



United States Department of Agriculture

Characterizing Forest Insect Outbreak in Colorado by Using MODIS NDVI Phenology Data and Aerial Detection Survey Data

Charlie Schrader-Patton, Nancy E. Grulke, and Melissa E. Dressen



Forest
Service

Pacific Northwest
Research Station

General Technical Report
PNW-GTR-940e

August
2016

In accordance with Federal civil rights law and U.S. Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotape, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720-2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877-8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD-3027, found online at http://www.ascr.usda.gov/complaint_filing_cust.html and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632-9992. Submit your completed form or letter to USDA by: (1) mail: U.S. Department of Agriculture, Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue, SW, Washington, D.C. 20250-9410; (2) fax: (202) 690-7442; or (3) email: program.intake@usda.gov.

USDA is an equal opportunity provider, employer, and lender.

Authors

Charlie Schrader-Patton is a geospatial analyst, RedCastle Resources, Inc., under contract with the U. S. Department of Agriculture, Forest Service, Remote Sensing Applications Center, 2222 West 2300 South, Salt Lake City, UT 84119; **Nancy E. Grulke** is director, U. S. Department of Agriculture, Forest Service, Western Wildlands Environmental Threat Assessment Center, 3160 NE 3rd St., Prineville, OR 97754; **Melissa E. Dressen** is a wildlife biologist, U. S. Department of Agriculture, Forest Service, Medicine Bow-Routt National Forest, Yampa Ranger District, 300 Roselawn Ave., Yampa, CO 80483.

Cover: Buffalo Park Unit No. 16. Photo by Melissa Dressen.

Abstract

Schrader-Patton, Charlie; Grulke, Nancy E.; Dressen, Melissa E. 2016. Characterizing a forest insect outbreak in Colorado by using MODIS NDVI phenology data and aerial detection survey data. Gen. Tech. Rep. PNW-GTR-940e. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 35 p.

Forest disturbances are increasing in extent and intensity, annually altering the structure and function of affected systems across millions of acres. Land managers need rapid assessment tools that can be used to characterize disturbance events across space and to meet forest planning needs. Unlike vegetation management projects and wildfire events, which typically are well documented, there is often insufficient data on the extent and intensity of insect and disease outbreaks during periods between intensive inventories. This report describes a rapid assessment approach using normalized difference vegetation index (NDVI) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor at a resolution of 250 m to survey within-year forest damage from insect outbreaks. We aggregated the mean biennial NDVI loss (ratio of NDVI values in the target year and NDVI values in the baseline year) for vegetation polygons (stands) in a study area within the Medicine Bow-Routt National Forest in north-central Colorado and classified these stands to produce tabular summaries of NDVI loss by stand species composition, canopy cover, and tree size. NDVI loss by species class corresponds well at the regional scale with trends in forest health aerial detection survey estimates of trees killed by damage agents. However, our results were confounded by drought response and scale/aggregation issues at the stand level. The methods presented here show promise and can be quickly applied to any forested landscape with spatially explicit stand information. Stand-level data produced with these techniques can be used to characterize vegetation for stand reassessments, forest planning efforts, as well as to study insect and disease activity across a range of spatial and temporal scales.

Keywords: Aerial detection survey, NDVI, forest health, disturbance, MODIS.

Contents

1	Introduction
4	Methods
4	Study Area
6	Causes of Disturbance
7	Classification of Stands
8	Calculating NDVI Loss
10	ADS Data
10	Results
11	NDVI Target Year/Baseline Year Ratios (NDVI Loss)
22	Discussion
22	ADS Data
24	ADS and NDVI—Two Views Across Space and Time
25	Sources of Error
26	MODIS Data Issues
27	Drought Effects
28	Biennial Analysis Periods
28	Conclusions
29	Acknowledgments
29	English Equivalents
30	Literature Cited

Introduction

Forests and woodlands in the United States are increasingly susceptible to large disturbances that can alter the structure, function, and composition of these ecosystems (Dale et al. 2001). Disturbances can be attributed to wildfire or prescribed fire, harvest, extreme weather events, and insect and disease outbreaks that can result in extensive overstory mortality. Managers are challenged with monitoring the condition of these forests and maintaining accurate data on forest conditions while facing limited resources and administrative constraints. Disturbances of an emergent nature such as wildfire are usually well documented both in terms of location and intensity during suppression and subsequent rehabilitation efforts (USGS 2014), and data on vegetation management activities (harvest, prescribed fire) are also typically well maintained. Forest pest outbreaks develop over multiple years and vary greatly in intensity across the landscape. Although forest pest outbreaks are monitored in many areas annually, near-real-time outbreaks can be monitored at a coarse resolution using satellite imagery.

Forest health aerial detection surveys (ADS) are conducted annually over all forested land in the United States to map pest and weather damage. Data from these surveys are the basis of regional and national insect and disease monitoring reports (e.g., Harris 2013). Data from the ADS are collected by an observer trained in visual identification of host species and damage agents in the survey area. Observed damage is sketched on an electronic map, and the host, damaging agent, and intensity (affected trees per acre) are recorded. Such ADS data are a subjective interpretation of the landscape and can differ considerably in quality, extent, and resolution (Harris and Dawson 1979, Wulder et al. 2006). Lighting conditions, experience of the observer, intensity of the damage, and multiple years of damage are factors in the accuracy of mapping (McConnell et al. 2000). Additionally, products derived from ADS can be difficult to compile across multiple years with different observers and damage levels. Despite these shortcomings, ADS data are the standard for local, regional, and national monitoring of forest insect and disease activity. See Johnson and Wittwer (2008) for details on ADS.

The U.S. Forest Service Forest Inventory and Analysis (FIA) program maintains a network of plots on forest land across all ownerships in the United States. Remeasurement of these plots has fostered efforts to use these data to assess forest mortality (Shaw et al. 2005, Thompson 2009). However, remeasurement of the same plot (30 m diameter, 1 plot per 2428 ha) is conducted every 5 years in the Eastern United States and every 10 years in the West. Remeasurement requires significant expertise and may be difficult to relate to continuous stand

data as assessed by imagery. Traditional stand exam approaches are not practical across large landscapes, provide little insight on disturbance history (Hummel et al. 2011), and give a view of the stand at a single point in time. Stand exams have some of the same drawbacks as FIA plots; however, they may be conducted once every 5 to 30 years.

Remote-sensing technology has the potential to provide unbiased, place-based, temporally repeatable information on forest insect and disease outbreaks consistently across large landscapes by recording changes in the spectral reflectance resulting from these outbreaks. Researchers have successfully used satellite data to detect impacts from forest insect and disease outbreaks (de Beurs and Townsend 2008, Hicke and Logan 2009, Meddens et al. 2013, Spruce et al. 2011a, Wulder et al. 2006). Increased availability of current and historical satellite data has spawned new approaches to extract forest disturbance information for retrospective monitoring at 1- to 5-year intervals (e.g., Masek et al. 2013, Wulder et al. 2012), as well as historical disturbance (Assal et al. 2014, Neigh et al. 2014). Trend analysis methods using the Landsat data archive have shown some success in discerning insect and disease damage from other forms of forest disturbance (Goodwin et al. 2008, Masek et al. 2013, Meddens et al. 2013, Meigs et al. 2011). Near-real-time applications such as the forest disturbance recognition and tracking system (ForWARN) developed by the U.S. Forest Service Eastern Forest Environmental Threat Assessment Center (Norman et al. 2013, 2014), and the Forest Disturbance Monitor (FDM) developed by the U.S. Forest Service Forest Health and Technology Enterprise Team (FHTET) (USDA FS 2015), use intensity of disturbance and recovery patterns in the normalized difference vegetation index (NDVI) from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument to detect and attribute source of disturbance. MODIS is on the National Aeronautics and Space Administration (NASA) EOS (Earth Observing System) Terra and Aqua Earth-imaging satellites, collecting energy reflected or emitted from the Earth in 36 different spectral bands with ground resolutions of 250-m (Bands 1–2), 500 m (Bands 3–7), and 1000 m (Bands 8–36) (Townshend and Justice 2002). The published resolution for 250 m products is based on arc-seconds at the equator, and actual resolution of MODIS 250-m data is 232 m. Because of its presence on two satellites with offsetting orbits, MODIS instruments can obtain two daily views of the Earth's surface for most locations across the globe. The ForWARN and FDM applications leverage changes in NDVI from this database to distinguish and attribute vegetation or land surface changes over time.

A need exists for methods that translate raster-based data available from satellite imagery into forest stand information used by land managers. In this report, we describe a process we have developed to build geospatial databases of forest disturbances using NDVI data, and we provide examples of how these data can be interpreted. Forest disturbance in this case is characterized as a reduction in NDVI, specifically where the ratio of the maximum NDVI value for the target year and the maximum NDVI value for the baseline year is less than one. In our study, the baseline had minimal disturbance once disturbance attributable to wildfire and harvest had been removed. The progression of the disturbance can be tracked through the analysis period based on this ratio. Last, we qualitatively compared our NDVI loss measurements with tree mortality estimates from the ADS data.

The NDVI has been extensively used to monitor and assess vegetation greenness based on the reflectance data from the red R (MODIS Band 1) and near-infrared (NIR, MODIS Band 2) bands, and is highly correlated with the chlorophyll content of plants. It is considered to be a measure of plant production, health, or vigor (Jensen 2005). Studies have related NDVI to vegetation metrics such as leaf-area index (Wang et al. 2005), gross primary productivity (Rossini et al. 2012), evapotranspiration (Seevers and Ottman 1994), forest biomass (Dong et al. 2003) and forest insect and disease mortality (Assal et al. 2014, Meigs et al. 2011). Mathematically, the index is a ratio of the difference of the NIR and R bands and the sum of the same two bands. It is considered to be an improvement upon the simple ratio of the two bands because of its sensitivity to low vegetation densities and its ability to mitigate topographic and illumination effects (Huete et al. 2002). Scientists at NASA's Stennis Space Center have developed phenology products covering the conterminous United States, including the maximum annual NDVI value achieved on a per-pixel basis (NDVI MAX) (Hargrove et al. 2009). This product is an annual composite of the maximum NDVI value pixels that occur at peak vegetation greenness of the growing season.

Our intent was to provide Medicine Bow-Routt National Forest (MBRNF) forest managers and resource specialists with maps of the intensity and time of disturbance, aggregated by forest stand polygon. These data can then indicate how much of the study area has been disturbed, where the disturbance has occurred, and what stand types and tree size classes have been affected. This information can also be used for prioritizing and allocating resources for re-censusing. Our approach was to classify the forest stand polygons into size (diameter), canopy cover, and composition classes, then calculate the decrease in NDVI for the polygons. Given that these datasets already exist, we intended the assessment tool to be fast (requiring less than 2 weeks to complete) and approximate.

Methods

Study Area

The MBRNF in north-central Colorado and south-central Wyoming has been experiencing an outbreak of mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) for more than 10 years, with a peak disturbance occurring in 2008 and decline in subsequent years owing to host depletion (Harris 2013, Harris et al. 2002). The MPB is a native insect that reproduces in live trees. Feeding activities of the larvae typically result in the killing of the host tree. The preferred host species for MPB is lodgepole pine (PICO) (*Pinus contorta* Douglas ex Loudon). The bark beetle outbreak in the Western United States has resulted in extensive loss of mature PICO. For a complete discussion of MPB ecology and population dynamics, see Bentz et al. (2010). Concurrent with the MPB outbreak was widespread mortality of subalpine fir (ABLA) (*Abies lasiocarpa* Hooker) caused by a combination of root rot (*Armillaria* spp.) and western balsam bark beetle (*Dryocoetes confusus* Swaine) (Ciesla 2006); mortality of Engelmann spruce (PIEN) (*Picea engelmannii* Parry ex Engelmann) resulting from infestation by spruce beetles (SB) (*Dendroctonus rufipennis* Kirby); and mortality in quaking aspen (POTR) (*Populus tremuloides* Michx.) related to severe drought in 2000–2003. This aspen mortality has been named sudden aspen decline (SAD) (Worrall et al. 2010) and the combination of root rot and western balsam bark beetle infestation is called ABLA decline.

Because of dramatic changes in tree cover resulting from these outbreaks, MBRNF managers sought help to prioritize remeasurement of stands by locating undisturbed and disturbed stands and obtaining data on the type of disturbance and post-disturbance stand composition and basal area.

We selected the southern portion of the Parks Ranger District of the MBRNF (hereafter referred to as the study area) to cross-reference our results with another ongoing pilot project to redelineate and update the attributes of these stands.¹ The study area ranges from 2500 to 3700 m in elevation and consists primarily of PICO- and ABLA-dominated forest stands (fig. 1). POTR and PIEN are also major components.

To gain a better understanding of the relationship of the MODIS NDVI loss to stand-level conditions, we qualitatively assessed the (MODIS) raster layers with current and historical aerial photography and with the MODIS NDVI Graph Tool, which is a utility available in the Forest Change Assessment Viewer, a Web-based interface for the ForWARN system (Norman et al. 2013). This tool allowed us to

¹Stam, C. 2013. Personal communication, 2013. Remote sensing analyst, USDA Forest Service Remote Sensing Applications Center, 2222 W 2300 South, Salt Lake City, UT 84119-2020.

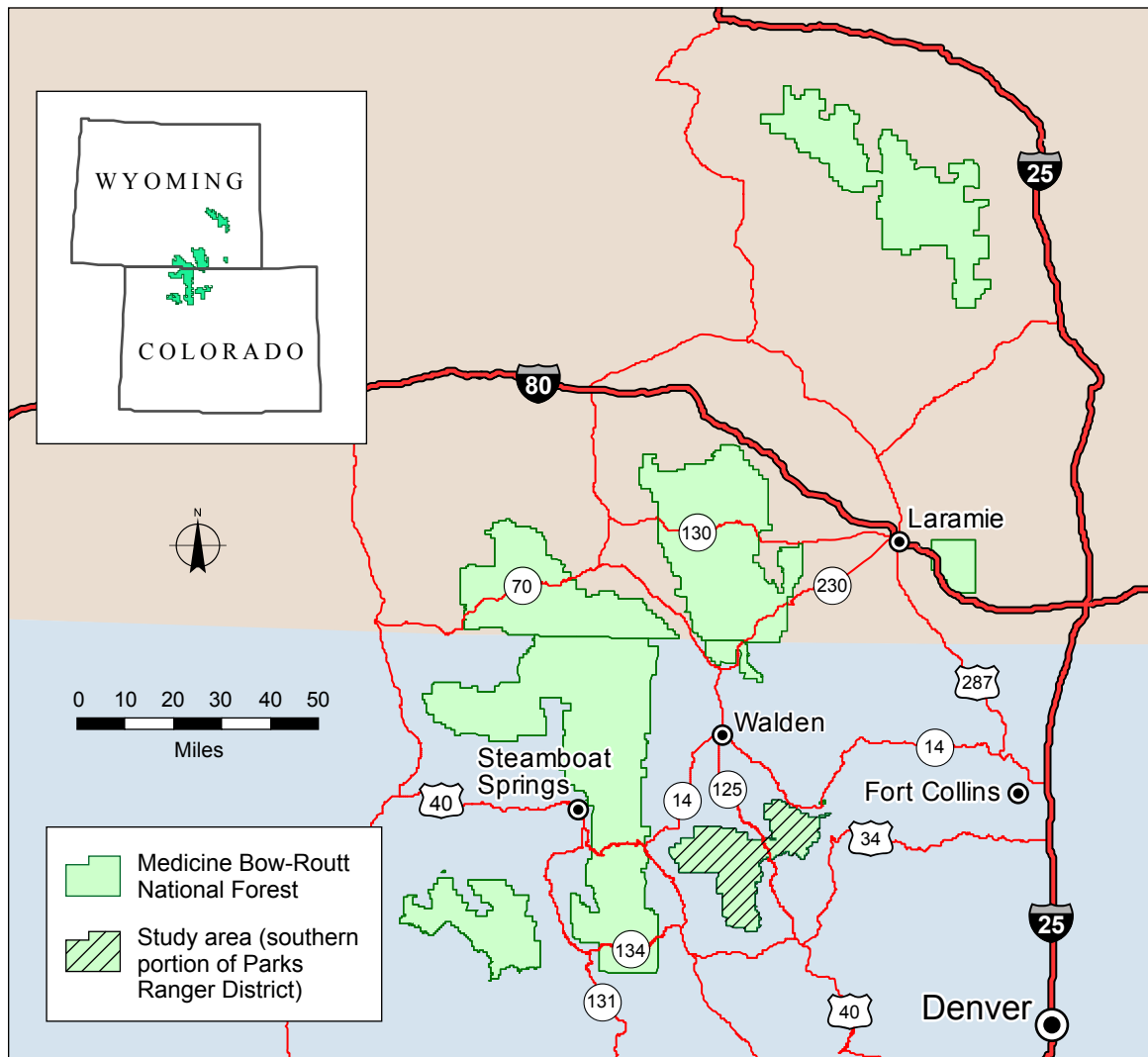


Figure 1—The Medicine Bow-Routt National Forest spans the Wyoming-Colorado border. The 179808 ha Parks Ranger District study area is located in north-central Colorado.

select a location on the map and return a graph with NDVI values in 8-day intervals for the period 2000–2013 (fig. 2). We examined the NDVI record for the years for which we have photography (2005, 2009, 2011, and 2013) and correlated decreases in NDVI observed in the raster layers and the graphs (for individual pixels) with mortality seen on the aerial photography. Geolocation error was minimized by use of an extension developed to integrate the MODIS NDVI Graph Tool into ArcMap[™] software² (Esri 2011). The extension allowed the user to select a location on the aerial photography and view the NDVI graph for that location.

²The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Causes of Disturbance

An observed decrease in the NDVI MAX value between 2 years can have several causes in forested landscapes. Anthropogenic disturbances include harvest, fuels management (e.g., prescription burns), conversion to other uses, and road construction. Natural disturbance events such as wildfire, insect and disease outbreaks, and weather events account for the greatest amount of disturbance in this landscape. Separating these types of disturbances solely by using the MODIS spectral data is difficult. Even with advanced trend analysis of NDVI through time for a given pixel, confusion among causal factors exists (Schmidt 2014). Because our focus was on characterizing the insect and disease outbreak occurring in the study area, we excluded areas with vegetation management and wildfire activity; these areas were identified using ancillary data. The MBRNF staff provided data from the FACTS (Forest Service Activity Tracking System) database, which contains polygons of management activity for the analysis period. These activities were largely confined to the northern portion of the study area and included clearcutting, overstory removal, thinning, and fuels reduction treatments. These areas were masked out of the analysis to avoid any confusion with insect and disease disturbance. We used the data from GeoMAC (Geospatial Multi-Agency Coordination, a geospatial data service for current and historical wildfires) to identify any wildfires that occurred during 2000–2012 (USGS 2014). We determined that there were no major wildfires in the study area in the period 2000–2012 (USGS 2014).

NDVI loss resulting from canopy damage caused by windstorms, hail, and ice damage can also be mistakenly identified as insect and disease damage. Forest health aerial surveyors map damage to forests from weather-related events in addition to insect and disease damage (Johnson and Wittwer 2008). We extracted any weather-related damage polygons from the ADS database and used these data to attribute areas of NDVI loss to weather events. The ADS collected from 2001 to 2012 did not contain any areas of damage resulting from weather events in the study area.

Drought conditions can depress NDVI values, but the degree to which they are reduced is highly dependent on the cover type. Evergreen needleleaf forests (the predominant cover type in the study area) have been shown to have low NDVI sensitivity to drought relative to other vegetation cover types such as grasslands and shrublands (Sims et al. 2014). Considering the large pixel size and thus the possibility that drought-sensitive cover types within a single pixel could depress NDVI, we identified drought periods in 2000–2012 and examined the NDVI loss data for error related to these conditions.

Classification of Stands

A polygon layer of stands in the study area was obtained from MBRNF staff; this layer was developed using common vegetation Unit (CVU) methods. CVUs are components of the Integrated Resource Inventory, which was developed by the Forest Service Rocky Mountain Region as a land classification system based on aerial photo interpretation (Wolf 1994). Attributes in the stand data are in the Forest Service field-sampled vegetation (FSVeg) format (USDA FS 2014). Dominant tree species were the primary criteria in delineating stands, with canopy cover and tree size as secondary characteristics.³ Polygons were attributed with photointerpreted percentages of canopy cover for four tree species (ABLA, PICO, PIEN, POTR); the percentage of canopy cover of three size classes—small (2.54 to 12.45 cm diameter at breast height [dbh]), medium (12.46 to 22.61 cm dbh), and large (>22.61 cm dbh); and total percentage of tree canopy cover (TCC). The sum of the percentages of species canopy cover equals the total percentage of canopy cover, which may not be greater than 100 percent. Relative canopy cover (RCC) was calculated for each species by dividing the species canopy cover by the total TCC. The source imagery for this photointerpretation was collected in 2001.

A classification scheme was developed by using the Model Maker Tool in ArcMap 10.1 software (Esri 2011) and applying it to the polygons. We developed our classification independent of any preexisting scheme. Our class definitions and breaks were heuristically based and designed to capture the variation in the landscape. The stands were classified by one composition type (dominant species) and two structural classes (canopy cover and size class). We attempted to design class breaks to capture the diversity of stand types within the study area. Each stand was placed into one of three total canopy cover classes: low ($TCC \leq 40$ percent), moderate ($TCC = 40$ to 60 percent), and high ($TCC > 60$ percent). We defined seven species classes: nonforest ($TCC \leq 10$ percent), woodland ($TCC = 10$ to 20 percent), ABLA (ABLA RCC > 60 percent), PICO (PICO RCC > 69 percent), PIEN (PIEN RCC > 60 percent), POTR (POTR RCC > 65 percent), and mixed (none of the other species criteria were met). Finally, each stand was assigned a size class based on RCC by tree size: small (RCC of small trees > 50 percent), medium (RCC of medium trees > 50 percent), and large (RCC of large and medium trees > 50 percent). Combining all three characteristics (specified by species, canopy cover, and size class) produced 63 potential composite forest classes, although not all were represented in the study area.

³ **Caulkins J. 2014.** Personal communication, 2014. Biological scientist, USDA Forest Service, Rocky Mountain Region, 952 Weiss Drive, Steamboat Springs, CO 80487.

Calculating NDVI Loss

Annual NDVI MAX raster data for the years 2000–2012 were obtained from personnel at NASA’s Stennis Space Center. These 250-m-resolution files were produced by using validated U.S. Geological Survey MODIS NDVI data (MOD13), which were processed to identify low-quality pixels and the maximum NDVI value for the specific year (McKellip et al. 2008; Ramsey et al. 2011; Spruce et al. 2011a, 2011b). The low-quality pixels were designated as “NoData.” For detailed information on MOD13 data, see Solano et al. (2010). We created NDVI change products by dividing the target year NDVI MAX values by the base year NDVI MAX values (fig. 2). This calculation was performed on each pixel. Values of less than 1 represented NDVI loss relative to the base year; conversely, values of more than 1 represented NDVI gain. Thus, NDVI change products compare peak of growing season NDVI for a given year to that of a base year. Our focus was on NDVI loss so those pixels with NDVI gain, which might represent understory recovery after canopy disturbance, were set to null (NoData) and so would have no effect on mean NDVI loss values. NDVI loss raster layers were created for the following base/target year pairs: 2000/2002, 2002/2004, 2004/2006, 2006/2008, 2008/2010, and 2010/2012.

We chose to calculate the NDVI loss raster layers biennially to reduce processing time and because we felt that comparing NDVI max values 2 years apart would adequately capture the changes of interest, and specifically new disturbance. The NDVI ratio raster files effectively isolate vegetation changes between two points in time—the target year and the base year. We prepared maps of these biennial raster layers to view the spatial distribution of NDVI loss through the analysis period. In this case, the NDVI change was due to loss, because NDVI gains were masked. To analyze the change that occurred on the landscape over the entire analysis period (2001–2012), we calculated the mean of the six biennial NDVI loss raster layers; this layer is a measure of overall mortality for each pixel during 2000–2012. In calculating this mean loss value, pixels with NDVI gain were masked out. We refer to this product as the 2001–2012 MEAN NDVI loss raster layer. To make a valid comparison to 2001–2012 ADS cumulative mortality, we summed the biennial raster layers, creating the 2000–2012 SUM NDVI loss raster layer. Before calculating this layer, “NoData” pixels were set to 1, which represented a pixel with no NDVI loss. Thus in the 2001–2012 SUM NDVI loss raster layer, a pixel with no NDVI loss had a value of 6 and pixels with loss were less than 6.

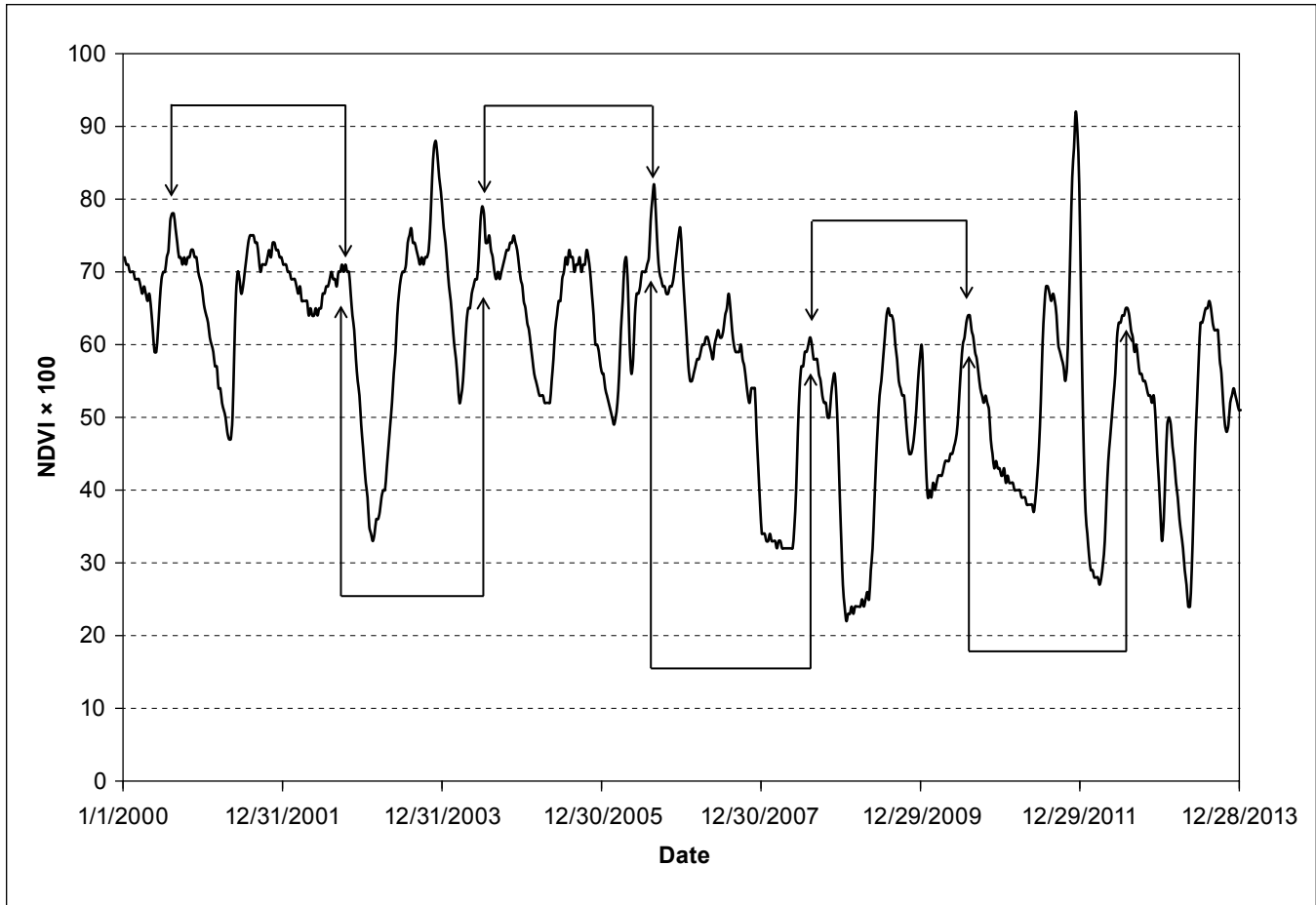


Figure 2—Normalized difference vegetation index (NDVI) graph for a single lodgepole pine pixel with the NDVI value (y-axis) in 8-day increments from 2000 to 2013 (x-axis). The six biennial NDVI MAX ratios (target year/floating 2-year baseline; identified by arrows in figure) are averaged to produce the overall disturbance mean for 2001–2012. The data in this graph were extracted from the Forest Change Assessment Viewer (Norman et al. 2013).

To apply the calculated NDVI loss to the vegetation polygons, we first resampled the raster data from 250 to 30 m so that the mix of NDVI loss values would be more equally represented in the polygons. Nearest neighbor methods were used to preserve the original pixel values. Next, we calculated the mean NDVI loss value for each polygon using the Zonal Statistics Tool in ArcGIS 10.1 software and summarized NDVI loss statistics for the various polygon classes.

A MODIS quarter-kilometer pixel covers 5.37 ha (231.66 by 231.66 m) and can include multiple vegetation types, each with potentially variable NDVI values. Thus, NDVI returned is the average for the whole pixel. Without ground truth data, it is not possible to determine which vegetation cover types contribute to this averaged, whole-pixel value. This has implications for small (≤ 10 ha) stands in which

very few or no whole MODIS pixel contributes to the MEAN NDVI loss value for the stand (polygon). Also, if one or more pixels overlapped the stand boundary, the area outside of the stand will influence the NDVI loss value and possibly result in a value that is not representative of the stand. To compensate for this source of error, we statistically ranked the composite classes by NDVI loss and area using Microsoft Excel® 2010 software. Ranking serves to identify classes that are high in total area. We have greater confidence in NDVI loss values for these classes because a greater number of pixels are contributing to the calculated values. To calculate a combined NDVI loss/area rank, we ranked the mean of these two values and produced a table of the composite classes sorted by this higher confidence, combined rank.

ADS Data

ADS polygon data for the study area were obtained from FHTET for each year in the period 2001–2012. Damage polygons were attributed with a primary damage agent, damage type (mortality or defoliation), intensity (trees per acre killed for mortality or severity [low: ≤ 50 percent defoliation or high: ≥ 50 percent defoliation] for defoliating agents), survey year, and polygon acres (USDA FS 2005). With these attributes, we were able to summarize the number of trees killed by the primary damage agents for the analysis period (2001–2012) and for each of the biennial periods. The ADS mortality (trees killed) for the 2 years in each biennial period was summed, for example, the ADS mortality for the period 2006–2008 would be the sum of trees killed in 2007 and 2008. In this example, ADS mortality in 2006 is not included because it is the baseline year in the NDVI loss calculation. Using intersect and union geographic information system (GIS) tools (Esri 2011), we created a cumulative mortality layer that depicts all mortality in the period 2001–2012. The zonal statistics tool (Esri 2011) was used to calculate the mean 2001–2012 cumulative mortality value for each stand.

Results

The most abundant species class both in terms of area and number of polygons was PICO (40 026 ha; 2,735 polygons) (table 1). The high canopy cover class was the most represented canopy class by areal extent and number of polygons (51 359 ha; 3,254 polygons). The large size class was the most abundant size class by area (39 477 ha), and the medium size class was represented by the most polygons (3,086) (table 1). In the woodland class, the mean relative percentage of canopy cover of tree species was PICO (47 percent), followed by ABLA (27 percent), PIEN (10 percent), and POTR (16 percent). Similarly, the mean values for the mixed class were PICO (36 percent), ABLA (25 percent), PIEN (30 percent), and POTR (9 percent).

Table 1—Summary of the area and number of field-sampled vegetation stands (FSVeg) in each of the categories based on the Jenks natural breaks algorithm

		Dominant tree species	Area	Number of polygons
			Hectares	
FSVeg stand type	ABLA	<i>Abies lasiocarpa</i>	2216	226
	PICO	<i>Pinus contorta</i>	40 026	2,735
	PIEN	<i>Picea engelmannii</i>	3467	289
	POTR	<i>Populus tremuloides</i>	7508	795
	Woodland	<i>Pinus contorta</i>	3232	413
	Mixed	<i>Pinus contorta</i> , <i>Abies lasiocarpa</i>	20 253	1,473
	Nonforest		14 311	1,387
Size class	Large	>22.61 cm	39 477	2,707
	Medium	12.46–22.61 cm	37 031	3,086
	Small	2.54–12.45 cm	14 503	1,525
Canopy cover	High	>60 percent	51 359	3,254
		>40 percent, <60 percent		
	Moderate		15 416	1,498
	Low	<40 percent	24 237	2,566

ABLA = subalpine fir; PICO = lodgepole pine; PIEN = Engelmann spruce; POTR = quaking aspen.

NDVI Target Year/Baseline Year Ratios (NDVI Loss)

Both the biennial target-baseline and the 2001–2012 MEAN NDVI loss raster datasets ranged from 0 to 1. These ratios represent the NDVI loss of the target year relative to the baseline year with smaller values representing greater decrease from the baseline year (greater loss). Figure 3A displays the SUM NDVI loss values for each stand; it is the sum of the NDVI loss for each biennial period compiled at the FSVeg stand level. For comparison, the cumulative (total) number of trees killed according to ADS data is displayed in fig. 3B. Similarly, the 2001–2012 mean NDVI loss raster values for the stands are shown in figure 4A. The majority of the stands in the top two symbol classes (0.814–0.924 NDVI loss) in figure 4A are in the PICO and mixed species classes. The mean number of trees killed according to ADS data is displayed in figure 4B.

The extent and intensity of NDVI loss and ADS mortality for each biennial time period are displayed in figures 5 and 6. The biennial NDVI raster layers show temporal and spatial variation in NDVI loss within the analysis period. For example, in the period 2000–2002 (fig. 5A), there was substantial NDVI loss in PICO stands in the southern and western portions of the study area, followed by relatively dispersed loss

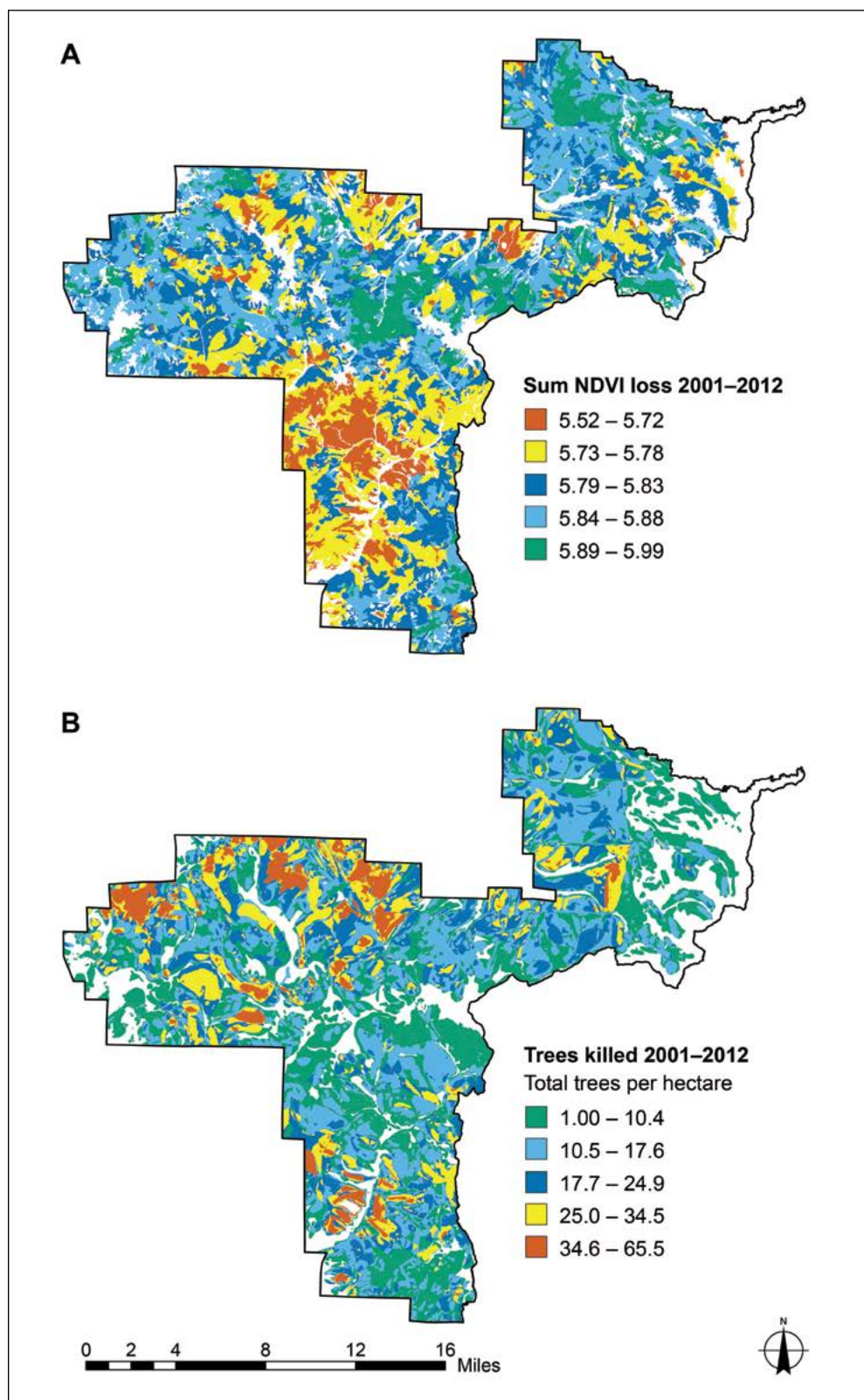


Figure 3—(A) Sum of normalized difference vegetation index (NDVI) loss during the period 2001–2012 for the FSVeg stands. Biennial NDVI loss pixel values were averaged for each stand and then summed over the six biennial periods. Nonforest and timber harvest areas are rendered in white. Class breaks were determined using the Jenks natural breaks algorithm; (B) total tree mortality as detected over the same period by aerial detection surveys.

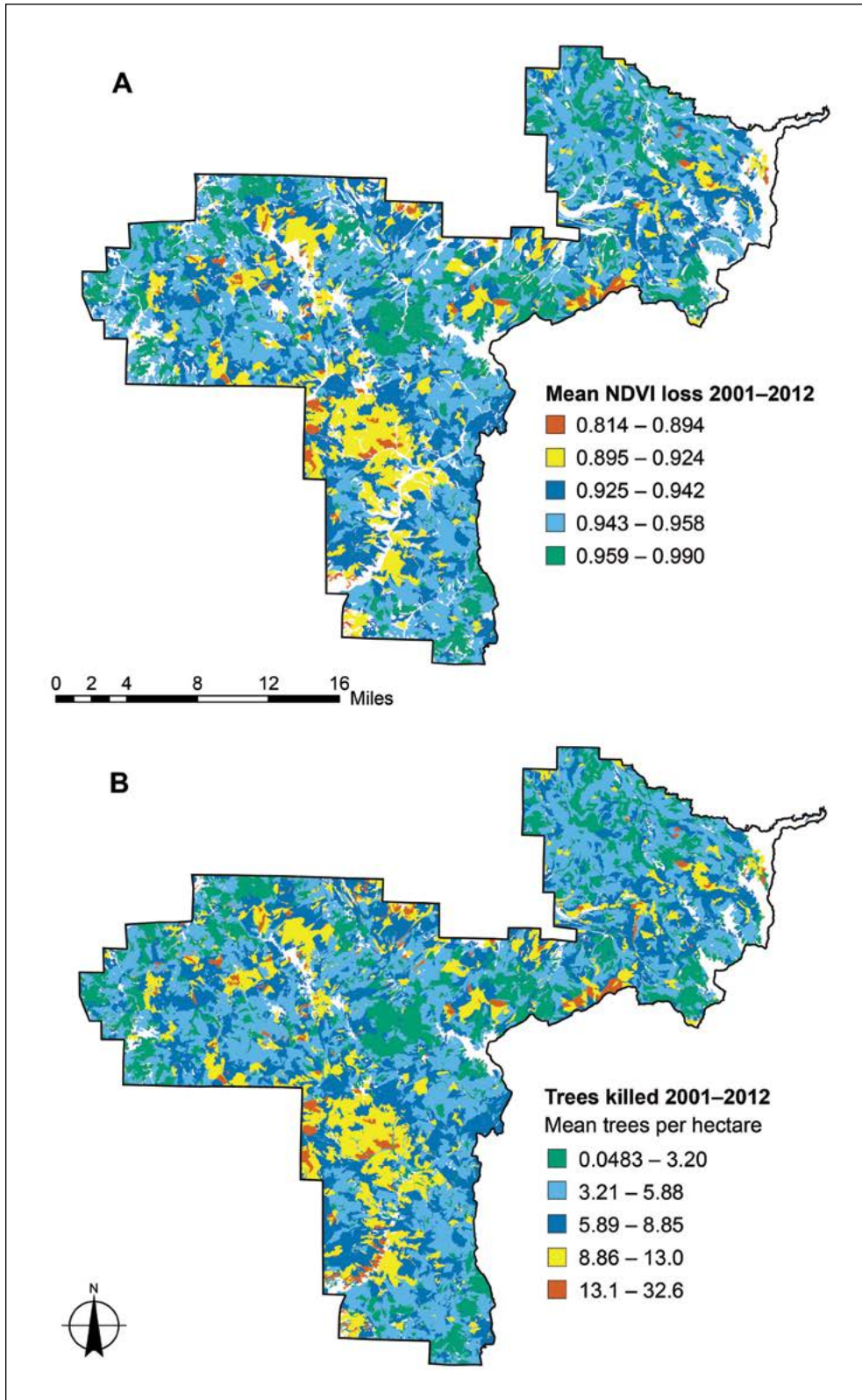


Figure 4—(A) Mean normalized difference vegetation index (NDVI) loss during the period 2001–2012 for the FSveg stands. Biennial NDVI loss pixel values were averaged and these values spatially averaged for each stand. Nonforest and timber harvest areas are rendered in white. Class breaks were determined using the Jenks natural breaks algorithm; (B) mean tree mortality as detected over the same period by aerial detection surveys.

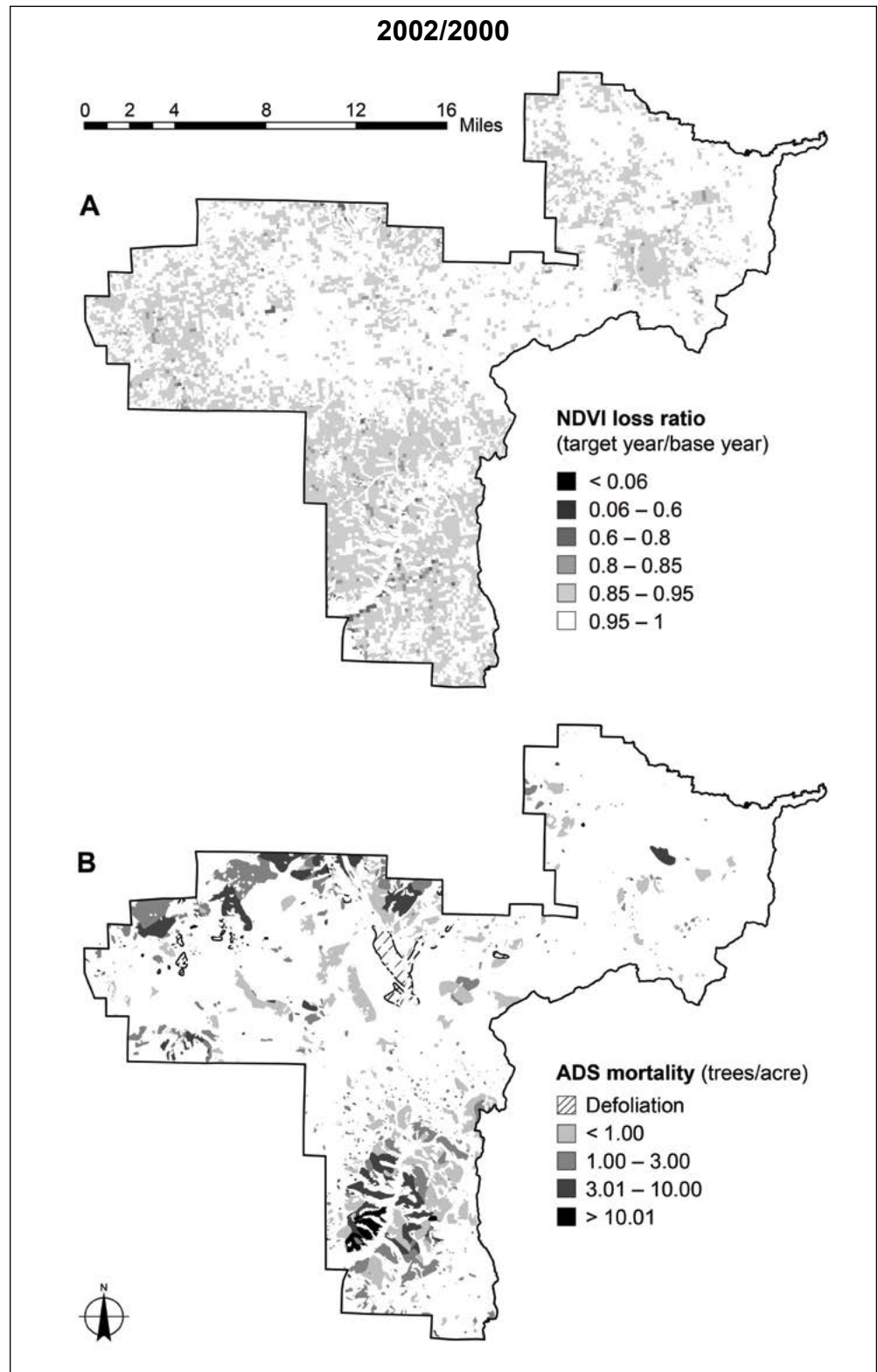


Figure 5—Study area maps for each biennial period between 2000 and 2006 showing the variation in normalized difference vegetation index (NDVI) loss vs. mortality detected by aerial observers (aerial detection survey [ADS] data). The NDVI pixel values are the ratio of the NDVI annual maximum value for the target year over the NDVI annual maximum value baseline year. For example, in (A), the pixel values are the ratio of 2002 NDVI max/2000 NDVI max. The corresponding map (B) displays the cumulative ADS data mortality for the same time period (2001 and 2002). (C) NDVI loss vs. (D) ADS mortality for the period 2002–2004; (E) NDVI loss vs. (F) ADS mortality for the period 2004–2006.

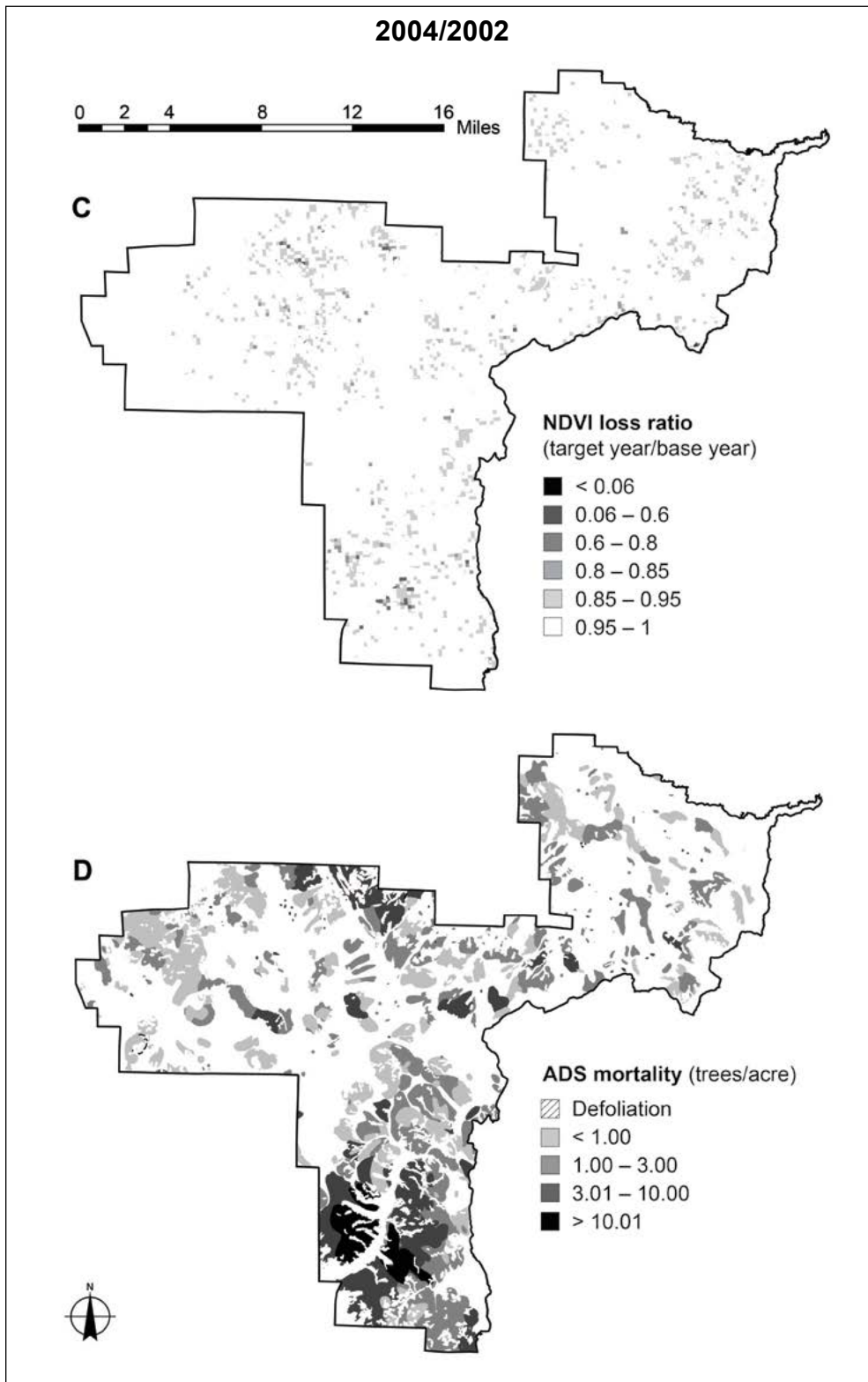


Figure 5—continued.

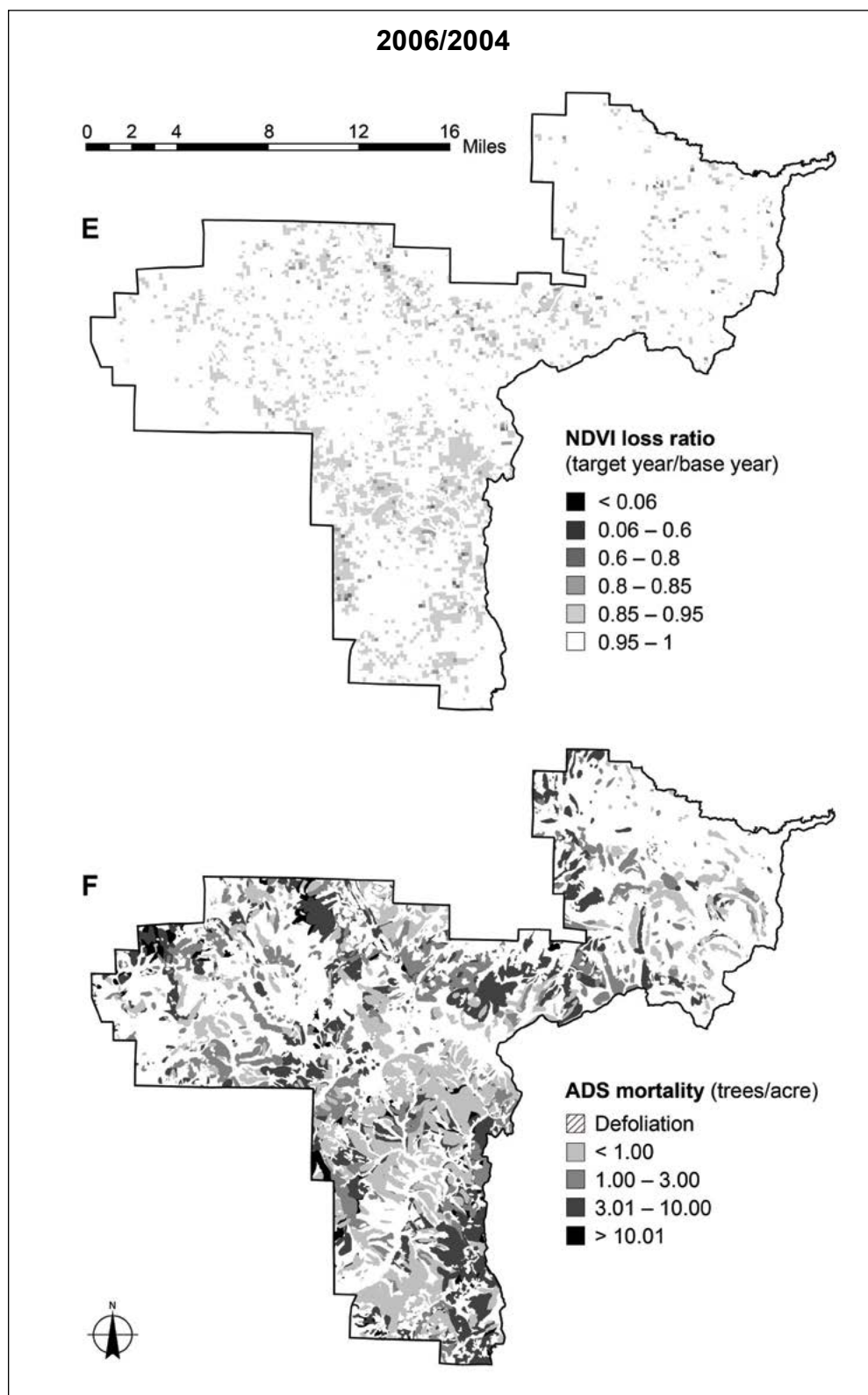


Figure 5—continued.

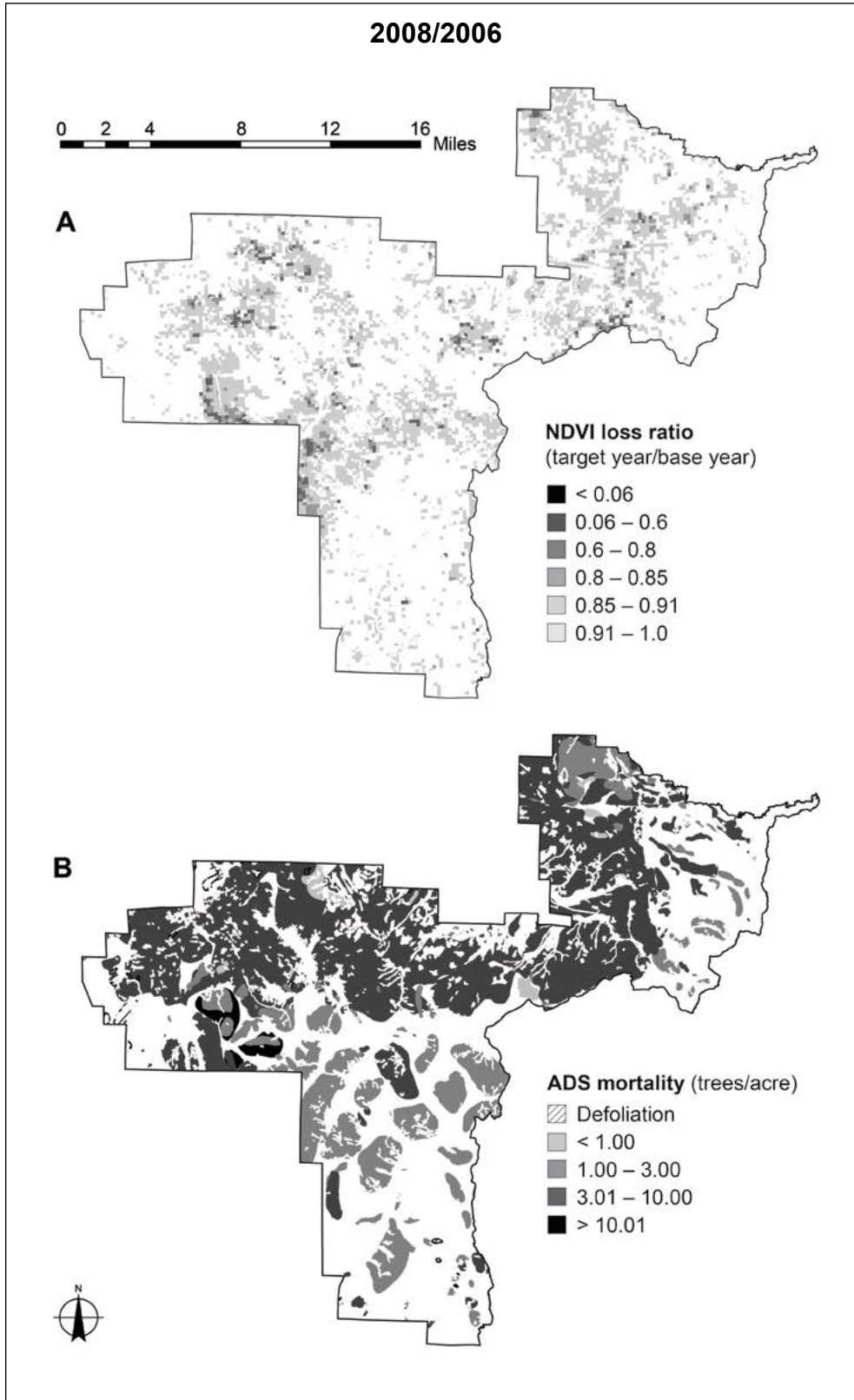


Figure 6—Study area maps for each biennial period between 2006 and 2012 showing the variation in normalized difference vegetation index (NDVI) loss and mortality detected by aerial observers (aerial detection survey [ADS] data) (see fig. 5). (A) 2008 NDVI max over 2006 NDVI max; (B) cumulative ADS data mortality for the same time period (2007 and 2008); (C) NDVI loss vs. (D) ADS mortality for the period 2008–2010; (E) NDVI loss vs. (F) ADS mortality for the period 2010–2012.

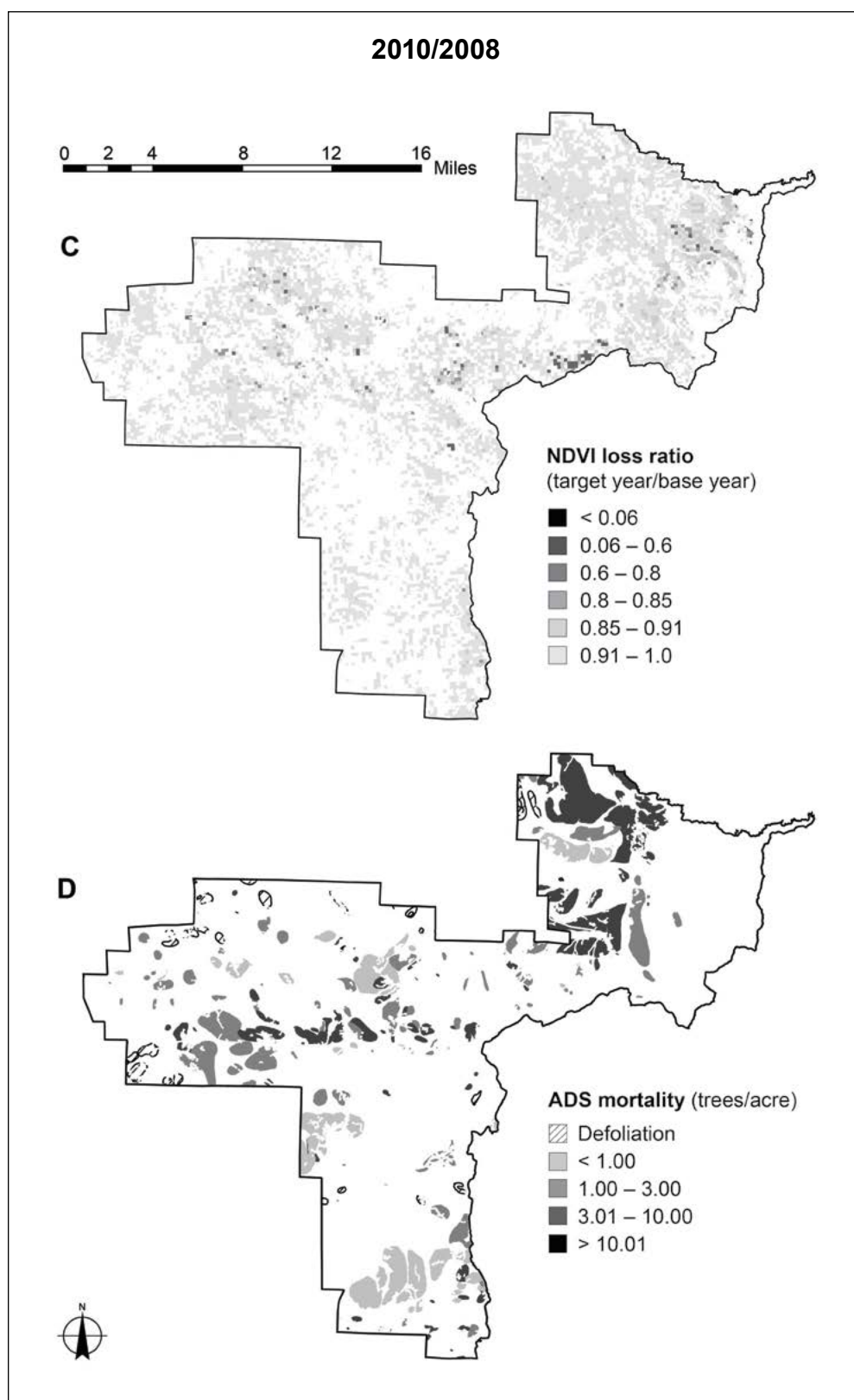


Figure 6—continued.

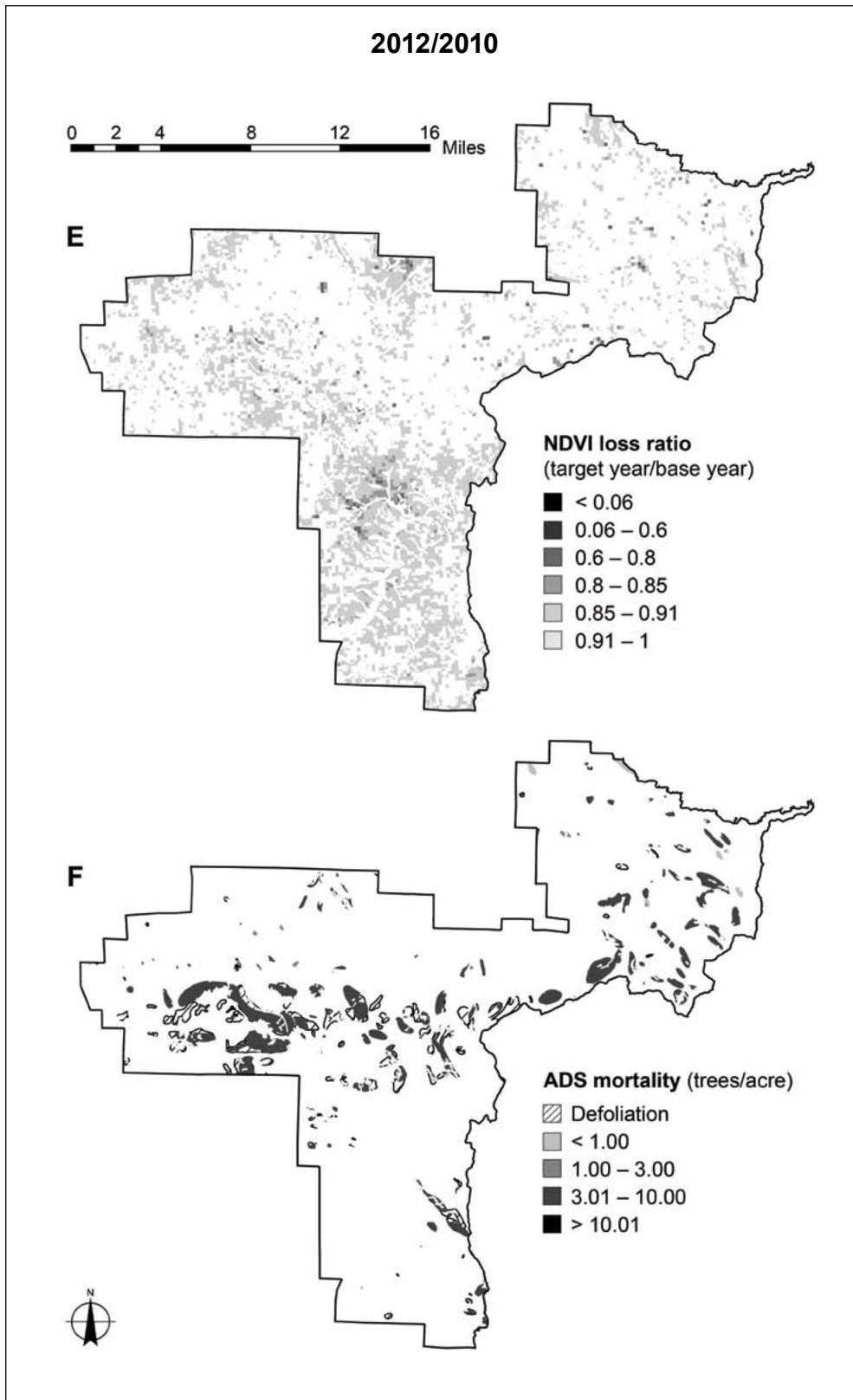


Figure 6—continued.

for the next two biennial periods (figs. 5C and 5E). The period 2006–2008 shows some concentrated NDVI loss in stands of large PICO in the west-central portion of the study area (fig. 6A). 2010–2012 (fig. 6E), and marked a loss comparable to 2000–2002.

The analysis area was surveyed completely each year during the study period (2000–2012). The damage agents with the highest number of affected acres and trees killed (or damaged as in the case for aspen) from the 2001–2012 ADS data were (1) MPB, (2) ABLA decline, (3) spruce beetle, and (4) SAD/aspen defoliation (table 2). In terms of intensity (trees killed/hectare), MPB was highest, followed by spruce beetle, ABLA decline, and SAD/aspen defoliation. The mean size of the ADS damage polygons collected was 79 ha, and the mean number of trees killed per hectare was 9.3.

Open woodlands (WL) had the greatest average biennial NDVI loss of all the forested species classes, followed by PICO, ABLA, mixed, PIEN, and POTR (table 3). The NDVI loss was the highest in the moderate canopy cover classes of medium-sized PICO (table 4). The least disturbance was experienced by the POTR stand type, with moderate cover in the small tree size class (table 5). PICO–high–medium (dominant tree species/canopy cover/tree size class) had the highest combined rank of disturbance (greatest damage and areal cover), and ABLA–moderate–large had the lowest combined rank (table 5).

High NDVI loss was evident in the 2000–2002 period, with some species classes (Woodland, PICO, ABLA, mixed) having the highest loss values of any biennial period. Loss was also significant for all species classes in the next (2002–2004) period (fig. 5). The PICO class had its highest loss in the 2000–2002 and 2006–2008 periods (fig. 6), while PIEN had high losses in 2000–2002, then increasing loss in 2006–2008 and 2008–2010. The ABLA class had high losses in 2000–2002 and in 2010–2012. POTR, and woodland class NDVI loss was greatest in 2000–2002 and in the 2010–2012 biennial periods. Stands in the mixed class had the greatest NDVI losses in 2000–2002 and 2006–2008.

Table 2—Trees killed and affected area for each damage agent in the analysis period 2001–2012 extracted from the forest health aerial detection survey data

Damage agent	Area affected	Trees killed	Trees killed per hectare
	<i>Hectares</i>	<i>----- Number -----</i>	
Mountain pine beetle	184 755	3,312,729	17.9
<i>Abies lasiocarpa</i> decline	31 487	179,655	5.7
Spruce beetle	12 113	152,783	12.6
Sudden aspen decline and aspen tortrix defoliation ^a	1787	—	—

— = No data.

^a Aspen decline resulting from tortrix defoliation does not typically cause tree mortality.

Table 3—Normalized difference vegetation index (NDVI) loss statistics (mean and standard deviation [SD]) during 2001–2012 for the field-sampled vegetation (FSVeg) classes

FSVeg stand class	Mean NDVI loss 2001–2012	SD NDVI loss 2001–2012
Woodland	0.939	0.0265
PICO	0.940	0.0291
ABLA	0.941	0.0302
Mixed	0.944	0.0290
PIEN	0.945	0.0293
POTR	0.947	0.0256

Note: Classes are presented in order of decreasing disturbance.

PICO = lodgepole pine; ABLA = subalpine fir; PIEN = Engelmann spruce; POTR = quaking aspen.

Table 4—Combined ranking values for the five forested (canopy cover > 10 percent) composite classes with the highest combined rank scores

FSVeg class	Canopy cover	Size class	Rank, mean NDVI loss	Rank, area	Combined rank ^a
PICO	High	Medium	4	2	2
Woodland	High	Medium	12	10	3
Mixed	High	Large	19	3	4
PICO	Moderate	Large	13	11	5.5
PICO	Moderate	Medium	20	5	8

FSVeg = field-sampled vegetation; NDVI = normalized difference vegetation index; PICO = lodgepole pine; PIEN = Engelmann spruce; POTR = quaking aspen.

^a Combined rank is the mean of area and NDVI loss rank. Only forested composite classes with > 10 polygons were considered in this ranking. The nonforest class was ranked 1.

Table 5—Combined ranking values for the five forested (canopy cover > 10 percent) composite classes with the lowest combined rank scores

FSVeg class	Canopy cover	Size class	Rank, mean NDVI loss	Rank, area	Combined rank ^a
PIEN	Moderate	Medium	30	41	40
Mixed	Low	Small	19	39	42
POTR	High	Small	42	38	43.5
POTR	Moderate	Small	43	37	43.5
ABLA	Moderate	Large	41	40	45

FSVeg = field-sampled vegetation; NDVI = normalized difference vegetation index; PIEN = Engelmann spruce; POTR = quaking aspen; ABLA = subalpine fir.

^a Combined rank is the rank of the mean of area rank and mean NDVI loss rank. Only forested composite classes with > 10 polygons were considered in this ranking.

Discussion

NDVI loss as observed in this study generally reflected the characteristics of the MPB epidemic, the dominant disturbance agent that affected the dominant stand type in the study area during the analysis period (2000–2012). The preferred host for MPB in the study area is large PICO trees in relatively dense stand conditions. Three of the top five NDVI loss stand types were of the PICO type with moderate or high canopy cover and medium or large trees (table 4). In addition, the stand type exhibiting the highest 2001–2012 NDVI loss was WL, which had a high PICO component (47 percent relative canopy cover) (table 3).

However, the high NDVI loss in WL may be indicative of understory drought stress, given that tree canopy cover was less than 20 percent in this class. The POTR stands had the least NDVI loss of all the stand types (table 5). With overstory POTR decline (sudden aspen decline), understory vegetation likely increased owing to increased resource availability (light, nutrients, and water), and the decrease in overstory vegetation was likely compensated for by the increase in NDVI resulting from understory “release.” Also, NDVI has the tendency to saturate on high-biomass sites (Huete et al. 2002), so the loss of POTR overstory canopy may not be detected. In contrast, woodlands are lower in overstory canopy cover and are less likely to saturate, and understory is more consistently detectable by the satellite sensor. Any changes in woodlands understory would affect the NDVI response.

ADS Data

Aspen defoliation is typically the result of an infestation of the large aspen tortrix (*Choristoneura conflictana* Walker) and was grouped for this analysis with SAD. Theoretically, aspen defoliation owing to tortrix infestation and SAD could be differentiated on the basis of the rate of defoliation (fast, within growing season, or slow, over several years). However, in the ADS data, aspen defoliation was recorded as either mortality or defoliation depending on the year of the survey, thus we were not able to reliably calculate the number of trees killed prior to 2007.

Mountain Pine Beetle mortality was the dominant damage agent over the period of study 2001–2012, and the preferred host, medium and large PICO in high-canopy-cover stands, was also the most common stand type. The total number of trees that succumbed to MPB was 18 to 21 times that of other common damage agents, ABLA decline and spruce beetle (table 2). On a biennial basis, MPB mortality was 2 to 10 times that of the other damage agents (fig. 7B). The majority of mortality in mixed stands was recorded in 2005–2008 (fig. 6B). Subalpine fir mortality was

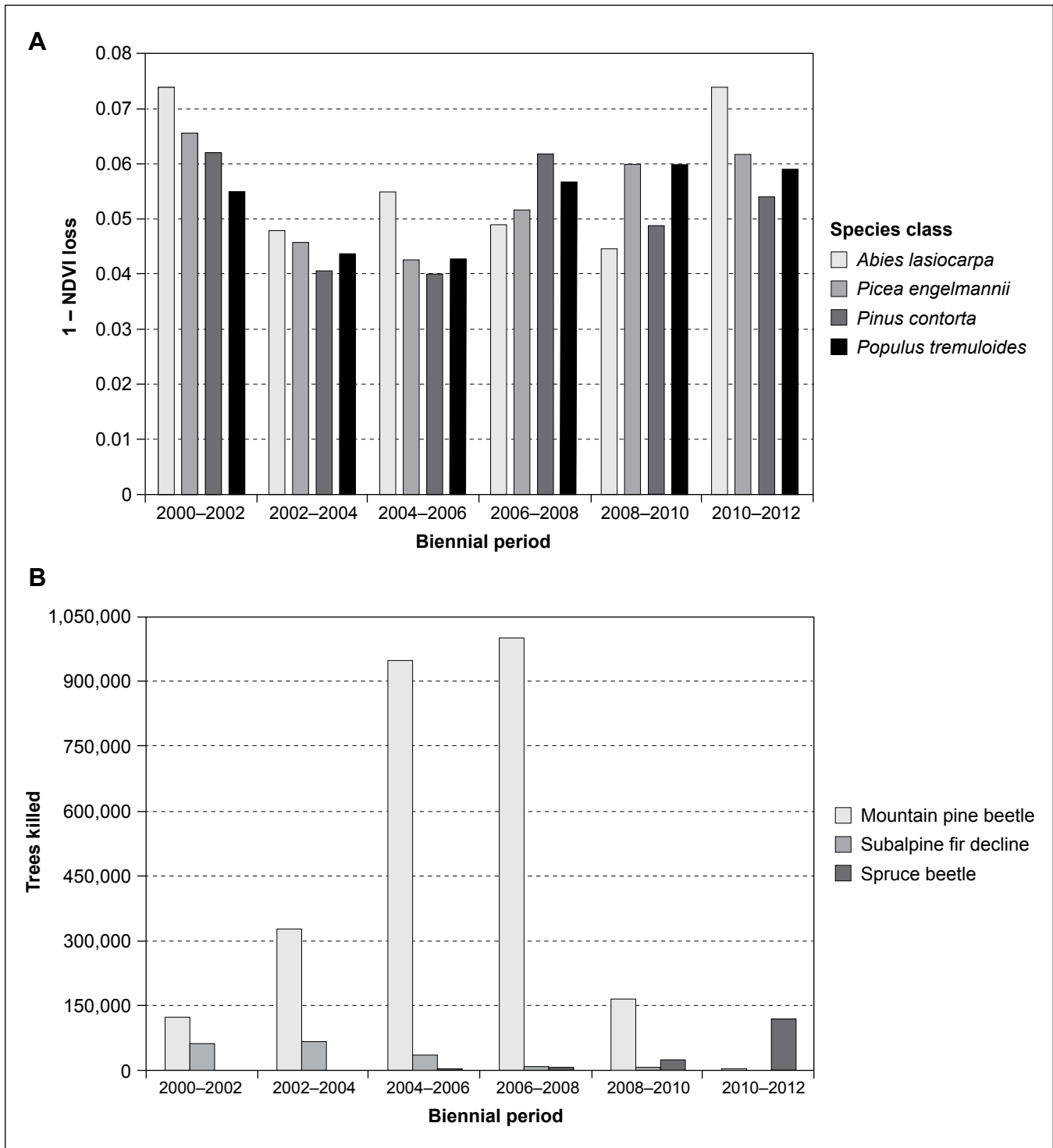


Figure 7—(A) Mean normalized difference vegetation index (NDVI) loss (expressed as 1 - NDVI loss) for each of the FSveg stand classes with a single dominant species. Values are displayed for each biennial period. (B) number of trees killed by the top three damage agents in each biennial period from the aerial detection survey (ADS) database.

more than 60,000 trees (according to the ADS data) in 2000–2002 and 2002–2004, then decreased steadily to around 500 trees in 2011 and 2012. The trend for spruce beetle was the opposite, with no mortality recorded in 2001 or 2002, followed by a steady increase to more than 118,000 trees in 2011 and 2012.

ADS and NDVI—Two Views Across Space and Time

The 2001–2012 mean NDVI loss generally reflects the characteristics of the insect and disease outbreaks that occurred in the study area during the analysis period. These patterns are consistent with the observations in the Forest Service’s Forest Health Conditions Reports for the analysis period (Harris et al. 2002; Harris 2010, 2013), and in the metrics extracted from the ADS data. The four dominant insect and disease disturbance agents identified in the ADS data for the study area—MPB, ABLA decline, spruce beetle, and aspen decline (tortrix and SAD)—are generally attributable to a single host, and therefore we can relate them directly to the NDVI loss values in the stand types with their corresponding dominant host in table 3. The ADS estimates of trees killed over the analysis period (2001–2012) followed the same order as the NDVI loss values with MPB (PICO preferred host) followed by ABLA decline (ABLA preferred host), spruce beetle (PIEN preferred host), and aspen defoliation/SAD (table 2). Woodlands were an exception, although their high NDVI loss can be expected considering the high PICO content (47 percent relative canopy cover) and low (< 20 percent) total tree canopy cover, which exposes the more drought-sensitive understory vegetation.

When we examined NDVI loss and ADS trees killed for each of the biennial periods, the effect of drought recovery on NDVI values became apparent. Colorado experienced severe drought in 2002, and chronic drought in 2000, 2001, and 2003 (Spruce et al. 2011b). The NDVI values are sensitive to both production and foliar moisture, so we would expect to see substantial NDVI loss during this period. However, NDVI loss decreased from 2000 to 2006 (fig. 7A). During the same period, ADS PICO mortality increased from less than 150,000 trees to more than 900,000 (fig. 7B). This pattern can also be seen in the biennial maps for 2002–2004 (figs. 5C and 5D) and 2004–2006 (figs. 5E and 5F). A likely factor in this discrepancy is masking of NDVI loss resulting from PICO mortality by drought recovery in 2003–2004. The baseline year (2000) was at the height of a record-setting drought, so with the return of normal (average regional) precipitation in 2004, the NDVI ratio (target year/baseline year) in many areas showed NDVI gain rather than loss. This confounding factor to the direct relationship between ADS trees killed and NDVI loss also seems likely considering the possibility of mixed vegetation types within a single 5.37-ha MODIS pixel. Following

the drought recovery, ADS-assessed MPB tree mortality and PICO NDVI loss both peaked in 2007–2008, then a rapid decline in tree mortality occurred while NDVI loss values remained stable. NDVI loss in all stand classes was probably affected by this drought recovery. ABLA NDVI loss was reduced in 2003, while the ADS subalpine fir mortality remained stable. Another consideration is the nature of aerial survey compared to the way the MODIS instrument “sees” the landscape. The human eye is able to discern dispersed insect and disease overstory mortality in a drought recovery year, whereas the MODIS instrument cannot make this distinction. Especially problematic are open, mixed-species stands such as ABLA/PIEN mixes at high elevations. ABLA stands had an average TCC of only 38 percent and an average RCC of 38 percent PIEN. PIEN stands also contained a substantial amount of ABLA (33 percent RCC). Considering these mixed stands, timing of pests, and thus mixed reflectance as detected by MODIS, it is not surprising that ABLA and PIEN stands do not show a strong direct relationship between NDVI loss and trees killed. Drought recovery in the understory of the relatively open ABLA stands likely obscured NDVI loss associated with subalpine fir decline that we see in the ADS data for 2002–2004. The lack of trees killed by subalpine fir decline in 2011 and 2012 was not reflected in the NDVI loss data for the same period; NDVI loss for ABLA stands for 2011 and 2012 was nearly as high as in 2000–2002. At the same time, a substantial increase in trees killed by spruce beetle was apparent in the ADS data. It may be the PIEN component in the ABLA stands that drove this high NDVI loss. The NDVI loss in the POTR class followed the “drought recovery” pattern with a decrease in loss coinciding with increased precipitation in 2004. Aspen decline was recorded as defoliation and, as such, no tree mortality data are available for comparison to the NDVI loss metrics. In terms of hectares affected, the peak of aspen decline in the ADS data occurred in 2009–2010 (883 ha), which corresponded to the peak NDVI loss for POTR in 2008–2010.

Sources of Error

Undoubtedly, many of the polygons in the study area changed dramatically since 2001, the year the photography used in stand interpretation was collected, and thus the classification should be used cautiously. For example, a stand classified as PICO in 2001 may have had sufficient PICO mortality to be classed as a PIEN-dominant polygon in 2012. Some of this error is due to the stand being classified on the map as a polygon. The accuracy of the photo-interpreted stand variables (dominant overstory species, size class, canopy cover) used in the classification was not assessed, and errors would affect our results. The stand variables are linked

with the stand boundaries as the interpreter defines homogenous vegetation conditions and then classifies the structure and species attributes within this area. This process is inherently subjective; interpreters rely heavily on their local knowledge. Accuracy assessments of photo-interpreted data are rare (Congalton and Green 2009); however, validation by another qualified interpreter and field visits would perhaps improve the stand layer and increase confidence in its use. This validation is expected to be conducted in 2016 with both ground truth and high-resolution multispectral imagery.

Of particular importance when comparing ADS mortality or defoliation estimates to changes detected with remote sensing is the potential variation in the aggregation of damaged trees within an ADS polygon. Some observers tend to aggregate dispersed pockets of damage into one large low-intensity polygon (“lumpers”), whereas others may identify each of the small pockets individually (“splitters”) (McConnell et al. 2000). These approaches yield different results, especially in terms of acres affected. To minimize this issue, we compared NDVI loss with trees killed rather than acres affected. However, we are making the assumption that the trees killed are distributed uniformly within the ADS polygon, which usually is not the case. Error is then introduced when these data are aggregated spatially—the stand may be in the portion of the ADS polygon that contains little or no damage. Aerial estimates of trees killed per hectare (TPha) are also subject to error. Observers are trained to map only current-year damage, which is difficult when one is mapping 15 to 30 acres per second (Backsen and Howell 2013). ADS data have been shown to underestimate damage intensity (TPha) (Meddens et al. 2012) probably because of mid and understory trees not being visible to the observer. This does not affect our overall results, which document the trend of NDVI to track insect and disease damage, but would if we were attempting to quantitatively relate NDVI loss to TPha. Comparing stand maps of mean NDVI loss and mean cumulative TPha for the study period (fig. 3) shows areas of agreement and disagreement between the two metrics.

MODIS Data Issues

Our estimates of disturbance using these remote sensing methods are likely to be conservative because of the number of pixels identified as low quality in the NDVI MAX data (17 percent). These pixels were masked out in our process because they had insufficient data to calculate an NDVI MAX value, thus any NDVI loss associated with these pixels was not accounted for in the results. Future work may include assigning data values to these pixels based on an average of neighboring pixels and researching other sources for NDVI MAX data.

MODIS data are optimal for assessments at regional and larger extents, but this study showed inherent problems when the granularity (pixel size) of the remotely sensed data is large relative to the size of the minimum mapping unit. More than 35 percent of the stands in our study area were smaller than a MODIS pixel (5.37 ha). Summarizing 250-m pixel values for vegetation polygons smaller than 20 ha should be avoided where possible given the potential of these classification units to include many partial pixels. Nevertheless, we believe that it is possible to have confidence in results with smaller analysis units if the population size and areal extent of the given class is accounted for. In this study we used a minimum population size of 10 polygons and sorted our classes by a mean of the NDVI loss rank and area rank. Another solution to this problem is to use a higher spatial resolution NDVI data source such as 30-m Landsat data, data from commercial vendors (IKONOS, WorldView) or high-resolution (< 1 m) airborne multispectral data (Coleman et al. 2011).

Drought Effects

As previously described, Colorado experienced extreme drought conditions from 2000 through 2003 (Spruce et al. 2011b). NDVI values are sensitive to foliar moisture, so we would expect to see substantial NDVI loss during this period. This was not seen in our results because our baseline year (2000) was the first drought year, therefore no drought-related NDVI loss was detected in 2002. If MODIS NDVI data were available prior to 2000 and these data were used as a baseline, then NDVI loss calculated would likely be much greater because the data taken prior to 2000 would precede the drought. Drought stress effects differ depending on the vegetation type. Understory shrubs, forbs, and grasses likely will exhibit a reduction in NDVI based on a 1-year water deficit, while conifers may not show the effects of a drought until the second or third year of sustained water deficit. Conversely, recovery from drought may be rapid with understory vegetation and slower in overstory conifers. Anderegg et al. (2015) reported that tree recovery from drought may take as long as 4 years. The relatively low NDVI loss seen in the biennial 2002–2004 period may have been caused by understory vegetation recovery (NDVI gain) in 2004 following the 2000–2003 drought, counteracting canopy NDVI reduction resulting from MPB and other damage agents. Normalizing the NDVI data with climate data has been shown to improve detection of trends in NDVI greenness (Nash et al. 2014). This approach may help reduce the influence of short- and long-term climate variations in NDVI response. This may be particularly important in the Interior West of the United States, where forest cover is open and dry relative to the temperate forests in the East. Other vegetation indices may be better suited to change detection in coniferous forests (Huete et al. 1997). A comprehensive study of the performance of these indices in detecting foliar change (phenological and insect and disease damage) is needed.

Biennial Analysis Periods

Our decision to calculate biennial rather than annual NDVI loss may also have led to an underestimation of MPB disturbance, particularly if the dynamics of MPB infestation in PICO is considered. Typically, PICO trees infested with MPB do not show foliar damage until the following spring when the needles exhibit chlorophyll degradation and take on a red color of remnant foliar pigments (red attack stage). Two to three years after infestation, depending on site conditions, these trees drop their needles and become gray snags (gray attack stage) (Safranyik 2004). Detection of NDVI loss at the gray attack stage may be confounded by the response of the understory to the increased availability of sunlight and increased visibility owing to the loss of overstory foliage. Spruce et al. (2011b) noted that while MPB-infested stands appear to have significant mortality, there is actually a substantial amount of green vegetation present given the MODIS pixel resolution. Our biennial approach may miss the more easily detectable red attack stage, especially on low-productivity sites, thus NDVI loss would be underestimated or otherwise different from the response due to red-attack forest. Dead gray forest with intact forest overstory canopy would still show a drop in NDVI compared to nondisturbed green forest canopies. Investigators have focused on using remote sensing approaches to mapping red attack, but studies focusing on gray attack are comparatively fewer in number (Wulder et al. 2006). Calculating annual loss should consider site-specific forest successional sequences, particularly if the analysis period is short (less than 10 years) or if the primary insect or disease mechanism is such that understory vegetation response could possibly compensate for the NDVI loss in the upper canopy. The biennial vs. annual time period for NDVI was believed to be more appropriate for comparison with ADS data.

Conclusions

Overall, our NDVI loss data are conservative for several reasons: (1) it is likely that drought recovery masked the NDVI loss resulting from insect and disease damage; (2) the use of biennial periods may have caused us to miss some MPB red attack mortality; (3) the existence of low-quality pixels in the MODIS NDVI MAX dataset for which we were unable to calculate NDVI loss; and (4) nonlinear saturation of NDVI may have hidden NDVI loss on high-biomass sites.

Our results using NDVI loss summarized by stand generally coincide with the ADS data, although comparisons should be interpreted cautiously because of the subjective nature of ADS and issues with spatial and temporal aggregation of both datasets. Neither of these datasets can be considered “truth,” so a discussion of accuracy is not relevant. Rather, they are two different ways of looking at the landscape, each with strengths and weaknesses. The ADS data provide damage estimates for

specific agents that remotely sensed data cannot provide, while remotely sensed data can provide more accurate areal estimates of damage, especially during widespread intense outbreaks that are difficult to map accurately from aircraft.

The framework we have presented here can provide rapid response products to help forest managers assess the structure and composition of stands affected by insect and disease disturbance outbreaks as well as plan for and prioritize forest stand monitoring. Additionally, these methods provide a synoptic view of the progression of an insect or disease outbreak across the landscape, which can help managers assess the size, dominant species, and condition (time since mortality) of standing dead timber to aid planning and salvage management efforts. After development of the base NDVI change layers for the western conterminous United States, these methods can be applied to any landscape with stand polygon data. Managers with local knowledge of the landscape should be enlisted to help with the interpretation phase.

Existing forest inventory methods are designed to characterize current vegetation conditions, but they provide little information on the history and extent of insect and disease disturbance. Forest Inventory and Analysis program data have been used to successfully characterize mortality at regional scales (Shaw et al. 2005, Thompson 2009). The techniques described in this report provide an alternative to aerial surveys for characterizing mortality at subregional scales and have the advantage of quick delivery of temporal and spatial distributions of mortality by stand—the analysis unit for forest management information systems.

Future work to enhance these methods includes investigating higher resolution NDVI loss data sources, and development of methods to normalize NDVI data with climate and weather data.

Acknowledgments

The authors thank Carson Stam for providing data relevant to the study area and Craig Baker for his insightful review of the draft manuscript. Stam and Baker are on-site contract remote sensing analysts at the U.S. Forest Service Remote Sensing Applications Center in Salt Lake City, Utah.

English Equivalents

When you know:	Multiply by:	To find:
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet
Meters (m)	1.094	Yards
Hectares (ha)	2.47	Acres

Literature Cited

- Anderegg, W.R.L.; Schwalm, C.; Biondi, F.; Camarero, J.; Koch, G.; Litvak, M.; Ogle, K.; Shaw, J.; Shevliakova, E.; Williams, A.; Wolf, A.; Ziaco, E.; Pacala, S. 2015.** Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science*. 349(6247): 528–532.
- Assal, T.J.; Sibold, J.; Reich, R. 2014.** Modeling a historical mountain pine beetle outbreak using Landsat MSS and multiple lines of evidence. *Remote Sensing of Environment*. 155: 275–288.
- Backsen, J.; Howell, B. 2013.** Comparing aerial detection and photo interpretation for conducting forest health surveys. *Western Journal of Applied Forestry*. 28(1): 3–8.
- Bentz, B.J.; Régnière, J.; Fettig, C.; Hansen, M.; Hayes, J.; Hicke, J. 2010.** Climate change and bark beetles of the western United States and Canada: direct and indirect effects. *BioScience*. 60(8): 602–613.
- Ciesla, W.M. 2006.** Aerial signatures of forest insect and disease damage in the western United States. Report FHTET-01-06. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team. 94 p. <http://www.fs.fed.us/foresthealth/technology/pdfs/AerialSignatures.pdf>. (15 May 2014).
- Coleman, T.W.; Grulke, N.E.; Daly, M.; Godinez, C.; Schilling, S.; Riggan, P.J.; Seybold, S.J. 2011.** Coast live oak (*Quercus agrifolia*) susceptibility and response to goldspotted oak borer (*Agrilus auroguttatus*) injury in California. *Forest Ecology and Management*. 261: 1852–1865.
- Congalton, R.; Green, K. 2009.** Assessing the accuracy of remotely sensed data: principles and practices. 2nd ed. Boca Raton, FL: CRC/Taylor & Francis. 183 p.
- Dale, V.H.; Joyce, L.; McNulty, S.; Neilson, R.; Ayres, M.; Flannigan, M.; Hanson, P.; Irland, L.; Lugo, A.; Peterson, C.; Simberloff, D.; Swanson, F.; Stocks, B.; Wotton, B. 2001.** Climate change and forest disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. *BioScience*. 51(9): 723–734.
- Dong, J.R.; Kaufmann, R.; Myneni, R.; Tucker, C.; Kauppi, P.; Liski, J.; Buermann, W.; Alexeyev, V.; Hughes, M. 2003.** Remote sensing estimates of boreal and temperate forest woody biomass: carbon pools, sources, and sinks. *Remote Sensing of Environment*. 84: 393–410.

- de Beurs, K.M.; Townsend, P.A. 2008.** Estimating the effect of gypsy moth defoliation using MODIS. *Remote Sensing of Environment*. 112(2008): 3983–3990.
- Esri. 2011.** ArcGIS Desktop: Release 10.1. Redlands, CA: Environmental Systems Research Institute.
- Goodwin, N.; Coops, N.; Wulder, M.; Gillanders, S.; Schroeder, T.; Nelson, T. 2008.** Estimation of insect infestation dynamics using a temporal sequence of Landsat data. *Remote Sensing of Environment*. 112(2008): 3680–3689.
- Hargrove, W.; Spruce, J.; Gasser, G.; Hoffman, F. 2009.** Toward a national early warning system for forest disturbances using remotely sensed canopy phenology. *Photogrammetric Engineering and Remote Sensing*. 75: 1150–1156.
- Harris, J.L., comp. 2010.** Rocky Mountain Region forest health conditions, 2006–2008. R2-2010-RO-31. Lakewood, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Region. 56 p. https://fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5251119.pdf. (25 June 2014).
- Harris, J.L., comp. 2013.** 2013 forest insect & disease conditions in the Rocky Mountain Region (R2). R2-14-RO-32. Lakewood, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Region. 68 p. http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3827821.pdf. (26 June 2014).
- Harris, J.L.; Mask, R.; Witcosky, J., comps. 2002.** Forest insect and disease conditions in the Rocky Mountain Region, 2000–2001. Lakewood, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Region. 42 p. http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsbdev3_039465.pdf. (25 June 2014).
- Harris, J.W.E.; Dawson, A.F. 1979.** Evaluation of aerial forest pest damage survey techniques in British Columbia. Report BC-X-228. Victoria, BC: Canadian Forest Service.
- Hicke, J.; Logan, J. 2009.** Mapping whitebark pine mortality caused by a mountain pine beetle outbreak with high spatial resolution satellite imagery. *International Journal of Remote Sensing*. 30(2009): 4427–4441.
- Huete, A.; Didan, K.; Miura, T.; Rodriguez, E.; Gao, X.; Ferreira, L. 2002.** Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*. 83: 195–213.
- Huete, A.; Liu, H.; Batchily, K.; Leeuwen, W. 1997.** A comparison of vegetation indices over a global set of TM images for EOS-MODIS. *Remote Sensing of Environment*. 59: 440–451.

- Hummel, S.; Hudak, A.; Uebler, E.; Falkowski, M.; Megown, K. 2011.** A comparison of accuracy and cost of LiDAR versus stand exam data for landscape management on the Malheur National Forest. *Journal of Forestry*. 109(5): 267–273.
- Jensen, J. 2005.** Introductory digital image processing. 3rd ed. Upper Saddle River, NJ: Prentice Hall. 526 p.
- Johnson, E.; Wittwer, D. 2008.** Aerial detection surveys in the United States. *Australian Forestry*. 71(3): 212–215.
- Masek, J.; Goward, S.; Kennedy, R.; Cohen, W.; Moisen, G.; Schleweiss, K.; Huang, C. 2013.** United States forest disturbance trends observed with Landsat time series. *Ecosystems*. 16(2013): 1087–1104.
- McConnell, T.; Johnson, E.; Burns, B. 2000.** A guide to conducting aerial sketchmap surveys. Report FHTET-00-01. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team. 88 p.
- McKellip, R.; Prados, D.; Ryan, R.; Ross, K.; Spruce, J.; Gasser, G. 2008.** Remote sensing time series analysis, a vegetation monitoring tool. *NASA Technical Briefs*. 32(4): 63–64.
- Meddens, A.; Hicke, J.; Ferguson, C. 2012.** Spatiotemporal patterns of observed bark beetle-caused tree mortality in British Columbia and the western United States. *Ecological Applications*. 22(7): 1876–1891.
- Meddens, A.; Hicke, J.; Vierling, L.; Hudak, A. 2013.** Evaluating methods to detect bark beetle-caused tree mortality using single-date and multi-date Landsat imagery. *Remote Sensing of Environment*. 132(2013): 49–58.
- Meigs, G.; Kennedy, R.; Cohen, W. 2011.** A Landsat time series approach to characterize bark beetle and defoliator impacts on tree mortality and surface fuels in conifer forests. *Remote Sensing of Environment*. 115(2011): 3707–3718.
- Nash, M.; Bradford, D.; Wickham, J.; Wade, T. 2014.** Detecting change in landscape greenness over large areas: an example for New Mexico, USA. *Remote Sensing of Environment*. 150(2014):152–162.
- Neigh, C.S.; Bolton, D.; Diabate, M.; Williams, J.; Carvalhais, N. 2014.** An automated approach to map the history of forest disturbance from insect mortality and harvest with Landsat time-series data. *Remote Sensing*. 6(4): 2782–2808.

- Norman, S.; Hargrove, W.; Spruce, J.; Christie, W. 2014.** Monitoring forest disturbances across seasons using the *ForWarn* recognition and tracking system. In: Potter, K.; Conkling, B., eds. Forest health monitoring: national status, trends, and analysis 2013. Gen. Tech. Rep. SRS-207. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 85–99. Chapter 6.
- Norman, S.; Hargrove, W.; Spruce, J.; Christie, W.; Schroeder, S. 2013.** Highlights of satellite-based forest change recognition and tracking using the ForWarn System. Gen. Tech. Rep. SRS-GTR-180. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 30 p.
- Ramsey, E.; Spruce, J.; Rangoonwala, A.; Suzuoki, Y.; Smoot, J.; Gasser, J.; Bannister, T. 2011.** Daily MODIS data trends of hurricane-induced forest impact and early recovery. *Photogrammetric Engineering and Remote Sensing*. 77(11): 133–143.
- Rossini, M.; Cogliati, S.; Meroni, M.; Migliavacca, M.; Galvagno, M.; Busetto, L.; Cremonese, E.; Julitta, T.; Siniscalco, C.; Morra di Cella, U.; Colombo, R. 2012.** Remote sensing-based estimation of gross primary production in a sub-alpine grassland. *Biogeosciences*. 9: 2565–2584.
- Safranyik, L. 2004.** Mountain pine beetle epidemiology in lodgepole pine. In: Shore, T.L.; Brooks, J.E.; Stone, J.E., eds. Mountain pine beetle symposium: challenges and solutions. Information Report BC-X399. Victoria, BC: Canadian Forest Service, Pacific Forestry Centre: 33–40.
- Schmidt, C. 2014.** Challenges to Sierra Nevada forests and their local communities: an observational and modeling perspective. Santa Cruz, CA: University of California–Santa Cruz. 125 p. Ph.D. dissertation.
- Seevers, P.; Ottmann, R. 1994.** Evapotranspiration estimation using a normalized difference vegetation index transformation of satellite data. *Hydrological Science*. 39(4): 333–345.
- Shaw, J.; Steed, B.; DeBlander, L. 2005.** Forest Inventory and Analysis (FIA) annual inventory answers the question: What is happening to pinyon-juniper woodlands? *Journal of Forestry*. 103(6): 280–285.
- Sims, D.; Brzostek, E.; Rahman, A.; Dragoni, D.; Phillips, R. 2014.** An improved approach for remotely sensing water stress impacts on forest C uptake. *Global Change Biology*. 20: 2856–2866.

- Solano, R.; Didan, K.; Jacobson, A.; Huete, A. 2010.** MODIS Vegetation Indices (MOD13) C5 users guide. <http://www.ctahr.hawaii.edu/grem/modis-ug.pdf>. (30 July 2014).
- Spruce, J.; Hargrove, W.; Gasser, G.; Smoot, J.; Kuper, P. 2011b.** Potential of MODIS satellite data for assessing forests vulnerable to climate change impacts based on a Colorado Rockies case study. Presentation, 26th annual meeting. Portland, OR: International Association for Landscape Ecology.
- Spruce, J.; Sader, S.; Ryan, R.; Smoot, J.; Kuper, P.; Ross, K.; Prados, D.; Russell, J.; Gasser, G.; McKellip, R.; Hargrove, W. 2011a.** Assessment of MODIS NDVI time series data products for detecting forest defoliation from gypsy moth outbreaks. *Remote Sensing of Environment*. 115(2): 427–437.
- Thompson, M. 2009.** Analysis of conifer mortality in Colorado using Forest Inventory and Analysis's annual forest inventory. *Western Journal of Applied Forestry*. 24(4): 193–197.
- Townshend, J.; Justice, C. 2002.** Towards operational monitoring of terrestrial systems by moderate-resolution remote sensing. *Remote Sensing of Environment*. 83(1–2): 351–359.
- U.S. Department of Agriculture, Forest Service [USDA FS]. 2005.** Aerial survey geographic information system handbook: sketchmaps to digital geographic information. 27 p. http://www.fs.fed.us/foresthealth/technology/pdfs/GISHandbook_body_apndxA-C.pdf. (15 January 2015).
- U.S. Department of Agriculture, Forest Service [USDA FS]. 2014.** Field sampled vegetation (FSVeg). <http://www.fs.fed.us/nrm/fsveg/>. (25 June 2014).
- U.S. Department of Agriculture, Forest Service [USDA FS]. 2015.** Forest health protection–mapping and reporting. <http://foresthealth.fs.usda.gov/portal/>. (4 January 2015).
- U.S. Department of the Interior, Geological Survey [USGS]. 2014.** Geospatial multi-agency coordination (GeoMAC) wildland fire support. <http://geomac.usgs.gov>. (15 March 2014).
- Wang, Q.; Adiku, S.; Tenhunen, J.; Granier, A. 2005.** On the relationship of NDVI with leaf-area index in a deciduous site. *Remote Sensing of Environment*. 94(2): 244–255.

Wolf, D. 1994. Forest Service Rocky Mountain Region Integrated Resource Inventory. In: Greer, J., ed. Remote sensing and ecosystem management: proceedings of the fifth remote sensing applications conference. Collingdale, PA: Diane Publishing Company: 111–114.

Worrall, J.; Marchetti, S.; Egeland, L.; Mask, R.; Eager, T.; Howell, B. 2010. Effects and etiology of sudden aspen decline in Colorado, USA. *Forest Ecology and Management*. 260(2010): 638–648.

Wulder, M.; Dymond, C.; White, J.; Leckie, D.; Carroll, A. 2006. Surveying mountain pine beetle damage of forests: a review of remote sensing opportunities. *Forest Ecology and Management*. 221(2006): 27–41.

Wulder, M.; Masek, J.; Jeffrey, G.; Cohen, W.; Loveland, T.; Woodcock, C. 2012. Opening the archive: how free data has enabled the science and monitoring promise of Landsat. *Remote Sensing of Environment*. 122: 2–10.

Pacific Northwest Research Station

Website	http://www.fs.fed.us/pnw/
Telephone	(503) 808-2592
Publication requests	(503) 808-2138
FAX	(503) 808-2130
E-mail	pnw_pnwpubs@fs.fed.us
Mailing address	Publications Distribution Pacific Northwest Research Station P.O. Box 3890 Portland, OR 97208-3890



Federal Recycling Program
Printed on Recycled Paper

U.S. Department of Agriculture
Pacific Northwest Research Station
1220 SW 3rd Ave., Suite 1400
P.O. Box 3890
Portland, OR 97208-3890

Official Business
Penalty for Private Use, \$300