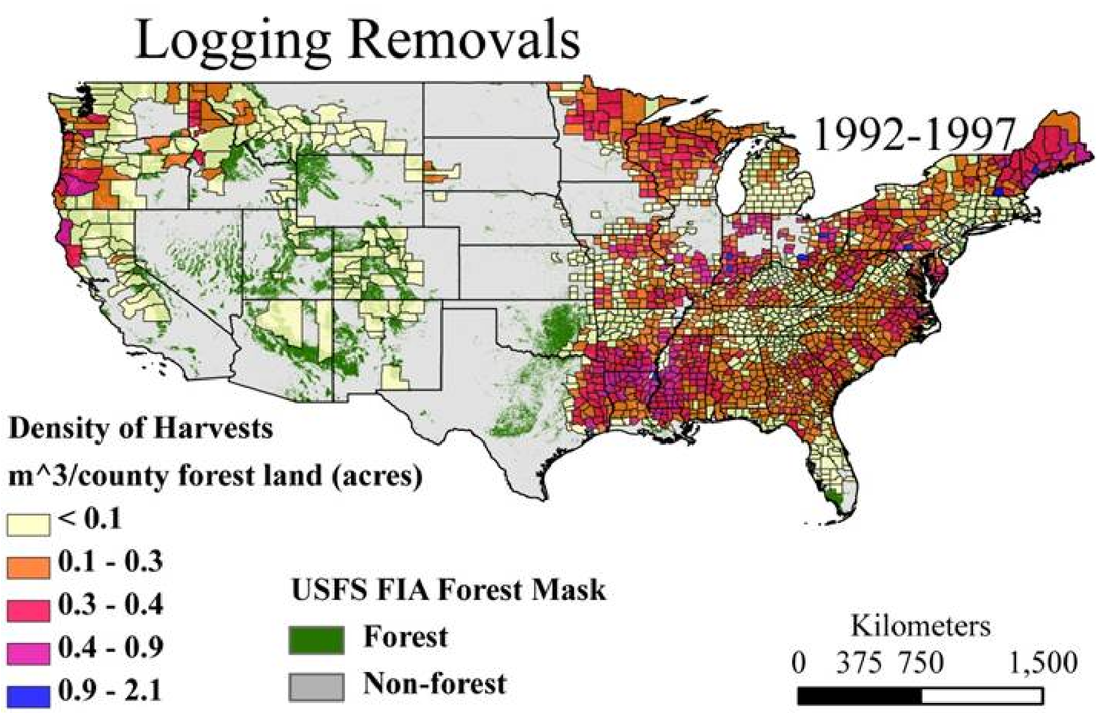
G. Maps of the total number of Southern Pine Beetle (SPB) Infestation spots recorded by the Forest Health Program for Region 8 (R8) per year

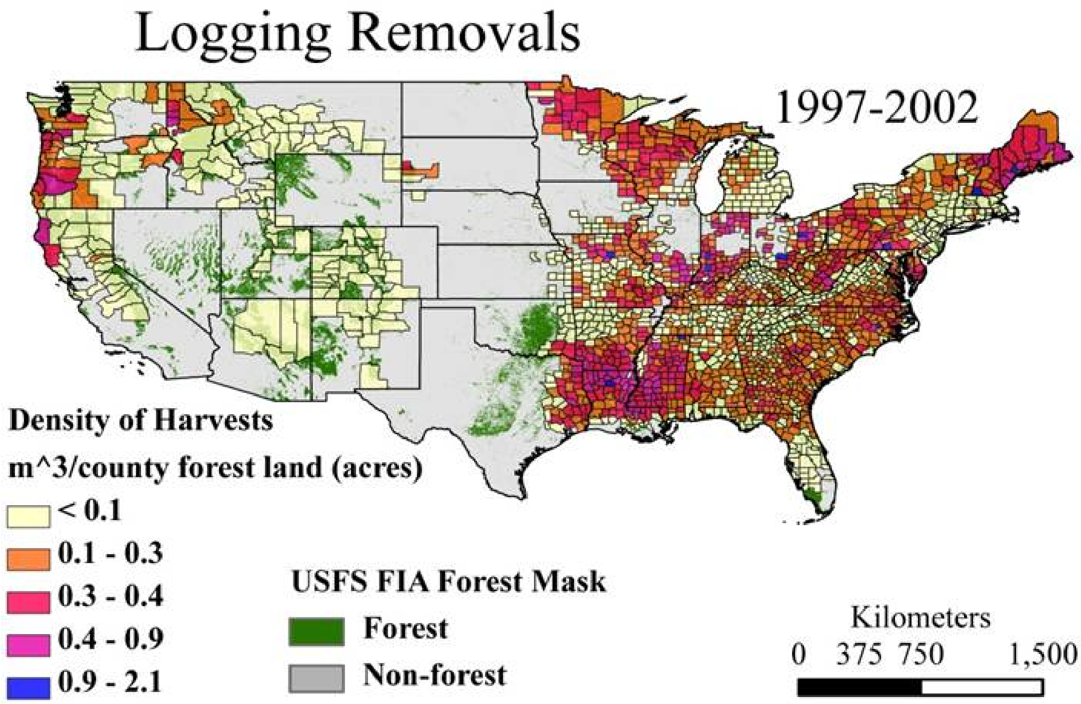

Southern Pine Beetle Infestations
in R8 counties : 1991
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000
Southern Pine Beetle Infestations
in R8 counties : 1992
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000
Southern Pine Beetle Infestations
in R8 counties : 1993
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000
Southern Pine Beetle Infestations
in R8 counties : 1994
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000
Southern Pine Beetle Infestations
in R8 counties : 1995
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000
Southern Pine Beetle Infestations
in R8 counties : 1996
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000

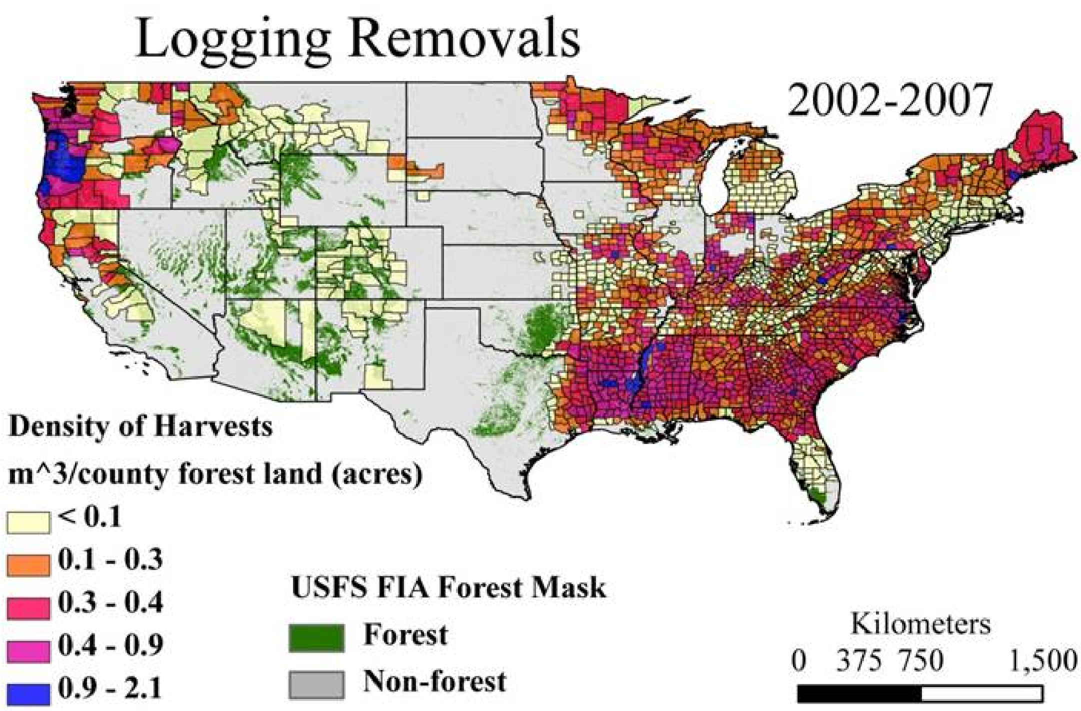

Southern Pine Beetle Infestations
in R8 counties : 1997
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000
Southern Pine Beetle Infestations
in R8 counties : 1998
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000
Southern Pine Beetle Infestations
in R8 counties : 1999
USFS FIA Forest Mask
forest
non-forest
number of spots
tspot
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000
Southern Pine Beetle Infestations
in R8 counties : 2000
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000
Southern Pine Beetle Infestations
in R8 counties : 2001
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000
Southern Pine Beetle Infestations
in R8 counties : 2002
USFS FIA Forest Mask
forest
non-forest
number of spots
1 - 100
101 - 200
201 - 300
301 - 400
401 - 600
601 - 800
801 - 1000
1001 - 1500
1501 - 2000
2001 - 4000



H. Maps of County level Harvest Intensity




Logging Removals
1997-2002
Density of Harvests
m^3/county forest land (acres)
< 0.1
0.1 - 0.3
0.3 - 0.4
0.4 - 0.9
0.9 - 2.1
USFS FIA Forest Mask
Forest
Non-forest
Kilometers
0 375 750 1,500


Logging Removals
2002-2007
Density of Harvests
m^3/county forest land (acres)
< 0.1
0.1 - 0.3
0.3 - 0.4
0.4 - 0.9
0.9 - 2.1
USFS FIA Forest Mask
Forest
Non-forest
Kilometers
0 375 750 1,500

References

(FAO), Food and Agrigucltural Organization (2001), State of the World's Forest, United Nations Food and Agrigucltural Organization, Rome.

(IPCC), Intergovernmental Panel on Climate Change (2000), Land use, land-use change, and forestry in IPCC Special Report on Land Use, Land-Use Change, and Forestry, chap. 2, (Available at http://www.grida.no/publications/other/ipcc_sr/?src=/Climate/ipcc/land_use/049.htm, retrieved September 9, 2011)

(MEA), Millennium Ecosystem Assessment (2003), Ecosystems and Human Wellbeing A Framework for Assessment., 245 pp, Island Press, Washington DC.

(MTBS), Montinoring Trends in Burn Severity (2010), Montinoring Trends in Burn Severity. (Available at http://mtbs.gov/data/search.html, retrieved July 5, 2010)

(USDA), U.S. Department of Agriculture (1995), Forest insect and disease conditions in the United States 1994, U.S. Department of Agriculture, Forest Service, Forest Health Protection, Washington (DC).

(USDA), U.S. Department of Agriculture (2000), Forest Insect and Disease Conditions in the United States 1999, U.S. Department of Agriculture, Forest Service, Forest Health Protection, Washington (DC).

(USDA), U.S. Department of Agriculture (2001), National resource inventory. Unnumbered report, 178 pp, Washinton DC.

(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)

(USDA), U.S. Department of Agriculture (2005), Forest Insect and Disease Conditions in the United States 2004, U.S. Department of Agriculture, Forest Service, Forest Health Protection, Washington (DC).

(USDA), U.S. Department of Agriculture (2009), Forest Insect and Disease Conditions in the United States 2008, U.S. Department of Agriculture, Forest Service, Forest Health Protection, Washington (DC).

(USDA), U.S. Department of Agriculture (2010), Forest Inventory and Analysis National Program, Forest Inventory Data Online (FIDO). (Available at (http://fiatools.fs.fed.us/fido/index.html) retrieved June 2010)

(USDA), U.S. Department of Agriculture Forest Service (2010), Timber Products Output (TPO) Reports. (Available at http://nrs.fs.fed.us/inventory_monitoring/inventory/tpo/, retrieved June 2010)

(USFS), US Forest Service (2005), Aerial Survey Geographic Information System Handbook. Sketchmaps to Digital Geographic Information.

Achard, F., Eva, H. D., Stibig, H., Mayaux, P., Gallego, J., Richards, T., and Malingreau, J. (2002), Determination of deforestation rates of the world's humid tropical forests, *Science*, *297*, (5583), 999-1002.

Adams, D. M., Alig, R. J., and McCarl, B. A. (1998), Ecological and economic impacts of forest policies: interactions across forestry and agriculture., *Ecological Economics*, *27*, (63-78),

Alberti, M. (2005), The effects of urban patterns on ecosystem function, *International Regional Science Review*, *28*, (2), 168-192.

Aldrich, R. C. (1975), Detecting disturbances in a forest environment, *Photogrammetric Engineering and Remote Sensing*, *41*, (1), 39-48.

Alig, R. J., Plantinga, A. J., Ahn, S., and Kline, J.D. (2003), Land use changes involving forestry in the United States: 1952 to 1997, with projections to 2050. Gen. Tech. Rep. PNW-GTR-587., 92 pp, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Alig, R. J., Plantinga, A. J., Haim, D., and Maribeth, T. (2010), Area changes in U.S. forests and other major land uses, 1982 to 2002, with projections to 2062. Gen. Tech. Rep. PNW-GTR-815, 98 pp, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station., Portland, Oregon.

Allen, T. F. H., and Star, T. B. (1982), *Hierarchy, Perspectives for Ecological Complexity*, 310 pp., Chicago Press, Chicago.

Allen, T. R., and Kupfer, J. A. (2000), Application of spherical statistics to change vector analysis of Landsat data: Southern Appalachian spruce-fir forests, *Remote Sensing of Environment*, *74*, (3), 482-493.

Amiro, B. D., Todd, J. B., Wotton, B. M., Logan, K. A., Flannigan, M. D., Stocks, B. J., Mason, J. A., Martell, D. L., and Hirsch, K. G. (2001), Direct carbon emissions from Canadian forest fires, 1959-1999, *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, *31*, 512 - 525.

Amiro, B. D., Barr, A. G., Barr, J. G., Black, T. A., Bracho, R., Brown, M., Chen, J., Clark, K. L., Davis, K. J., Desai, A. R., Dore, S., Engel, V., Fuentes, J. D., Goldstein, A. H., Goulden, M. L., Kolb, T. E., Lavigne, M. B., Law, B. E., Margolis, H. A., Martin, T., McCaughey, J. H., Misson, L., Montes-Helu, M., Noormets, A., Randerson, J. T., Starr, G., and Xiao, J. (2010), Ecosystem carbon dioxide fluxes after disturbance in forests of North America, *J. Geophys. Res.*, *115*, G00K02.

Amo, S. F. (2000), Fire in western forest ecosystems, in *Wildland Fire in Ecosystems: Effects of Fire on Flora. Gen. Tech. Rep. RMRS-42*, edited by Brown, J. K. and Smith, J. K., pp. 97-120, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT.

Baker, W. L. (1992), Effects of settlement and fire suppression on landscape structure, *Ecology*, *73*, (5), 1879-1887.

Barnes, B. V., Zak, D. R., Denton, S. R., and Spurr, S. H. (1998), *Forest Ecology*, 4th ed., Wiley, New York.

Bengt, H. (2006), World trade in forest products and wood fuel, *Biomass and Bioenergy*, *30*, (10), 815-825.

Bentley, M. L., and Mote, T. L. (1998), A climatology of Derecho-producing mesoscale convective systemsi n the central and eastern United States, 1986-95. Part I: Temporal and spatial distribution, *Bulletin of the American Meteorological Society*, *79*, 2527-2540.

Bentz, B. J., Régnière, J., Fettig, C. J., Hansen, E. M., Hayes, J. L., Hicke, J. A., Kelsey, R. G., Negrón, J. F., and Seybold, S. J. (2010), Climate change and bark beetles of the western United States and Canada: direct and indirect effects, *Bioscience*, *60*, (8), 602-613.

Birdsey, R. A., and Lewis, G. M. (2003), Current and historical trends in use, management, and disturbance of U.S. forestlands, in *The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect*, edited by Kimble, J. M. H., Linda S.; Birdsey, Richard A.; Lal, R., pp. 15-34, CRC Press, Boca Raton, FL.

Botkin, D. B., Janak, J. F., and Wallis, J. R. (1973), Estimating Effects of Carbon Fertilization on Forest Composition by Ecosystem Simulation, *Brookhaven Symposia in Biology*(24), 328-344.

Bowman, David M. J. S., Balch, Jennifer K., Artaxo, Paulo, Bond, William J., Carlson, Jean M., Cochrane, Mark A., D'Antonio, Carla M., DeFries, Ruth S., Doyle, John C., Harrison, Sandy P., Johnston, Fay H., Keeley, Jon E., Krawchuk, Meg A., Kull, Christian A., Marston, J. Brad, Moritz, Max A., Prentice, I. Colin, Roos, Christopher I., Scott, Andrew C., Swetnam, Thomas W., van der Werf, Guido R., and Pyne, Stephen J. (2009), Fire in the Earth System, *Science*, *324*, (5926), 481-484.

Bradford, J. B., Birdsey, R. A., Joyce, L. A., and Ryan, M. G. (2008), Tree age, disturbance history, and carbon stocks and fluxes in subalpine Rocky Mountain forests, *Global Change Biology*, *14*, 2882-2897.

Bradford, J. B., Weishampel, P., Smith, M. L., Kolka, R. K., Birdsey, R. A., Ollinger, S. V., and Ryan, M. G. (2010), Carbon pools and fluxes in small temperate forest landscapes: variability and implications for sampling design, *Forest Ecology and Management*, *259*, 1245-1254.

Brewer, C. K., Winne, J. C., Redmond, R. L., Opitz, D. W., and Mangrich, M. V. (2005), Classifying and mapping wildfire severity: A comparison of methods, *Photogrammetric Engineering and Remote Sensing*, *71*, (11), 1311-1320.

Brown, D. G., Johnson, K. M., Loveland, T. R., and Theobald, D. M. (2005), Rural land-use trends in the conterminous United States, 1950-2000, *Ecological Applications*, *15*, (6), 1851-1863.

Brown, J. K., and Smith, J. K. (2000), Wildland fire in ecosystems: effects of fire on flora.   Gen. Tech. Rep. RMRS-GTR-42-vol. 2. , 257 pp, USDA, Forest Service, Rocky Mountain Research Station, Ogden, UT.

Broyles, C., and Crosbie, C. (2010), Evidence of smaller tornado alleys across the United States based on a long track F3 to F5 tornado climatology study from 1880 to 2003, (Available at http://ams.confex.com/ams/11aram22sls/techprogram/paper_81872.htm, retrieved June 2009)

Burnett, C., and Blaschke, T. (2003), A multi-scale segmentation/object relationship modelling methodology for landscape analysis, *Ecological Modelling*, *168*, (3), 233-249.

Busing, R. T., and White, P. S. (1997), Species diversity and small-scale disturbance in an old-growth temperate forest: A consideration of gap partitioning concepts, *Oikos*, *78*, (3), 562-568.

Chambers, J. Q., Fisher, J. I., Zeng, H. C., Chapman, E. L., Baker, D. B., and Hurtt, G. C. (2007), Hurricane Katrina's carbon footprint on U. S. Gulf Coast forests, *Science, 318*, (5853), 1107-1107.

Clements, F. E. (1916), *Plant Succesion*, Carnegie Institute, Washington Pub 242.

Clinton, B. D. (2003), Light, temperature, and soil moisture responses to elevation, evergreen understory, and small, canopy gaps in the southern Appalachians, *Forest Ecology and Management*, *186*, (1-3), 243-255.

Cochran, William G. (1977), *Sampling Techniques*, 3 ed., John Wiley & Sons, New York.

Cocke, A. E., Fule, P. Z., and Crouse, J. E. (2005), Comparison of burn severity assessments using Differenced Normalized Burn Ratio and ground data, *International Journal of Wildland Fire*, *14*, (2), 189-198.

Cohen, W. B., and Goward, S. N. (2004), Landsat's role in ecological applications of remote sensing, *Bioscience*, *54*, (6), 535-545.

Cohen, W. B., Spies, T. A., Alig, R. J., Oetter, D. R., Maiersperger, T. K., and Fiorella, M. (2002), Characterizing 23 years (1972-95) of stand replacement disturbance in western Oregon forests with Landsat imagery, *Ecosystems*, *5*, (2), 122-

137.

Collins, S., Darr, D., Wear, D., and Brown, H. (2008), Global markets and the health of America's forests: A forest service perspective, *Journal of Forestry*, *106*, (1), 47-52.

Collins, S. L., and Smith, M. D. (2006), Scale-dependent interaction of fire and grazing on community heterogeneity in tallgrass prairie, *Ecology*, *87*, (8), 2058-2067.

Congalton, R. G. (1991), A review of the accuracy assesment of classification of remotely sensed data, *Remote Sensing of Environment*, *37*, 35-46.

Congalton, R. G., and Greene, K. (1999), *Assessing the Accuracy of Remotely Sensed Data: Principles and Practice*, 137 pp., CRC/Lewis Press, Boca Raton, FL.

Coniglio, M. C., Stensrud, D. J., and Richman, M. B. (2004), An observational study of Derecho-producing convective systems, *Weather & Forecasting*, *19*, (2), 320-337.

Coop, J. D., and Givnish, T. J. (2007), Spatial and temporal patterns of recent forest encroachment in montane grasslands of the Valles Caldera, New Mexico, USA, *Journal of Biogeography*, *34*, (5), 914-927.

Coops, N. C., Wulder, M. A., and White, J. C. (2007), Identifying and describing forest disturbance and spatial pattern: Data selection issues and methodoloical implications, in *Understanding Forest Disturbance and Spatial Pattern. Remote Sensing and GIS Approaches*, edited by Wulder, M. A. and Franklin, S. E., pp. 31-61, Taylor and Francis, Boca Raton.

Coppin, P., Jonckheere, I., Nackaerts, K., Muys, B., and Lambin, E. (2004), Digital change detection methods in ecosystem monitoring: a review, *International Journal of Remote Sensing*, *25*, (9), 1565-1596.

Costanza, R., Perez-Maqueo, O., Martinez, M. L., Sutton, P., Anderson, S. J., and Mulder, K. (2008), The value of coastal wetlands for hurricane protection, *Ambio*, *37*, (4), 241-248.

Coulson, R. N., McFadden, B. A, Pulley, P. E., Lovelady, C. N., Fitzgerald, J.W., and Jack, S. B. (1999), Heterogeneity of forest landscapes and the distribution and abundance of the southern pine beetle, *Forest Ecology and Management*, *114*, 471-

485.

Czaplewski, R. L. (2002), Can a sample of Landsat sensor scenes reliably estimate the global extent of tropical deforestation?, *International Journal of Remote Sensing*, *24*, 1409-1412.

Dale, V. H., Joyce, L. A., and McNulty, S. (2001), Climate change and forest disturbances, *Bioscience*, *51*, (9), 723 - 734.

De Fries, R. S., Hansen, M., Townshend, J. R. G., and Sohlberg, R. (1998), Global land cover classifications at 8 km spatial resolution: the use of training data derived from Landsat imagery in decision tree classifiers, *International Journal of Remote Sensing*, *19*, (16), 3141-3168.

DeFries, R. S., Hansen, M., and Townshend, J. R. G. (1995), Global discrimination of land cover types from metrics derived from AVHRR pathfinder data, *Remote Sensing of Environment*, *54*, (3), 209-222.

Delcourt, H. R., and Delcourt, P. A. (1988), Quaternary landscape ecology relevant scales in space and time, *Landscape Ecology*, *2*, (1), 23-44.

DellaSala, D. A., Staus, N. L., Strittholt, J. R., Hackman, A., and Lacobelli, A. (2001), An updated protected areas database for the United States and Canada, *Natural Areas Journal*, *21*, 124-135.

DNR), Wisconsin Department of Natural Resources (WI (2008), Wisconsin DNR. Guides for Predicting Gypsy Moth Damage for Forest Landowners. Pub-FR 195.

Drummond, M. A., and Loveland, T. R. (2010), Land-use pressure and a transition to forest-cover Loss in the eastern United States, *Bioscience*, *60*, (4), 286-298.

Dubayah, R. O., and Drake, J. B. (2000), Lidar remote sensing for forestry, *Journal of Forestry*, *98*, (6), 44-46.

Dudley, N., and Phillips, A. (2006), *Forests and Protected Areas: Guidance on the use of the IUCN protected area management categories*, International Union for Conservation of Nature (IUCN), Gland and Cambridge.

Eastman, J. R., and Fulk, M. (1993), Long sequence time-series evaluation using standardized principal components, *Photogrammetric Engineering and Remote Sensing*, *59*, (6), 991-996.

Eidenschenk, J., Schwind, B., Brewer, K. , Zhu, Z., Quayle, B. , and Howard, S. (2007), A project for monitoring trends in burn severity, *Fire Ecology Special Issue*, *3*, (1), 3-21.

Estes, J. E., and Thorley, G. A. (1983), Vol. II: Interpretation and Applications, in *Manual of Remote Sensing, 2nd ed.*, edited by Estes, J. E. and Thorley, G. A., American Society of Photogrammetry, Falls Church, Va.

Evans, A. M., and Perschel, R. (2009), A review of forestry mitigation and adaptation strategies in the Northeast US, *Climatic Change*, *96*, (1-2), 167-183.

Everham, E. M., and Brokaw, N. V. L. (1996), Forest damage and recovery from catastrophic wind, *Botanical Review*, *62*, (2), 113-185.

Fisher, J. I., Hurtt, G. C., Thomas, R. Q., and Chambers, J. Q. (2008), Clustered disturbances lead to bias in large-scale estimates based on forest sample plots, *Ecological Letters*, *11*, 554-563.

Foster, D. R. (1992), Land-use history (1730-1990) and vegetation dynamics in central New-England, USA, *Journal of Ecology*, *80*, (4), 753-772.

Foster, D. R., and Boose, E. R. (1995), Hurricane disturbance regimes in temperate and tropical forest ecosystems, *Wind and trees*305-339.

Foster, D. R., Knight, D. H., and Franklin, J. F. (1998), Landscape patterns and legaies resulting from large, infrequent forest disturbances, *Ecosystems*, *1*, 497-541.

Foster, D. R., Aber, J. D., Melillo, J. M., Bowden, R. D., and Bazzaz, F. A. (1997), Forest response to disturbance and anthropogenic stress, *Bioscience*, *47*, (7), 437-445.

Fox, T. R., Jokela, E. J., and Allen, H. L. (2004), The evolution of pine plantation silviculture in the Southern United States. In: Gen. Tech. Rep. SRS–75, 63-82 pp, U.S. Department of Agriculture, Forest Service, Southern Research Station., Asheville, NC.

Franklin, J. F. (1995), Sustainability of managed temperate forest ecosystems, in *Defining and Measuring Sustainability. The Biophysical Foundations*, edited by Munasinghe, M. and Shearer, W., pp. 355-385, The World Bank.

Frelich, L. E., and Lorimer, C. G. (1991), A simulation of landscape-level stand dynamics in the northern hardwood region, *Journal of Ecology*, *79*, (1), 223-233.

Frolking, S., Palace, M. W., Clark, D. B., Chambers, J. Q., Shugart, H. H., and Hurtt, G. C. (2009), Forest disturbance and recovery: A general review in the context of spaceborne remote sensing of impacts on aboveground biomass and canopy structure, *J. Geophys. Res.*, *114*,

Fry, J. A., Coan, M. J., Homer, C. G., Meyer, D. K., and Wickham, J. D. (2009), Completion of the National Land Cover Database (NLCD) 1992–2001 land cover change retrofit product: U.S. Geological Survey Open-File Report 2008–1379, 18 pg, (Available at http://pubs.usgs.gov/of/2008/1379/, retrieved June 2010)

Fujita, T. T. (1971), Proposed Characterization of Tornadoes and Hurricanes by Area and Intensity. Satellite and Mesometeorology Research Paper 91, edited, p. 42, Department of the Geophy. Sci., University of Chicago, Chicago, IL.

Gibbs, J. N., and Wainhouse, D. (1986), Spread of forest pests and pathogens in the northern hemisphere, *Forestry*, *59*, (2), 141-153.

Gillespie, A. J. R. (1999), Rationale for a national annual forest inventory program, *Journal of Forestry*, *97*, (12), 16 –20.

Goodale, C. L., Apps, M. J., Birdsey, R. A., Field, C. B., Heath, L. S., Houghton, R. A., Jenkins, J. C., Kohlmaier, G. H., Kurz, W. A., Liu, S. G., Nabuurs, G. J., Nilsson, S., and Shvidenko, A. Z. (2002), Forest carbon sinks in the northern hemisphere, *Ecological Applications*, *12*, (3), 891-899.

Goward, S. N., and Williams, D. L. (1997), Landsat and Earth systems science: development of terrestrial monitoring, *Photogrammetric Engineering and Remote Sensing*, *63*, (7), 887-900.

Goward, S. N., Cohen, W., Masek, J. G., Moisen, G., Huang, C., Kennedy, R., Schleeweis, K., and Thomas, N. (2012), Trends in U.S. forest disturbance 1984-2010 mapped from satellite time series, *in progress*

Goward, S. N., Masek, J. G., Cohen, W., Moisen, G., Collatz, G. J., Healey, S., Houghton, R., Huang, C., Kennedy, R., Law, B., Powell, S., Turner, D., and Wulder, M.A (2008), Forest disturbance and North American carbon flux, *Eos Transactions*, *89*, 105 -116.

Griffith, J. A., Stehman, S. V., and Loveland, T. R. (2003a), Landscape trends in Mid-Atlantic and southeastern United States ecoregions, *Environmental Management*, *32*, (5), 572-588.

Griffith, J. A., Stehman, S. V., Sohl, T. L., and Loveland, T. R. (2003b), Detecting trends in landscape pattern metrics over a 20-year period using a sampling-based monitoring programme, *International Journal of Remote Sensing*, *24,* (1), 175-181.

Gumpertz, M. L., Wu, C., and Pye, J. M. (2000), Logistic regression for southern pine beetle outbreaks with spatial and temporal autocorrelation, *Forest Science*, *46*, (1),

Gustafson, E. J. (1998), Clustering timber harvests and the effect of dynamic forest management policy on forest fragmentation, *Ecosystems*, *1*, (5), 484-492.

Haack, R. A, and Byler, J. W. (1993), Insects and pathogens regulators of forest ecosystems, *Journal of Forestry*, *91*, (9), 32-37.

Hall, F. G., Botkin, D. B., Strebel, D. E., Woods, K. D., and Goetz, S. J. (1991), Large-scale patterns of forest succession as determined by remote sensing, *Ecology*, *72*, (2), 628-&.

Hansen, M. C., Stehman, S. V., and Potapov, P. V. (2010a), Quantification of global gross forest cover loss, *Proceedings of the National Academy of Sciences*, *107,* (19), 8650-8655.

Hansen, M. C., Stehman, S. V., and Potapov, P. V. (2010b), Reply to Reams et al.: Quantifying forest cover change at local and global scales, *Proceedings of the National Academy of Sciences*, *107,* (38), E146.

Hansen, M. C., Defries, R. S., Townshend, J. R. G., and Sohlberg, R. (2000), Global land cover classification at 1km spatial resolution using a classification tree approach, *International Journal of Remote Sensing*, *21*, (6-7), 1331-1364.

Hansen, M. C., Townshend, J. R. G., Defries, R. S., and Carroll, M. (2005), Estimation of tree cover using MODIS data at global, continental and regional/local scales, *International Journal of Remote Sensing*, *26*, (19), 4359-4380.

Hastings, A. (2003), Metapopulation persistence with age-dependent disturbance or succession, *Science*, *301*, (5639), 1525-1526.

Haynes, R. W. (2002), Forest management in the 21st century: changing number, changing context, *Journal of Forestry*, *100*, (2), 38-43.

He, L., Chen, J. M., Zhang, S., Gomez, G., Pan, Y., McCullough, K., Birdsey, R. A., and Masek, J. G. (2011), Normalized algorithm for mapping and dating forest disturbances and regrowth for the United States, *International Journal of Applied Earth Observation and Geoinformation*, *13*, (2), 236-245.

Healey, S. P., Cohen, W. B., Yang, Z. Q., and Krankina, O. N. (2005), Comparison of tasseled cap-based Landsat data structures for use in forest disturbance detection, *Remote Sensing of Environment*, *97*, (3), 301-310.

Heath, L. S., Birdsey, R. A., Row, C., and Plantinga, A. J. (1996), Carbon pools and flux in U.S. forest products, in *Forest Ecosystems, Forest Management, and the Global Carbon Cycle. NATO ASI Series I: Global Environmental Changes*, edited by Apps, M. J. and Price, D. T., pp. 271-278, Springer Verlag, Keiner.

Hermy, M., and Verheyen, K. (2007), Legacies of the past in the present-day forest biodiversity: a review of past land-use effects on forest plant species composition and diversity, *Ecological Research*, *22*, (3), 361-371.

Homer, C., Dewitz, J., Fry, J., Coan, M., Hossain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J. N., and Wickham, J. (2007), Completion of the 2001 National Land Cover Database for the conterminous United States, *Photogrammetric Engineering and Remote Sensing*, *73*, (4), 337-341.

Hooper, R. G., and McAdie, C. J. (1995), Hurricanes and the long-term management of the red-cockaded woodpecker., in *Red-cockaded Woodpecker: Recovery, Ecology and Management.* , edited by Kulhavy, K. L., Hooper, R. G. and Costa, R., pp. 148-

166, Stephen F. Austin State Universisty, Nacogdoches, TX.

Houghton, R. A., and Hackler, J. L. (2000), Changes in terrestrial carbon storage in the United States. 1: The roles of agriculture and forestry, *Global Ecology and Biogeography*, *9*, (2), 125-144.

Houghton, R. A., Hackler, J. L., and Lawrence, K. T. (1999), The U.S. carbon budget: contributions from land-use change, *Science*, *285*, (5427), 574-578.

Houghton, R. A., Hackler, J. L. , and Lawrence, K. T. (2000), Changes in terrestrial carbon storage in the United States. 2: The role of fire and fire management, *Global Ecology & Biogeography*, *9*, (2), 145-170.

Huang, C., Schleeweis, K., Thomas, N. , and N., Goward S. (in press), Forest dynamics within and around the Olympic National Park assessed using time series Landsat observations., in *Remote Sensing of Protected Lands*, edited by Wang, Y., Taylor & Francis, London.

Huang, C., Schleeweis, K., Goward, S. N., and Thomas, N. (in progress), Assessment of biennial vs. annual Landsat time-series stacks for forest history mapping

Huang, C., Goward, S. N., Masek, J. G., Thomas, N., Zhu, Z., and Vogelmann, J. E. (2010), An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks, *Remote Sensing of Environment*

Huang, C., Goward, S. N., Masek, J. G., Gao, F., Vermote, E. F., Thomas, N., Schleeweis, K., Kennedy, R. E., Zhu, Z., Eidenschenk, J. C., and Townshend, J. R. G. (2009), Development of time series stacks of Landsat images for reconstructing forest disturbance history, *International Journal of Digital Earth*(2), 195-218.

Hurtt, G. C., Dubayah, R., Jason, D., Moorcroft, P. R., Pacala, S. W., Blair, J. B., and Fearon, M. G. (2004), Beyond potential vegetation: combining lidar data and a height-structured model for carbon studies, *Ecological Applications*, *14*, (3), 873-883.

Jackson, R. B., Jobbagy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., Farley, K. A., le Maitre, D. C., McCarl, B. A., and Murray, B. C. (2005), Trading water for carbon with biological sequestration, *Science*, *310*, (5756), 1944-1947.

Jacobs, D. M. (2007), Forest inventory, catastrophic events and historical geospatial assessments in the South, paper presented at ASPRS Annual Conference Tampa, Florida, May 7-11

Jin, S. M., and Sader, S. A. (2005), MODIS time-series imagery for forest disturbance detection and quantification of patch size effects, *Remote Sensing of Environment*, *99*, (4), 462-470.

Jin, S. M., and Sader, S. A. (2006), Effects of forest ownership and change on forest harvest rates, types and trends in northern Maine, *Forest Ecology and Management*, *228*, (1-3), 177-186.

Johnson, E. W., and Wittwer, D. (2008), Aerial detection surveys in the United States, *Australian Forestry*, *71*, (3), 212-215.

Johnson, E. W., and Ross, J. (2008), Quantifying error in aerial survey data, *Australian Forestry*, *71*, (3),

Johnson, T. G. (Ed.) (2001), *United States Timber Industry—An assessment of timber product output and use, 1996. Gen. Tech. Rep. SRS–45*, 145 pp., U.S. Department of Agriculture, Forest Service, Southern Research Station., Asheville, NC.

Kennedy, R. E., Cohen, W. B., and Schroeder, T. A. (2007), Trajectory-based change detection for automated characterization of forest disturbance dynamics, *Remote Sensing of Environment*, *110*, (3), 370-386.

Kennedy, R. E., Cohen, W. B., Moisen, G. G., Goward, S. N., Wulder, M., Powell, S. L., Masek, J. G., Huang, C., and Healey, S. P. (2006), A sample design for Landsat-based estimation of national trends in forest disturbance and regrowth., paper presented at NASA Joint Workshop on Biodiversity, Terrestrial Ecology and Related Applied Sciences, College Park, MD, August, 21-25, 2006.

Krist, F. J., Sapio, F. J., and Tkacz, B. M. (2006), Mapping Risk from Forest Insects and Disease. GTR FHTET 2007-06, Forest Health Technology Enterprise Team.

Kurz, W. A. (2010), An ecosystem context for global gross forest cover loss estimates, *Proceedings of the National Academy of Sciences*, *20*, 9025-9026.

Kurz, W. A., Stinson, G., Rampley, G. J., Dymond, C. C., and Neilson, E. T. (2008), Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain, *Proceedings of the National Academy of Sciences*, *105*, (5), 1551-1555.

Kurz, W. A., Dymond, C. C., White, T. M., Stinson, G., Shaw, C. H., Rampley, G. J., Smyth, C., Simpson, B. N., Neilson, E. T., Trofymow, J. A., Metsaranta, J., and Apps, M. J. (2009), CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards, *Ecological Modelling*, *220*, (4), 480-504.

Laiho, R., Sanchez, F., Tiarks, A., Dougherty, P. M., and Trettin, C. C. (2003), Impacts of intensive forestry on early rotation trends in site carbon pools in the southeastern US, *Forest Ecology and Management*, *174*, (1-3), 177-189.

Lambin, E. F., and Strahler, A. H. (1994), Indicators of land-cover change for change-vector analysis in multitemporal space at coarse spatial scales, *International Journal of Remote Sensing*, *15*, (10), 2099-2119.

Landers, J. L., Vanlear, D. H., and Boyer, W. D. (1995), The longleaf pine forests of the southeast - requiem or renaissance, *Journal of Forestry*, *93*, (11), 39-44.

Larouche, C., Ruel, J. C., and Belanger, L. (2007), Effect of dispersed patterns of patch cuttings on the damages caused by windthrow: study of the case in the white birch plantation of the East, *Forestry Chronicle*, *83*, (1), 84-91.

Lawrence, R. L., and Ripple, W. J. (1999), Calculating change curves for multitemporal satellite imagery: Mount St. Helens 1980-1995, *Remote Sensing of Environment*, *67*, (3), 309-319.

Lefsky, M. A., and Cohen, W. B. (2003), Selection of remotely sensed data, in *Remote Sensing of Forest Environments: Concepts and Case Studies*, edited by M, W. and S, F., pp. 13-46, Kluwer Academic, Boston.

Lefsky, M. A., Cohen, W. B., Parker, G. G., and Harding, D. J. (2002), Lidar remote sensing for ecosystem studies, *Bioscience*, *52*, (1), 19-30.

Levin, S. A. (1992), The problem of pattern and scale in ecology, *Ecology*, *73*, (6), 1943-1967.

Lindenmayer, D. B., Foster, D. R., Franklin, J. F., Hunter, M. L., Noss, R. F., Schmiegelow, F. A., and Perry, D. (2004), Salvage harvesting policies after natural disturbance, *Science*, *303*, (5662), 1303.

Linke, J., Betts, M. G., Lavigne, M. B., and Franklin, S. E. (2007), Introduction: structure, function, and change of forest landscapes, in *Understanding Forest Disturbance and Spatial Pattern*, edited by Wulder, M. A. and Franklin, S. E., CRC Press, Boca Raton, FL.

Liu, K. B., Lu, H. Y., and Shen, C. M. (2008), A 1200-year proxy record of hurricanes and fires from the Gulf of Mexico coast: Testing the hypothesis of hurricane-fire interactions, *Quaternary Research*, *69*, 29-41.

Lorimer, C. G. (1985), Methodological considerations in the analysis of forest disturbance history, *Can. J. For. Research*, *15*, 200-213.

Lorimer, C. G. (2001), Historical and ecological roles of disturbance in eastern North American forests: 9,000 years of change, *Wildlife Society Bulletin*, *29*, (2), 425-439.

Lorimer, C. G., and White, A. S. (2003), Scale and frequency of natural disturbances in the northeastern US: implications for early successional forest habitats and regional age distributions, *Forest Ecology and Management*, *185*, (1-2), 41-64.

Loveland, T. R., and Belward, A. S. (1997), The IGBP-DIS global 1km land cover data set, DISCover: First results, *International Journal of Remote Sensing*, *18*, (15), 3289-3295.

Loveland, T. R., Sohl, T., Sayler, K., Gallant, A. L., Dwyer, J. F., Vogelmann, J. E., and Zylstra, G. (1999), Land cover trends: rates, cuases, and consequences of late-twentieth century U.S. land cover change. EPA/600/R-99/105, US Environmental Protection Agency, Washington, DC.

Lu, D., Mausel, P., Brondizio, E., and Moran, E. (2004), Change detection techniques, *International Journal of Remote Sensing*, *25*, (12), 2365-2407.

Lunetta, R. S., Johnson, D. M., Lyon, J. G., and Crotwell, J. (2004), Impacts of imagery temporal frequency on land-cover change detection monitoring, *Remote Sensing of Environment*, *89*, (4), 444-454.

Lunetta, R. S., Knight, J. F., Ediriwickrema, J., Lyon, J. G., and Worthy, L. D. (2006), Land-cover change detection using multi-temporal MODIS NDVI data, *Remote Sensing of Environment*, *105*, (2), 142-154.

MacArthur, R. H., and Wilson, E. O. (1967), *Theory of Island Biogeography*, Princeton University Press, Princeton , N.J.

Macie, E. A., and Hermansen, L.A. (2002), Human Influences on Forest Ecosystems. The Southern Wildland-Urban Interface Assessment. General Technical Report SRS-55., 160 pp, Ashville, NC.

Malamud, B. D., Millington, J. D. A., and Perry, G. L. W. (2005), Characterizing wildfire regimes in the United States, *Proceedings of the National Academy of Sciences*, *102*, (13), 4694-4699.

Markham, B. L., Storey, J. C., Williams, D. L., and Irons, J. R. (2004), Landsat sensor performance: history and current status, *Geoscience and Remote Sensing, IEEE Transactions on*, *42*, (12), 2691-2694.

Martinson, S., Hofstetter, R. W., and Ayres, M. P. (2007), Why does longleaf pine have low susceptibility to southern pine beetle?, *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, *37*, 1966-1977.

Masek, J. G., and Collatz, G. J. (2006), Estimating forest carbon fluxes in a disturbed southeastern landscape: Integration of remote sensing, forest inventory, and biogeochemical modeling, *Journal of Geophysical Research-Biogeosciences*, *111*, (G1),

Masek, J. G., Huang, C. Q., Wolfe, R., Cohen, W., Hall, F., Kutler, J., and Nelson, P. (2008), North American forest disturbance mapped from a decadal Landsat record, *Remote Sensing of Environment*, *112*, (6), 2914-2926.

Masek, J. G., Vermote, E. F., Saleous, N. E., Wolfe, R., Hall, F. G., Huemmrich, K. F., Goa, F., Kutler, J., and Lim, T. (2006), A Landsat surface reflectance dataset for North America, 1990–2000, *IEEE Geoscience and Remote Sensing Letters*, *3,* (1), 68-72.

McIntire, E. J. B., and Fortin, M. J. (2006), Structure and function of wildfire and mountain pine beetle forest boundaries, *Ecography*, *29*, (3), 309-318.

McNulty, S. G. (2002), Hurricane impacts on US forest carbon sequestration, *Environmental Pollution*, *116*, S17-S24.

McNulty, S. G., Vose, J. M., and Swank, W. T. (1996), Loblolly pine hydrology and productivity across the southern United States, *Forest Ecology and Management*, *86*, (1-3), 241-251.

Mildrexler, D. J., Zhao, M., Heinsch, F. A., and Running, S. W. (2007), A new satellite-based methodology for continental-scale disturbance detection, *Ecological Applications*, *17*, (1), 235-250.

Miller, D. H. (1978), The factor of scale: ecosystem, landscape mosaic, and region, in *Sourcebook on the Environmnet*, edited by Hammond, K. A., G., M. and W., F., University of Chicago Press, Chicago.

Miller, Matthew D. (2012), The impacts of Atlanta's urban sprawl on forest cover and fragmentation, *Applied Geography*, *34*, (0), 171-179.

Mitchell, R. J., Hiers, J. K., O'Brien, J. J., Jack, S. B., and Engstrom, R. T. (2006), Silviculture that sustains: the nexus between silviculture, frequent prescribed fire, and conservation of biodiversity in longleaf pine forests of the southeastern United States, *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, *36*, (11), 2724-2736.

Morgan, P., Hardy, C. C., Swetnam, T. W., Rollins, M. G., and Long, D. G. (2001), Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns, *International Journal of Wildland Fire*, *10*, 329-342.

Morgan, T. A., Spoelma, T. P., Keegan, C. E. , Chase, A. L., and Thompson, M. T. (2005), Wyoming's forest Products Industry and Timber Harvest, 2000. Resource Bulletin. RMRS-RB-5., Rocky Mountain Research Center, Fort Collins, CO.

Murray, B. C., Prisley, S. P., Birdsey, R. A., and Sampson, R. N. (2000), Carbon sinks in the Kyoto Protocol - potential relevance for US forests, *Journal of Forestry*, *98*, (9), 6-11.

Nagubadi, R., and Zhang, D. W. (2005), Determinants of timberland use by ownership and forest type in Alabama and Georgia, *Journal of Agricultural and Applied Economics*, *37*, (1), 173-186.

Nash, R. (1967), *Wilderness and the American Mind*, Yale University Press, New Haven, CT.

Nelson, J. L., Groninger, J. W., Battaglia, L. L., and Ruffner, C. M. (2008), Bottomland hardwood forest recovery following tornado disturbance and salvage logging, *Forest Ecology and Management*, *256*, (3), 388-395.

Nelson, M. D., and Vissage, J. (2007), Mapping forest inventory and analysis forest land use: timberland, reserved forest land, and other forest land. Gen. Tech. Rep. WO-77, paper presented at The seventh annual forest inventory and analysis symposium, Washington, DC: U.S. Department of Agriculture, Forest Service:, Portland, ME.

Nelson, M. D., Healey, S., Moser, W. K., and Hansen, M. H. (2009), Combining satellite imagery with forest inventory data to assess damage severity following a major blowdown event in northern Minnesota, USA, *International Journal of Remote Sensing*, *30*, (9), 5089-5108.

Nonaka, E., and Spies, T. A. (2005), Historical range of variability in landscape structure: A simulation study in Oregon, USA, *Ecological Applications*, *15*, (5), 1727-1746.

Noss, R. F., Franklin, J. F., Baker, W. L., Schoennagel, T., and Moyle, P. B. (2006), Managing fire-prone forests in the western United States, *Frontiers in Ecology and the Environment*, *4*, 481 - 487.

Nowak, D. J., and Crane, D. E. (2002), Carbon storage and sequestration by urban trees in the USA, *Environmental Pollution*, *116*, (3), 381-389.

Nowak, D. J., Walton, J. T., Dwyer, J. F., Kaya, L. G., and Myeong, S. (2005), The increasing influence of urban environments on US forest management, *Journal of Forestry*, *103*, (8), 377-382.

Nusser, S. M., and Goebel, J. J. (1997), The National Resources Inventory: a long-term multi-resource monitoring programme, *Environmental and Ecological Statistics*, *4*, (3), 181-204.

O'Neill, R. V. (1988), Hierarchy theory and global change, in *Scales and global change. Spatial and temporal variability in biospheric and geospheric processes.*

SCOPE edited by Rosswall T, W. R. G., Risser, P.G., pp. 29-45, John Wiley & Sons ltd., Chichester.

Ohmann, J. L., Gregory, M. T., and Spies, T. A. (2007), Influence of environment, disturbance, and ownership on forest vegetation of coastal Oregon, *Ecological Applications*, *17*, (1), 18-33.

Oliver, C. D., and Larson, B. C. (1990), *Forest Stand Dynamics*, 467 pp., McGraw-Hill, New York.

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'Amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Colby, J. L., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., and Kassem, K. R. (2001), Terrestrial ecoregions of the world: A new map of Liife on Earth, *Bioscience*, *51*, (11), 933-938.

Pacala, S. W., Bridgham, S. D., Conant, R. T. , Davis, K., Hales, B., Houghton, R. A., Jenkins, J. C., Johnston, M., Marland, G., and Paustian, K. (2007), The North American carbon budget past and present, in *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle*, edited by Research, U. S. C. C. S. P. a. t. S. o. G. C., National Oceanic and Atmospheric Administration, National Climatic Data Center, Ashville, NC.

Pacala, S. W., Hurtt, G. C., Baker, D., Peylin, P., Houghton, R. A., Birdsey, R. A., Heath, L., Sundquist, E. T., Stallard, R. F., Ciais, P., Moorcroft, P., Caspersen, J. P., Shevliakova, E., Moore, B., Kohlmaier, G., Holland, E., Gloor, M., Harmon, M. E., Fan, S. M., Sarmiento, J. L., Goodale, C. L., Schimel, D., and Field, C. B. (2001), Consistent land- and atmosphere-based US carbon sink estimates, *Science*, *292*, (5525), 2316-2320.

Pan, Y., Chen, J.M., Birdsey, R. A., McCullough, L., He, L., and Deng, F. (2010), Age structure and disturbance legacy of North American forest, *Biogeosciences Discuss.*, *7*, 979-1020.

Papaik, M. J., and Canham, C. D. (2006), Species resistance and community response to wind disturbance regimes in northern temperate forests, *Journal of Ecology*, *94*, (5), 1011-1026.

Peterson, C. J. (2000), Catastophic wind damage to North American forests and the potential impact of climate change, *Science of the total environment*, *262*, (3), 287-311.

Peterson, C. J., and Pickett, S. T. A. (2000), Patch type influences on regeneration in a western Pennsylvania, USA, catastrophic windthrow, *Oikos*, *90*, (3), 489-500.

Peterson, G.D. (2002), Contagious disturbance, ecological memory, and the emergence of landscape pattern, *Ecosystems*, *5*, (4), 329-338.

Pickett, S. T. A., and White, P. S. (1985), *The Ecology of Natural Disturbance and Patch Dynamics*, Princeton University Press, Princeton, New Jersey, USA.

Pierce, D. J., Buchanan, J. B., Cosentino, B. L. , and Snyder, S. (2005), An Assessment of Spotted Owl Habitat on Non-federal Lands in Washington between 1996 and 2004. Final Report, 187 pp, Washington Department of Fish and Wildlife, Olympia, Washington.

Plantinga, A. J., Alig, R. J., and Cheng, H. (2001), The supply of land for conservation uses: evidence from the conservation reserve program, *Resources, Conservation and Recycling*, *31*, (3), 199-215.

Polyakov, M., Majumdar, I., and Teeter, L. (2008), Spatial and temporal analysis of the anthropogenic effects on local diversity of forest trees, *Forest Ecology and Management*, *255*, (5-6), 1379-1387.

Potter, C., Tan, P. N., Kumar, V., Kucharik, C., Klooster, S., Genovese, V., Cohen, W., and Healey, S. (2005), Recent history of large-scale ecosystem disturbances in North America derived from the AVHRR satellite record, *Ecosystems*, *8*, (7), 808-824.

Powell, M. D., Murillo, S., Dodge, P., Uhlhorn, E., Gamache, J., Cardone, V., Cox, A., Otero, S., Carrasco, N., Annane, B., and Fleur, R. St (2010), Reconstruction of Hurricane Katrina's wind fields for storm surge and wave hindcasting, *Ocean Engineering*, *37*, (1), 26-36.

Prestemon, J. P., Pye, J. M., and Holmes, T. P. (2001), Timber economics of natural catastrophes, in *Proceedings of the 2000 Southern Forest Economics Workshop*, edited, Lexington, KY.

Price, T. S., Dogget, H. C., Pye, J. M., and Smith, B. (1997), A history of southern pine beetle outbreaks in the southestern United States, 72 pp, Georgia Forestry Commission, Macon, Georgia.

Radeloff, V. C., Mladenoff, D. J., and Boyce, M. S. (2000), Effects of interacting disturbances on landscape patterns: budworm defoliation and salvage logging, *Ecological Applications*, *10*, (1), 233-247.

Radeloff, V. C., Hammer, R. B., and Stewart, S. I. (2005a), Rural and suburban sprawl in the US Midwest from 1940 to 2000 and its relation to forest fragmentation, *Conservation Biology*, *19*, (3), 793-805.

Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., and McKeefry, J. F. (2005b), The wildland-urban interface in the United States, *Ecological Applications*, *15*, (3), 799-805.

Raffa, K. F., Aukema, B. H., Bentz, B. J., Carroll, A. L., Hicke, J. A., Turner, M. G., and Romme, W. H. (2008), Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of bark beetle eruptions, *Bioscience*, *58*, (6), 501-517.

Reams, G. A., Brewer, C. K., and Guldin, R. W. (2010), Remote sensing alone is insufficient for quantifying changes in forest cover, *Proceedings of the National Academy of Sciences*, *107*, (38), E145.

Reilly, M. J., Wimberly, M. C., and Newell, C. L. (2006), Wildfire effects on plant species richness at multiple spatial scales in forest communities of the southern Appalachians, *Journal of Ecology*, *94*, (1), 118-130.

Roberts, M. J., and Lubowski, R. N. (2007), Enduring impacts of land retirement policies: evidence from the Conservation Reserve Program, *Land Economics*, *83*, (4), 516-538.

Robinson, G., and Zappieri, J. (1999), Conservation policy in time and space: lessons from divergent approaches to salvage logging on public lands, *Ecology and Society*, *3*, (1),

Ruefenacht, B., Finco, M. V., Nelson, M. D., Czaplewski, R., Helmer, E. H., Blackard, J. A., Holden, G. R., Lister, A. J., Salajanu, D., and Weyermann, K. (2008), Conterminous US and Alaska forest type mapping using Forest Inventory and Analysis data, *Photogrammetric Engineering and Remote Sensing*, *74*, (11), 1379-1388.

Rydgren, K., Økland, R. H., and Hestmark, G. (2004), Disturbance severity and community resilience in a boreal forest, *Ecology*, *85*, (7), 1906-1915.

Sader, S. A., Jin, S. M., Metzler, J. W., and Hoppus, M. (2006), Exploratory analysis of forest harvest and regeneration pattern among multiple landowners, *Forestry Chronicle*, *82*, (2), 203-210.

Samman, S., and Logan, J. (2000), Assessment and response to bark beetle outbreaks in the Rocky Mountain area. Gen. Tech. Rep. RMRS-GTR-62, 46 pp, Ogden, Utah.

Saveland, J. M., and Wade, D. D. (1991), Fire management ramifications of Hurricane Hugo, paper presented at 11th Conference on Fire and Forest Meteorology, Society of American Foresters, Missoula, MT, April 16-19, 1991.

Schneider, A., and Woodcock, C. E. (2008), Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census information, *Urban Studies*, *45*, (3), 659-692.

Schoennagel, T., Veblen, T. T., and Romme, W. H. (2004a), The interaction of fire, fuels, and climate across rocky mountain forests, *Bioscience*, *54*, (7), 661-676.

Schoennagel, T., Waller, D. M., Turner, M. G., and Romme, W. H. (2004b), The effect of fire interval on post-fire understorey communities in Yellowstone National Park, *Journal of Vegetation Science*, *15*, (6), 797-806.

Schroeder, T. A., Cohen, W. B., and Yang, Z. Q. (2007), Patterns of forest regrowth following clearcutting in western Oregon as determined from a Landsat time-series, *Forest Ecology and Management*, *243*, (2-3), 259-273.

Schroeder, T. A., Wulder, M. A., Healey, S. P., and Moisen, G. G. (2011), Mapping wildfire and clearcut harvest disturbances in boreal forests with Landsat time series data, *Remote Sensing of Environment*, *115*, (6), 1421-1433.

Schwind, B., Brewer, K., Quayle, B., and Eidenschenk, J. C. (2010), Establishing a nationwide baseline of historical burn-severity data to support monitoring of trends in wildfire effects and national fire policies, *U S Forest Service Pacific Northwest Research Station General Technical Report PNW-GTR*(802, Part 2), 381-396.

Seymour, R. S., White, A. S., and deMaynadier, P. G. (2002), Natural disturbance regimes in northeastern North America - evaluating silvicultural systems using natural scales and frequencies, *Forest Ecology and Management*, *155*, (1-3), 357-367.

Shapiro-Miller, L. B., Heyerdahl, E. K., and Morgan, P. (2007), Comparison of fire scars, fire atlases, and satellite data in the northwestern United States, *Canadian Journal of Forest Research*, *37*, (10), 1933-1943.

Sheffield, R. M., and Thompson, M. T. (1992), Hurricane Hugo - effects on South-Carolinas forest resource, *Usda Forest Service Southeastern Forest Experiment Station Research Paper*(SE-284), 1-51.

Skole, D., and Tucker, C. J. (1993), Evidence for tropical deforestation, fragmented habitat, and adversely affected habitat in the Brazilian Amazon: 1978–1988, *Science*, *260*, (5116), 1905-1910.

Smith, J. E., and Heath, L. S. (2008), Carbon stocks and stock changes in U.S. forests. USDA :U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2005, *Technical Bulletin No. 1921*, 28 p. pp, Technical Bulletin No. 1921. Washington, DC: Office of the Chief Economist: 65-80, C1-C7.

Smith, J. E., Heath, L. S., Skog, K. E., and Birdsey, R. A. (2006), Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343, 216 p. pp, U.S. Department of Agriculture, Forest Service, Northeastern Research Station.

Smith, W. B. (personal communication), edited.

Smith, W. B., and Darr, D. (2004), U.S. forest resource facts and historical trends, 40 pp, US Department of Agriculture Publication FS-801.

Smith, W. B., Miles, P. D., Vissage, J. S., and Pugh, S. A. (2004), Forest Resources of the United States, 2002. General Techincal Report NC-241. , St. Paul, MN:.

Smith, W. B., Miles, P. D., Perry, C. H., and Pugh, S. A. (2009), Forest Resources of the United States, 2007. Gen. Tech. Rep. WO-78, U.S. Department of Agriculture, Forest Service.

Song, C. H., and Woodcock, C. E. (2003), A regional forest ecosystem carbon budget model: impacts of forest age structure and landuse history, *Ecological Modelling*, *164*, (1), 33-47.

Sousa, W. P. (1979), Disturbance in marine intertidal boulder fields: The nonequilibrium maintenance of species diversity, *Ecology*, *60*, (6), 1225-1239.

Sousa, W. P. (1984), The role of disturbance in natural communities, *Annual Review of Ecology and Systematics*, *15*, 353-391.

Stanturf, J. A., Wade, D. D., Waldrop, T. A., Kennard, D. K., and Achtemeier, G. L. (2002), Fire in southern forest landscapes in *Southern Forest Resource Assessment*, edited by Wear, D. M. a. G., J. , pp. 607-630, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC.

Stehman, S. V. (2005), Comparing estimators of gross change derived from complete coverage mapping versus statistical sampling of remotely sensed data, *Remote Sensing of Environment*, *96*, (3-4), 466-474.

Stein, S. M., McRoberts, R. E., Alig, R. J., Nelson, M. D., Theobald, D. M., Eley, M., Dechter, M., and Carr, M. (2005), Forests on the Edge: housing development on America's private forests. Gen Tech. Re. PNW-GTR-636, 16 pp, Portland, OR.

Stephens, S. L. (2005), Forest fire causes and extent on United States Forest Service lands, *International Journal of Wildland Fire*, *14*, (3), 213-222.

Stephens, S. L., and Ruth, L. W. (2005), Federal forest-fire policy in the United States, *Ecological Applications*, *15*, (2), 532-542.

Stephens, S. L., Moghaddas, J. J., Edminster, C., Fieldler, C. E. , Hasse, S., Harrington, M., Keeley, J. E., Knapp, E. E., McIver, J. D., Metlen, K., Skinner, C. N., and Youngblood, A. (2009), Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests, *Ecological Applications*, *19*, (2), 305-320.

Stueve, K. M., Housman, I. W., Zimmerman, P. L., Nelson, M. D., Webb, J. B., Perry, C. H., Chastain, R. A., Gormanson, D. D., Huang, C., Healey, S. P., and

Cohen, W. B. (2011), Snow-covered Landsat time series stacks improve automated disturbance mapping accuracy in forested landscapes, *Remote Sensing of Environment*, *15*, (12), 3203–3219.

Sun, G., McNulty, S. G., Lu, J., Amatya, D. M., Liang, Y., and Kolka, R. K. (2005), Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States, *Journal of Hydrology*, *308*, (1-4), 258-268.

Sun, G., McNulty, S. G., Shepard, J. P., Amatya, D. M., Riekerk, H., Comerford, N. B., Skaggs, W., and Swift, L. (2001), Effects of timber management on the hydrology of wetland forests in the southern United States, *Forest Ecology and Management*, *143*, (1-3), 227-236.

Tarrega, R., Calvo, L., Marcos, E., and Taboada, A. (2006), Forest structure and understory diversity in Quercus pyrenaica communities with different human uses and disturbances, *Forest Ecology and Management*, *227*, (1-2), 50-58.

Theobald, D. M. (2005), Landscape patterns of exurban growth in the USA from 1980 to 2020, *Ecology and Society*, *10*, (1),

Thomas, N. E., Huang, C., Goward, S. N., Powell, S., Rishmawi, K., Schleeweis, K., and Hinds, A. (2011), Validation of North American forest disturbance dynamics derived from Landsat time series stacks, *Remote Sensing of Environment*, *115*, (1), 19-32.

Thomas, W. L. Jr. (Ed.) (1954), *Man's Role in Changing the Face of the Earth*, 817 pp., University of Chicago, Chicago.

Townshend, J. R. G., and Justice, C. O. (1988), Selecting the spatial resolutions of satellite sensors required for global monitoring of land transformations, *Int. J. Remote Sensing*, *9*, 187-236.

Townshend, J. R. G., Justice, C. O., and Kalib, V. T. (1987), Characterization and classification of South American land cover types using satellite data, *Int. J. Remote Sensing*, *8*, 1189-1207.

Trani, M. K., Brooks, R. T., Schmidt, T. L., Rudis, V. A., and Gabbard, C. M. (2001), Patterns and trends of early successional forests in the Eastern United States, *Wildlife*

Society Bulletin, *29*, (2), 413-424.

Tucker, C. J., and Townshend, J. R. G. (2000), Strategies for monitoring tropical deforestation using satellite data, *International Journal of Remote Sensing*, *21*, (6-7), 1461-1471.

Tucker, C. J., Townshend, J. R. G., and Goff, T. E. (1985), African land-cover classification using satellite data, *Science*, *227*, 369-375.

Turner, D. P., Koerper, G. J., Harmon, M. E., and Lee, J. J. (1995), A carbon budget for forests of the conterminous United States, *Ecological Applications, 5*, (2), 421-436.

Turner, M. G., Romme, W. H., and Gardner, R. H. (1994), Landscape disturbance models and the long-term dynamics of natural areas, *Natural Areas Journal*, *14*, (1), 3-11.

Turner, M. G., Gardner, R. H. , and ONeill, R. V. O (2001), *Landscape ecology in theory and practice*, Springer-Verlag, New York.

Turner, M. G., Baker, W. L., Peterson, C. J., and Peet, R. K. (1998), Factors influencing succession: lessons from large, infrequent natural disturbances, *Ecosystems*, *1*, (6), 511-523.

UNFCCC, (1997), Kyoto Protocol to the United Nations Framework Convention on Climate Change,UNFCC document FCC/CP/1997/7/Add.I.

USDA, NRCS (2009), Summary Report: 2007 National Resources Inventory, 123 pg, (Available at

http://www.nrcs.usda.gov/technical/NRI/2007/2007_NRI_Summary.pdf, retrieved June 2009)

Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melillo, J. M. (1997), Human domination of Earth's ecosystems, *Science*, *277*, (5325), 494-499.

Vogelmann, J. E., Tolk, B., and Zhu, Z. (2009), Monitoring forest changes in the southwestern United States using multitemporal Landsat data, *Remote Sensing of*

Environment, *113*, (8), 1739-1748.

Vogelmann, J. E., Howard, S.M., Yang, L., Larson, C.R., Wylie, B.K., and Van Driel, N. (2001), Completion of the 1990s National Land Cover Data set for the conterminous United States from Landsat thematic mapper data and ancillary data sources, *Photogrammetric Engineering & Remote Sensing*, *67*, 650-662.

Vogelmann, J. E., Kost, J.R., Tolk, B., Howard, S., Short, K., Chen, X., Huang, C., Pabst, K., and Rollins, M. G. (2011), Monitoring landscape change for LANDFIRE using multi-temporal satellite imagery and ancillary data, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 4,* (2),

Wade, D. D., Brock, B. L., Brose, P. H., Grace, J. B., Hoch, G. A., and Patterson, P. A. III (2000), Fire in eastern ecosystems, in *Wildland Fire in Ecosystems: Effects of Fire on Flora. Gen. Tech. Rep. RMRS-42*, edited by Brown, J. K. and Smith, J. K., pp. 53-96, US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, Utah.

Watt, A. S. (1947), Pattern and process in the plant community, *Journal of Ecology*, *35*, (1/2), 1-22.

Wear, D. N., and Greis, J. G. (2002), Southern forest resource assessment - summary of findings, *Journal of Forestry*, *100*, (7), 6-14.

Wear, D. N., and Murray, B. C. (2004), Federal timber restrictions, interregional spillovers, and the impact on US softwood markets, *Journal of Environmental Economics and Management*, *47*, (2), 307-330.

Wear, D. N., Abt, R.S, and Mangold, R. (1988), People, space, time: factors that will govern forest sustainability., in *Transactions of the 63rd North American Wildlife and Natural Resources conference*, edited, pp. 348-361, Wildlife Management Institute, Orlando, FL.

Wear, D. N., Lui, R., Foreman, M. J., and Sheffield, R. M. (1999), The effects of population growth on timber management and inventories in Virginia, *Forest Ecology and Management*, *118*, 107-115.

Weathers, K. C., Cadenasso, M. L., and Pickett, S. T. A. (2001), Forest edges as nutrient and pollutant concentrators: Potential synergisms between fragmentation, forest canopies, and the atmosphere, *Conservation Biology*, *15*, (6), 1506-1514.

Webster, P. J., Holland, G. J., Curry, J. A., and Chang, H. R. (2005), Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, *309*, (5742), 1844-1846.

White, P. S. , and Jentsch, A. (2001), The search for generality in studies of disturbance and ecosystem dynamics, *Progress in Botany*, *62*, 399-450.

Whitney, G. G. (1994), *From Coastal Wilderness to Fruited Plain: A History of Environmental Change in Temperate North America From 1500 to the Present*, 451 pp., Cambridge University Press, Cambridge.

Wildlife, Defenders of (2000), State Forestry Laws, (Available at http://www.defenders.org/resources/publications/programs_and_policy/habitat_conservation/federal_lands/state_forestry_laws.pdf, retrieved June 10, 2010)

Wilkens, R. T., Ayres, M. P., Lorio, P.L., and Hodges, J. D. (1998), Environmental effects on pine tree carbon budgets and resistance to bark beetles, in *The Productivity and Sustainability of Southern Forest Ecosystems in a Changing Environment*, edited by Mickler, R. A. and Fox, S., pp. 591-616, Springer-Verlag, New York.

Williams, D. W., and Birdsey, R. A. (2003), Historical patterns of spruce budworm defoliation and bark beetle outbreaks in North American conifer forests: an atlas and description of digital maps. Gen. Tech. Rep. NE-308, Newtown Square, PA.

Williams, K. M., Donoghue, E. M., Charnley, S., and Moseley, C. (2007), Northwest Forest Plan—the first 10 years (1994–2003): socioeconomic monitoring of the Mount Hood National Forest and three local communities. General Technical Report PNW-GTR-701, 97 pp, , Portland, OR.

Williams, M. (1982), Clearing the United-States forests - pivotal years 1810-1860, *Journal of Historical Geography*, *8*, (1), 12-&.

Wilson, E. H., and Sader, S. A. (2002), Detection of forest harvest type using multiple dates of Landsat TM imagery, *Remote Sensing of Environment*, *80*, (3), 385-396.

Wofsy, S. C., and Harris, R. C. (Eds.) (2002), *The North American Carbon Program (NACP).Report of the NACP Committee of the U.S. Interagency Carbon Cycle*

Science Program., US Global Change Research Program, Washington, DC.

Woodbury, P. B., Smith, J. E., and Heath, L. S. (2007), Carbon sequestration in the US forest sector from 1990 to 2010, *Forest Ecology and Management*, *241*, (1-3), 14-27.

Woodcock, C. E., Allen, R., Anderson, M., Belward, A., Bindschadler, R., Cohen, W., Gao, F., Goward, S. N., Helder, D., Helmer, E. H., Nemani, R. R., Oreopoulos, L., Schott, J., Thenkabail, P. S., Vermote, E. F., Vogelmann, J. E., Wulder, M. A., and Wynne, R. H. (2008), Free access to landsat iagery, *Science*, *320*, (5879), 1011-1011.

Wu, J. G. (2004), Effects of changing scale on landscape pattern analysis: scaling relations, *Landscape Ecology*, *19*, (2), 125-138.

Wu, J. G., and Loucks, O. L. (1995), From balance of nature to hierarchical patch dynamics: A paradigm shift in ecology, *Quarterly Review of Biology*, *70*, (4), 439-466.

Wulder, M. A., Franklin, S. E., White, J. C., Linke, J., and Magnussen, S. (2006), An accuracy assessment framework for large-area land cover classification products derived from medium-resolution satellite data, *International Journal of Remote Sensing*, *27*, (4), 663-683.

Xian, G., Homer, C., and Fry, J. (2009), Updating the 2001 National Land Cover Database land cover classification to 2006 by using Landsat imagery change detection methods, *Remote Sensing of Environment*, *113*, (6), 1133-1147.

Yu, Y. , Saatchi, S., Heath, L. S., LaPoint, E., Myneni, R. , and Knyazikhin, Y. (2010), Regional distribution of forest height and biomass from multisensor data fusion, *Journal of Geophysical Research*, *115*, (G00E12),

Zeng, H. C., Chambers, J. Q., Negron-Juarez, R. I., Hurtt, G. C., Baker, D. B., and Powell, M. D. (2009), Impacts of tropical cyclones on U.S. forest tree mortality and carbon flux from 1851 to 2000, *Proceedings of the National Academy of Sciences*, *106*, (19), 7888-7892.

Zheng, D. L., Heath, L. S., Ducey, M. J. , and Smith, J. E. (2011), Carbon changes in conterminous US forests associated with growth and major disturbances: 1992–2001, *Environ. Res. Lett.*, *6*, (1), 10.

Zhu, Z., and Evans, D. L. (1994), U.S. forest types and predicted percent forest cover from AVHRR data, *Photogrammetric Engineering & Remote Sensing*, *60*, 525-531.