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PRIVATE FORESTS IN THE WILDLAND-URBAN INTERFACE: USING GEOGRAPHIC INFORMATION SYSTEMS (GIS) TO IDENTIFY MANAGEMENT CHALLENGES IN EASTERN WASHINGTON, UNITED STATES

by

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26 March 2015

A capstone report submitted in partial
fulfillment of the requirements for the degree

of

MASTER OF NATURAL RESOURCES

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Abstract

Human activities have significantly altered forest conditions throughout Eastern Washington, United States, particularly in the wildland-urban interface where small acreage private landowners control a significant share of remaining forests. Focusing on Spokane County as a case study, this project used Geographic Information Systems, remotely sensed data, and property ownership information to estimate forest cover, identify private forest landowners in the wildland-urban interface, and measure vegetation changes between 1991 and 2011. Simplified reclassification of land cover yielded an estimated 315,268 acres (127,584 hectares) of forest in the county, approximately 28% of total land area. Forty-seven percent of forested land (149,236 acres - 60,393 hectares) is owned by 21,045 small forest landowners (defined here as individuals owning 2-180 acres). Change detection analysis using multi-temporal Landsat imagery measured slight increases in mean Normalized Difference Vegetation Index (+1.2 points) and mean Normalized Burn Ratio (+5.2 points). Visual comparison with aerial imagery suggested significant increases (>20 points) corresponded with forest growth or regeneration, while significant decreases (>20 points) corresponded with development or forest removal.

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Glossary of terms and acronyms

DNR – Washington State Department of Natural Resources.

EVT – Existing Vegetation Type, a LANDFIRE spatial layer estimating current vegetation and species composition at a given site.

Externality – In economics, third-party costs or benefits which are not directly reflected in market interactions between buyer and seller.

FIA – Forest Inventory and Analysis, a U.S. Forest Service Program to collect, analyze, and report information on the status and trends of America's forests.

GIS – Geographic Information Systems, computer-based systems to aid in the management and analysis of spatial data.

Historic range of variability – The range of dynamic ecosystem conditions observed over a time scale relevant to land management.

LANDFIRE – Landscape Fire and Resource Management Planning Tools, a United States interagency vegetation, fire, and fuels mapping program producing more than 20 geospatial layers with 30 meter spatial resolution and nationwide coverage. Layers are produced primarily from decision-tree classification of Landsat imagery.

Landsat – A long-running earth-observation satellite program providing global land-cover and land-use information since 1972. Landsat satellites provide moderate-resolution imagery of most vegetated areas every 16 days.

Lidar – Similar to radar, lidar measures distance using laser pulses to generate a point cloud.

NBR – Normalized Burn Ratio, a vegetation index developed primarily to measure wildfire burn severity, produced by comparing near-infrared and short-wave infrared reflected light.

NDVI – Normalized Difference Vegetation Index, an estimate of living vegetation density and health produced by comparing visible (red) and near-infrared reflected light.

NIPF – Non-industrial private forestland, a private ownership class in which the landowner does not operate wood processing plants. Within Washington State, NIPF is limited to total land ownership of less than 5,000 acres.

NIR – Near-infrared, measured by Landsat in wavelengths between 0.76-0.90 micrometers (μm).

NLCD – National Land Cover Database, a United States land cover product with 30 meter spatial resolution and 16 land cover types based on decision-tree classification of Landsat imagery.

PDSI – Palmer Drought Severity Index, a climate index intended to measure the duration and intensity of long-term drought conditions.

PLSS – Public Land Survey System, used by the United States government to survey most of the United States. The basic PLSS survey unit is the one-square-mile (640 acre) section.

Riparian area – The biological zone adjacent to an aquatic feature such as a river or stream.

RTI – Rural Technology Initiative, a cooperative program developed by the University of Washington and Washington State University to accelerate the implementation of new technologies in rural forest resource-based communities.

SCD – Spokane Conservation District (formerly SCCD).

SFLO – Small forest landowner. Washington State variously identifies small forest landowners as those who own less than 2,500 acres, 5,000 acres, 9,990 acres, or harvest less than 2 million board feet of timber per year. For this project, small forest landowners are defined as private parties owning between 2-180 contiguous acres containing a measurable forest component within Spokane County.

Spokane County Zoning Classifications (partial list):

F – Forest lands, higher elevation forests devoted to commercial wood production (20+ acres)

LDR-P – Low density residential plus, for single family residential development (1+ acres)

LTA – Large-tract agriculture, devoted to commercial crop production (40+ acres)

RCV – Rural conservation, environmentally sensitive areas (20+ acres)

RT – Rural traditional, large-lot residential and resource-based industry (10+ acres)

STA – Small-tract agriculture, devoted to commercial crop production (10+ acres)

UGA – Urban growth area, within which urban growth is encouraged

SWIR – Short-wave infrared, measured by Landsat in wavelengths between 1.55-1.75 μm and 2.08-2.35 μm.

USDA – United States Department of Agriculture.

USFS – United States Forest Service.

USGS – United States Geological Survey.

WUI – Wildland-urban interface, the transition zone between human development and undeveloped lands.

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Introduction

Problem statement

In the past 200 years, forest conditions in Eastern Washington have changed significantly (Hessburg et al 1999; Hessburg and Agee 2003; Washington DNR 2014a). This is particularly true in the ponderosa pine and mixed conifer forests of Spokane County, where European settlement, railroad construction, agriculture, and timber harvest have contributed to an overall reduction in forest cover (Johnson et al 1994). After 100 years of fire suppression, remaining forests are largely composed of dense even-aged stands susceptible to destruction by fire, insects, and disease (Oliver et al 1994; Spokane County 2014). Simultaneously, rapid population growth has brought increasing numbers of people into the wildland-urban interface (WUI) between forest and city (Spokane County 2007; 2014). Healthy forests are important to the safety and well-being of the county's nearly 500,000 residents, and active management is necessary to restore and protect remaining stands (Hessburg and Agee 2003; Long 2009; Washington DNR 2014a).

Forest management is particularly challenging in Spokane County. Unlike many parts of the Western United States, most of the forested land in Spokane County is privately owned (Rogers and Cooke 2010). Under private ownership, forest protection and restoration can be more responsive, but they are also more difficult (Blatner et al 1994; Creighton et al 2002). In particular, small forest landowners (SFLO) present specific challenges because they own relatively small properties with diverse and individualized management objectives. In Spokane County, more than 20,000 such landowners are estimated to own nearly 50% of forested land, considerably more than any other county in Washington (Rogers and Cooke 2010).

Natural resource administrators broadly understand the challenges facing these forests,

but they lack quantitative information specific to Spokane County. The federal LANDFIRE program estimated vegetation conditions and fire hazards, but nationwide modeling is limited without local ground verification (Vogelmann et al 2006; Provencher et al 2009). Washington sponsored a report in 2007 estimating small forest ownership statewide, but its utility is limited by both scope and age (Rogers and Cooke 2010). County resource managers conduct qualitative forest health assessments annually, but these are often limited to'windshield tours' of areas assumed to be at risk. If they had updated, countywide quantitative information regarding forest ownership and conditions, administrators could more effectively promote forest management in the wildland-urban interface.

Project objectives

This project focused on two primary objectives. First, small forest landownership in Spokane County was quantified using updated land cover and parcel information. Instead of using Washington's broad definition of small forest landowner, this project sought to identify those who are likely to live and recreate in the wildland-urban interface, not those who manage their land primarily for resource production.

Second, this project used multi-temporal Landsat imagery to detect and quantify long-term changes in forest condition. With more than 40 years of archived imagery freely available, Landsat is becoming increasingly popular for measuring forest health and disturbance (Collins and Woodcock 1996; Vogelmann et al 2009; Schroeder et al 2014). For simplicity, this project conducted straightforward time series comparison using two common vegetation indices: the Normalized Difference Vegetation Index (NDVI) and the Normalized Burn Ratio (NBR).

Background information

In the late 20th century, rapid population growth and increasing environmental regulation

brought significant changes to Washington's forests. In many ways, small forest landowners were caught in the middle: suburban and exurban growth pressured owners to subdivide and develop their property, while the increased burden of environmental compliance threatened the economic viability of non-industrial forest management.

Recognizing the importance of preserving forestland and the threats facing non-industrial private forests (NIPF), in 1999 the state legislature established a small forest landowner office as part of its salmon recovery plan. Fearing new regulations would “further erode small landowners' economic viability and willingness or ability to keep the lands in forestry use,” the legislature directed the office to provide technical assistance to small forest landowners statewide (Washington ESHB 2091 Sec. 501).

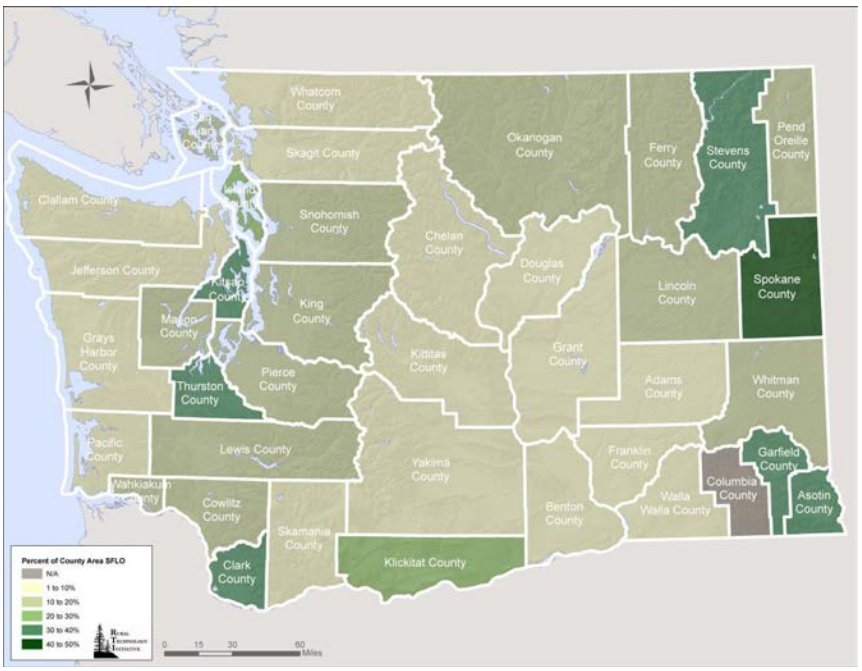

Figure 1 – Washington small forest landownership by county (Rogers and Cooke 2010). Using a broader definition of small forest landowner than this project, the Rural Technology Initiative found that as of 2007, more than 16,000 small forest landowners owned an estimated 60% of forestland and 46% of total land cover in Spokane County, significantly more than any other county.

To support the small forest landowner office, the newly-formed Rural Technology

Initiative (RTI) produced the Washington State Forestland Database to identify forest cover and ownership. Established as a joint venture between the University of Washington and Washington State University, RTI cooperated with the Family Forest Foundation and Washington Farm Forestry Association to create the database. Initially created in 2001, an updated 2007 version determined more than 215,000 small forest landowners (defined by RTI as those owning between 2-2,500 acres in Western Washington and 2-9,990 acres in Eastern Washington) owned 5.7 million acres of forestland statewide. Within Spokane County, more than 16,000 small forest landowners owned 241,000 acres of forest, more than 60% of the county's total forestland and 46% of total land cover, significantly more than any other county (Rogers and Cooke 2010).

The 2007 Forestland Database provided an effective estimate of industrial and non-industrial forest ownership in the state of Washington. However, population, land cover, land use, and land ownership have changed significantly since 2007, particularly in the wildland-urban interface. Further, because the database used standardized methods to quantify forest ownership in 39 individual counties, the results might have differed slightly from a study tailored specifically to a single county.

Study area

Spokane County is located in east-central Washington State, bordering Whitman County to the south, Lincoln County to the west, Stevens and Pend Oreille Counties to the north, and Idaho State to the east. With an area of approximately 1,780 mi^2 (4,610 km^2) and an estimated population of 480,000, Spokane County is Washington's 19th largest and 4th most populous county. Most of the population is concentrated in and around the city of Spokane, but a significant exurban and rural population exists with more than 130,000 people living in unincorporated areas (Washington OFM 2013). With the exception of Turnbull National Wildlife

Refuge in the south and Mount Spokane State Park in the north, most of the county is privately owned.

Figure 2 - Spokane County, Washington, which is the 19th largest and 4th most populous of the state's 39 counties.

Elevation in Spokane County ranges from 1,538 feet (468 m) to 5,883 feet (1,793 m). Vegetation ranges from arid shrub-steppe in the southwest to moist mixed conifer forest in the northeast. Precipitation ranges from less than 16 inches (40 cm) to more than 45 inches (114 cm), generally increasing with elevation and from southwest to northeast.

Within forested areas, ponderosa pine (*Pinus ponderosa*) dominates lower elevations, heavily disturbed areas, and sunny aspects of middle elevations. Higher elevations and shady aspects consist of mixed conifer forests featuring large components of Douglas fir (*Pseudotsuga Menziesii*), lodgepole pine (*Pinus contorta*), and western larch (*Larix occidentalis*). Historically, ponderosa pine forests in the county experienced low-severity wildfire every 5 to 35 years, while mixed conifer forests experienced mixed-severity wildfire every 35 to 200 years. After more than 100 years of fire suppression, overall density has increased in all forest types with large

populations of shade tolerant white fir (*Abies concolor*), grand fir (*Abies grandis*), subalpine fir (*Abies lasiocarpa*), western redcedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*) developing in the understory (Spokane County 2014).

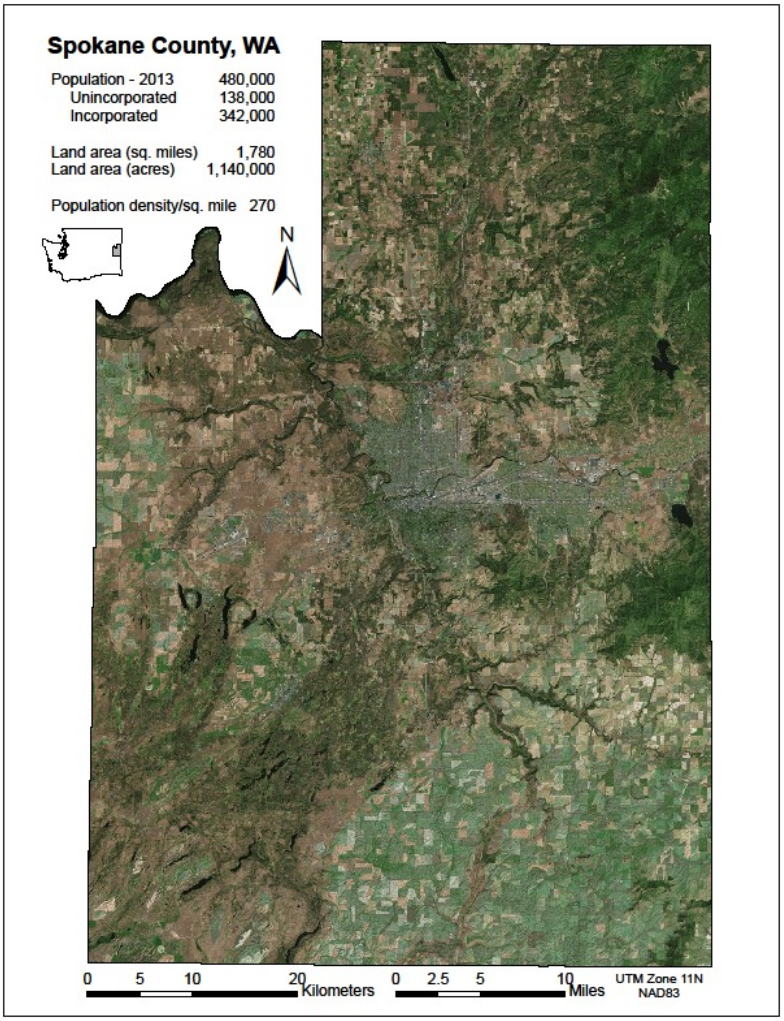

Figure 3 - Overhead imagery of Spokane County, Washington. Vegetation ranges from arid shrub-steppe to moist mixed conifer forest, with large portions of the county converted to agriculture and development. Elevation ranges from 1,538–5,883 feet, and precipitation ranges from 16–45 inches.

Methods

Forest delineation using LANDFIRE

Several methods have been developed to classify land cover using remotely sensed data. The purpose of this project was not to exhaustively compare the relative strengths and

weaknesses of existing land classification methods, but simply to classify land within Spokane County as either forested or non-forested. In determining the best method to accomplish this, the following sources were considered:

- Washington GAP Analysis Program – In cooperation with the U.S. Geological Survey (USGS), the Washington Department of Fish and Wildlife (WDFW) classified existing vegetation cover statewide. Completed in 1997 using 1991 Landsat imagery, GAP is the oldest GIS-based classification considered. GAP analysis also established a 100 hectare (250 acre) minimum size for vegetation type, making its scale unsuitable for this project.

- Washington State Forestland Database – As part of the Rural Technology Initiative (RTI), University of Washington researchers identified statewide forest cover and ownership as of 2007. Using existing data from the 2006 National Land Cover Database (NLCD), RTI created a simplified forest/non-forest map with 30 meter spatial resolution. This database was rejected for this project because it is based on an outdated version of the NLCD (Rogers and Cooke 2010).

- National Land Cover Dataset – Updated most recently with 2011 data, the NLCD classified nationwide land cover with 30 meter spatial resolution. Using decision-tree classification of remotely sensed data (primarily Landsat imagery), the NLCD identified 16 land cover types, 3 of which are forests. The NLCD was rejected for this project primarily due to its limitations in the wildland-urban interface, where areas classified as 'developed, open space' can include up to 80% vegetation (Jin et al 2013).

Ultimately, LANDFIRE was selected as the best available database from which to derive forest cover. Initiated in 2001 and recently updated with 2010 data, LANDFIRE used decision-tree classification of remotely sensed data to map nationwide vegetation, fire and fuel characteristics with 30 meter spatial resolution. LANDFIRE includes more than 20 distinct geospatial layers, including classification of existing vegetation type (EVT). LANDFIRE's EVT

layer identified 71 distinct vegetation types within Spokane County, 30 of which include a tree canopy. In addition to delineating many more vegetation types than the NLCD, the EVT layer includes categories for forests in the wildland-urban interface (Vogelmann et al 2006).

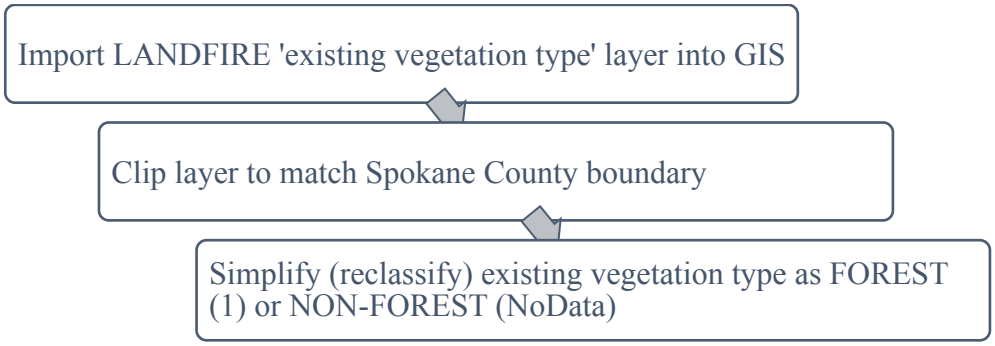

Figure 4 - GIS model for classification of forest cover.

Using GIS (Esri ArcGIS 10.2), the EVT layer was clipped and reclassified to generate a simplified map of forest cover in Spokane County (see Figure 4). Within EVT attributes, 'EVT_ORDER' served as the primary forest cover discriminator, with 32 'tree-dominated' classes tentatively identified as probable forest. After initial classification, 'EVT_CLASS' and 'EVT_SBCLS' (sub-class) served as secondary discriminators and 2 'mixed evergreen-deciduous shrubland' types were removed, leaving 30 vegetation types identified as 'forest.'

Identification of small forest landowners

Small forest landowner is a somewhat vague term which can be defined several ways. Often, the term is used interchangeably with non-industrial private forestland, defined by Washington State as “total individual land ownerships of less than five thousand acres and not directly associated with wood processing or handling facilities” (Washington RCW 76.13.010). Alternatively, the state adopted a volume-based definition for a small forest landowner as someone “harvesting no more than an average of 2 million board feet of timber per year” (Washington RCW 76.09.450). Based on average site productivity, the Washington State

Forestland Database established a maximum limit of 9,990 acres for small forest landowners in Eastern Washington. Minimum size was 2 acres, with at least 1 forested acre (Rogers and Cooke 2010).

Because this project focused on small forest landowners in the wildland-urban interface, state-defined acreage limits were deemed too large. For inclusion in this report, an ownership limit of 180 acres was established. Although this limit is somewhat arbitrary, it is based on survey history and zoning regulations. Parcel boundaries in Spokane County were first established by the Public Land Survey System (PLSS), which divided the county into 640 acre (259 hectare) sections in the late 19th century. The county zoning code – last amended in 2004 – dictates minimum parcel size based on the county's comprehensive plan. Maximum acreage for this project was selected based on the 160 acre ¼ section with a 20 acre buffer added to allow for survey errors and other local variables. Minimum acreage was set at 2 acres, consistent with the Washington State Forestland Database.

Small forest landowner size classes

Class	Size (acres)	Size (hectares)	Notes
10 acre	2-14	0.8-5.6	Primarily LDR-P, RT, STA zoning
20 acre	15-30	5.7-12	Primarily RCV, RT, STA zoning
40 acre	31-60	13-24	PLSS ¼-¼ section; primarily F, LTA, RCV zoning
80 acre	61-120	25-48	Primarily F, LTA, RCV zoning
160 acre	121-180	49-73	PLSS ¼ section; primarily F, LTA, RCV zoning

Table 1 – Author-defined size classes for small forest landowners. Ownership classes are based on the Public Land Survey System and county zoning regulations, especially low density residential plus (LDR-P), rural traditional (RT), rural conservation (RCV), small-tract agricultural (STA), large-tract agricultural (LTA), and forest (F) zones. See glossary for more information on these zoning categories.

Once identified, small forest landowners were further divided into five size classes as detailed in Table 1. The table lists classes in whole acres for simplicity, but size classes actually

begin immediately after the preceding acreage limit (e.g., 20 acre class displayed as 15-30 acres but really 14.0001-30.0000 acres). These classes further differentiate owners based on zoning and possible land use objectives. The zoning classifications most applicable to small forest landowners are listed in Table 1 and detailed in the glossary.

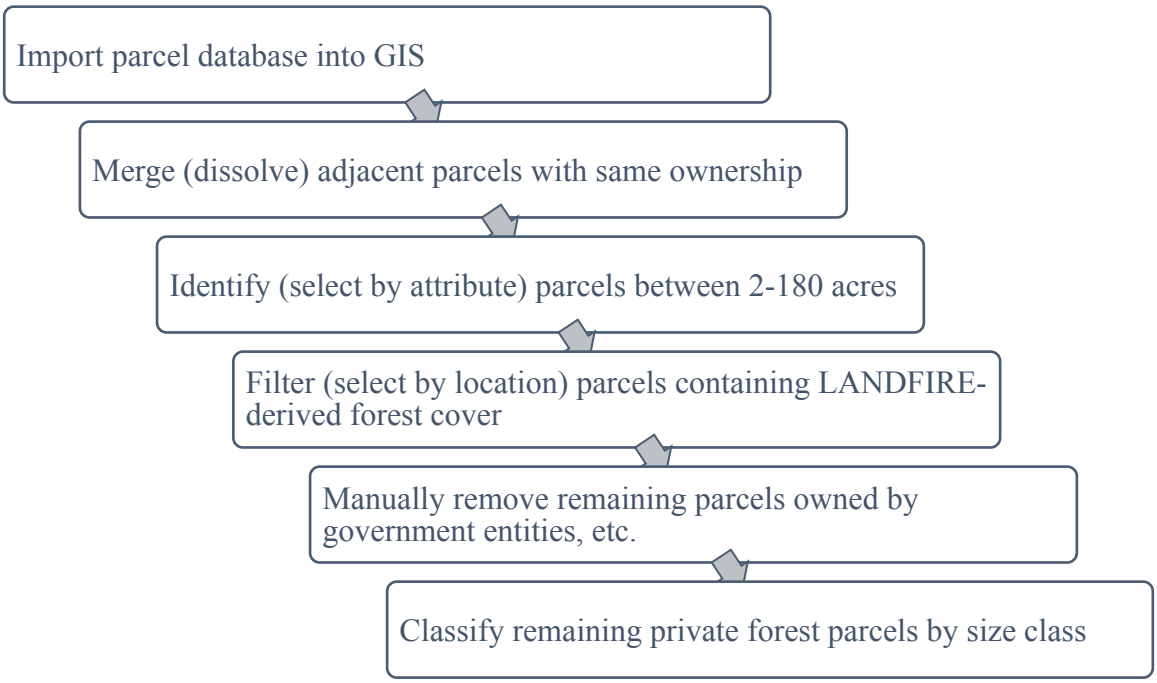

Figure 5 - GIS model for identification of small forest landowners.

Figure 5 displays the GIS model for identification and classification of small forest landowners in Spokane County. Parcel information from 2014 was acquired from the county assessor. Multiple adjacent or nearby parcels often have the same owner; these were merged together to form contiguous parcels reflecting total acreage. Parcels smaller than 2 or larger than 180 acres were excluded from the data, as were parcels lacking LANDFIRE-derived forest cover. Remaining parcels owned by government entities and major corporations (e.g., Burlington Northern Santa Fe Railroad, Avista Utilities, etc.) were manually removed. Lastly, small forest landowners were grouped into size classes.

Change detection using Landsat imagery

Many forests in Eastern Washington are considered unhealthy, but what exactly makes a forest healthy or unhealthy? Renowned conservationist Aldo Leopold (1949) envisioned ecosystem health as "the capacity of the land for self-renewal." Jay O'Laughlin et al (1994) proposed a straightforward definition of forest health as "a condition of forest ecosystems that sustains their complexity while providing for human needs." In recent years, severe disturbances from development, wildfire, and insects have reduced forests' capacity for self-renewal, complexity, and ability to provide for human needs (Washington DNR 2014a). According to the definitions above, these forests are therefore unhealthy.

Currently, two major programs monitor and report forest health in Eastern Washington:

- Aerial Forest Health Survey – The U.S. Forest Service and Washington Department of Natural Resources (DNR) conduct aerial surveys to map disturbance in Washington forests. The annual surveys primarily record wildfire, insect, and weather damage (e.g., wind-throw, drought mortality). While these visual surveys effectively detect large-scale damage, they are much less effective at detecting stress or other potential indicators of future damage (USDA Forest Service 2009).

- Forest Inventory and Analysis (FIA) Program – Using standardized ground survey techniques, the U.S. Forest Service collects, analyzes, and reports comprehensive forest information. Fixed survey plots are established every 6,000 acres and revisited every 5-10 years. More intensive Forest Health Monitoring plots are established every 96,000 acres. The FIA program is effective at detecting stress and damage, but the long return interval and limited number of plots hinders responsiveness (USDA Forest Service 2009; Schroeder et al 2014).

Landsat satellites have provided global land-cover and land-use information continuously since 1972. With broad coverage, moderate resolution, a 16-day return interval, and more than

40 years of archived imagery, Landsat can effectively augment existing forest health monitoring programs and is increasingly being used to this end (Vogelmann et al 2009; Schroeder et al 2014).

For this project, a total of 17 Landsat 5/7 scenes from late September and early October were considered for change detection analysis. The Landsat 5 and 7 satellites measure nearly identical band wavelengths facilitating consistent results, and together they provide continuous coverage from 1984 to the present (as of early 2015). Scenes from early autumn were selected to maximize phenological stability in the forest canopy (Vogelmann et al 2009). Spokane County normally experiences warm, dry summers followed by cool, moist autumn and winter weather. The transitional period from late September through early October is typically characterized by low cloud cover, low soil moisture, and mostly dormant understory vegetation.

Landsat 5 Thematic Mapper, Path 43 Row 27

Landsat 7 Enhanced Thematic Mapper Plus, Path 43 Row 27

Date Acquired	Cloud Cover	Sun Azimuth	Sun Elevation	PDSI
1986-10-08	0	150.24	32.19	-1.49
1987-10-11	0	153.14	31.96	-3.73
1989-10-16	0	153.45	29.86	-0.62
1991-09-20	0	146.73	38.66	-0.75
1992-10-24	3	153.84	26.87	-3.17
1993-09-25	0	147.84	36.71	-0.51
1995-10-01	0	143.25	32.81	3.2
1997-09-20	0	149.63	39.32	0
1998-09-23	0	152.19	38.86	-0.44
2001-10-01	0	154.54	36.06	-1.82
2003-09-21	1	151.21	39.51	-2.56
2005-09-26	0	155.79	38.37	-4.39
2006-09-29	0	158.28	37.80	-2.18
2009-09-21	0	155.16	40.25	-0.74
2011-09-11	0	151.88	43.71	-0.95
2012-09-21	0	157.05	40.56	0.96
2014-09-11	0	155.05	44.34	-2.34

Table 2 - Key metadata for available Landsat scenes. Green highlighted scenes were selected for change detection analysis. Items highlighted yellow did not meet screening criteria due to instrument malfunction, partial cloud cover, sun elevation less than 30 degrees, and/or Palmer

Drought Severity Index exceeding +/-2.

Available scenes were screened for cloud cover and sun azimuth/angle. Because most scenes were cloud-free, the only 2 scenes with measurable cloud cover were excluded. Sun azimuth and angle effect shadows and energy reflectance; sun angles less than 30 degrees are considered unsuitable for vegetation studies (Vogelmann et al 2009). All available scenes had comparable azimuths, but 2 scenes were excluded for low sun angle. On visual inspection, scenes from Landsat 7 were excluded due to data artifacts resulting from persistent instrument malfunction.

To further increase phenological consistency, available scenes were compared to the Palmer Drought Severity Index (PDSI), a measure of long-term drought conditions (Palmer 1965). PDSI values exceeding +/- 2 indicate moderate wetness or drought; 7 scenes were excluded based on PDSI. Of the remaining 8 scenes, 3 (1991, 1998, 2011) were selected for change detection analysis.

Multi-temporal Landsat imagery can be analyzed several ways to detect change. For simplicity, this project used two common vegetation indices to measure changes in forest condition: Normalized Difference Vegetation Index and Normalized Burn Ratio. NDVI estimates vegetation density and health by comparing reflectance in the red (Band 3 – 0.63-0.69 μm) and near-infrared (NIR) (Band 4 – 0.76-0.90 μm) bands using the following equation:

$$\mathbf{NDVI = (NIR - R) / (NIR + R)}$$

This equation generates a ratio between (-1) and 1. Because chlorophyll absorbs light in the red band and reflects light in the NIR band, higher NDVI values indicate greater live vegetation density and vigor.

NBR was developed primarily to measure vegetation responses to wildfire, but can also

be effectively used to detect change in the absence of fire (Miller and Thode 2007). Similar to NDVI, NBR estimates live vegetation and moisture content by comparing reflectance in the short-wave infrared (SWIR) (Band 7 – 2.08-2.35 µm) and NIR bands using the following equation:

$$\mathbf{NBR = (NIR - SWIR) / (NIR + SWIR)}$$

This equation also generates a ratio between (-1) and 1. SWIR waves are mostly absorbed by water and reflected by bare soil and rock, making Band 7 sensitive to moisture stress and disturbance such as wildfire. Like NDVI, higher NBR values indicate greater live vegetation density and vigor.

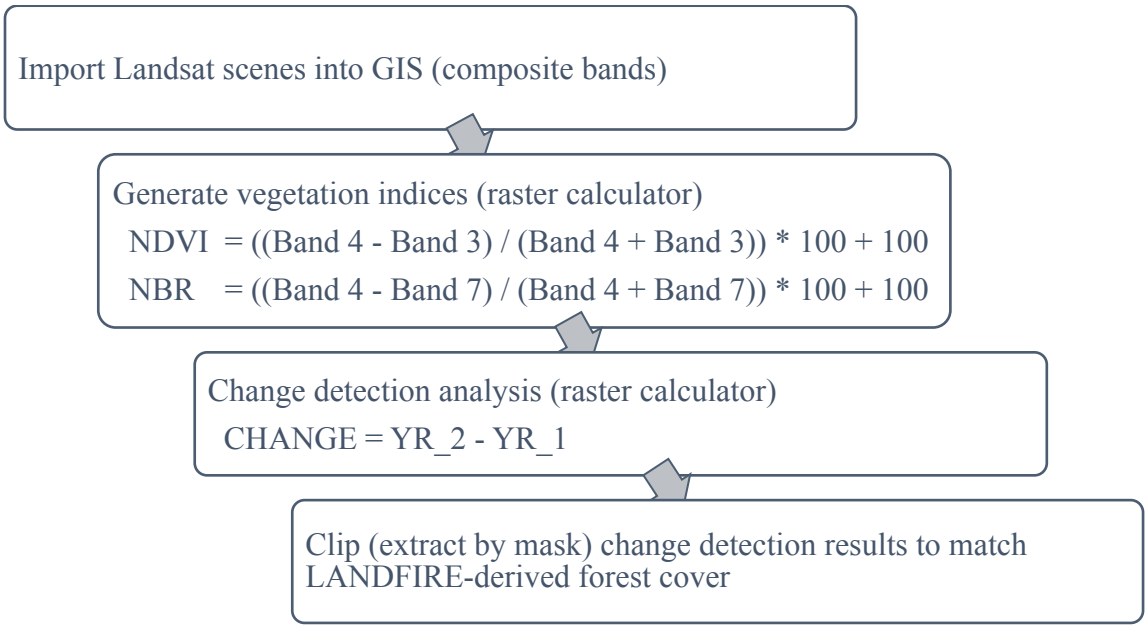

Figure 6 - GIS model for Landsat change detection.

To measure change over time, multi-temporal vegetation indices were simply subtracted from one another using GIS, as displayed in Figure 6. Individual bands from each Landsat scene were combined into composite rasters to facilitate analysis. In ArcGIS, NDVI and NBR equations were modified slightly to generate positive integer values between 0 and 200. After index values were subtracted from one another, they were clipped to include only forested areas.

Results

LANDFIRE-derived forest cover

Reclassification of LANDFIRE existing vegetation data yielded an estimated forest cover of 315,268 acres (127,584 hectares) in Spokane County, approximately 28% of total land area. Figure 7 displays the spatial distribution of forest cover, which is more prevalent in the northern half of the county where elevation and precipitation tend to be higher. However, LANDFIRE likely underestimated forest cover in the ponderosa pine-dominated southwest portion of the county. Informal comparison with aerial imagery revealed several areas where scattered LANDFIRE-derived forest pixels fragmented what appeared to be contiguous patches of low-density forest. This demonstrates one weakness of automatic classification of remotely sensed data, where each 900 m^2 (30 x 30 m) pixel is assigned a single vegetation type based on average conditions throughout the pixel. This can be relatively easy in homogenous landscapes, but becomes more difficult with increasing heterogeneity.

Comparison of forest classification systems

Source	Forest acres	Notes
WA Forestland Database (2007)	332,509	Derived from 2006 NLCD
LANDFIRE (2010)	315,268	Derived from Landsat imagery
NLCD (2011)	318,260	Derived from Landsat imagery
LANDFIRE or NLCD	378,207	Classified forest in either dataset
LANDFIRE and NLCD	255,321	Classified forest in both datasets
LANDFIRE only	59,947	Mostly northern portion of county
NLCD only	62,939	Mostly southwestern portion of county

Table 3 - Comparison of forest cover classifications. LANDFIRE and the NLCD have similar totals but considerable differences in specific pixels classified as forest. In general, LANDFIRE estimated more forest in northern Spokane County and the NLCD estimated more forest in southern Spokane County.

Results were compared with other readily available land classification systems, as shown in Table 3. Although LANDFIRE and the NLCD estimated similar total forest cover in Spokane County, the two differed considerably in spatial distribution. Only 255,321 acres were classified

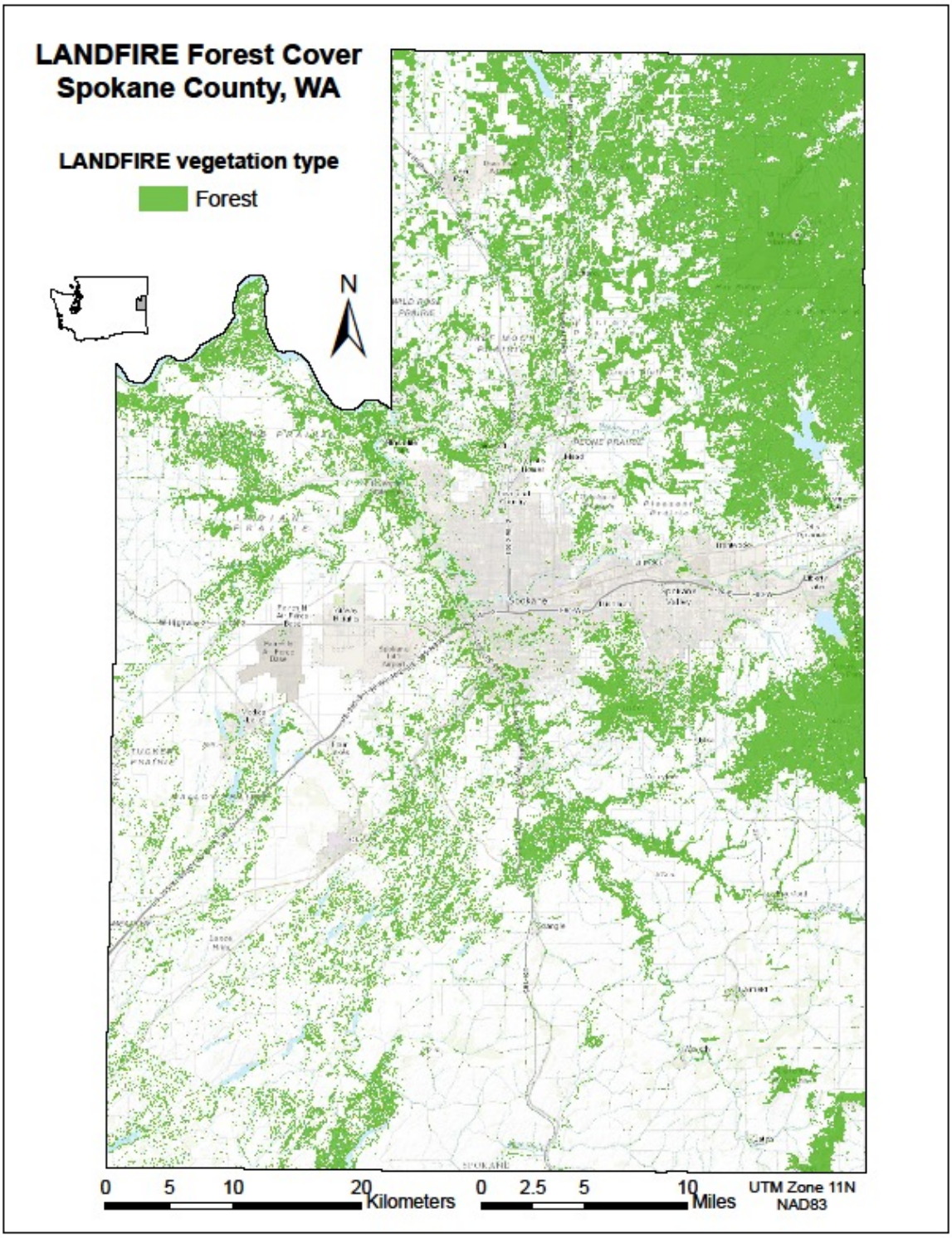

Figure 7 – LANDFIRE-derived forest cover in Spokane County, Washington, totaling an estimated 315,268 acres (127,584 hectares). Forest cover is likely underestimated in the southwest portion of the county, where scattered pixels depict an area dominated by low-density ponderosa pine.

as forest in both databases, compared to 378,207 acres identified as forest in at least one database. Individually, LANDFIRE generally estimated more forest cover in northern portions of the county while the NLCD generally estimated more forest cover in southern portions of the county. Aerial imagery revealed apparent inconsistencies with both databases; actual forest cover in Spokane County is likely somewhere between 315,000 and 378,000 acres.

Small forest landowners by size class

Based on LANDFIRE-derived forest cover, 21,045 small forest landowners in Spokane County own approximately 149,236 acres (60,393 hectares) of forest, accounting for 47% of forested land in the county. Table 4 details ownership by size class, and Figure 8 displays the spatial distribution of size classes throughout the county. More than 70% (14,795) of owners fell into the 10 acre size class, collectively owning nearly 35% (51,785) of small forest acres. These suburban and exurban properties were largely concentrated near the city of Spokane and along major transit corridors throughout the county.

Small forest ownership by size class

Class	Number of owners	Percent of owners	Total acres	Forested acres	Percent SFLO acres
10 acre	14,795	70.3	109,782	51,785	34.7
20 acre	3,429	16.3	70,493	31,489	21.1
40 acre	1,614	7.7	68,446	28,355	19
80 acre	831	3.9	70,070	23,579	15.8
160 acre	376	1.8	55,932	14,028	9.4
Total	21,045	100	374,723	149,236	100

Table 4 - Small forest landowners by size class. 21,045 small forest landowners own approximately 33% of total land and 47% of forested land in Spokane County; most (70.3 %) own between 2–14 acres.

The 160 acre size class was smallest in every category, with 376 owners accounting for only 9% (14,028) of small forest acres. With forested land only accounting for 25% of total parcel acreage, the 160 acre class also showed the lowest proportion of forest cover. Many of

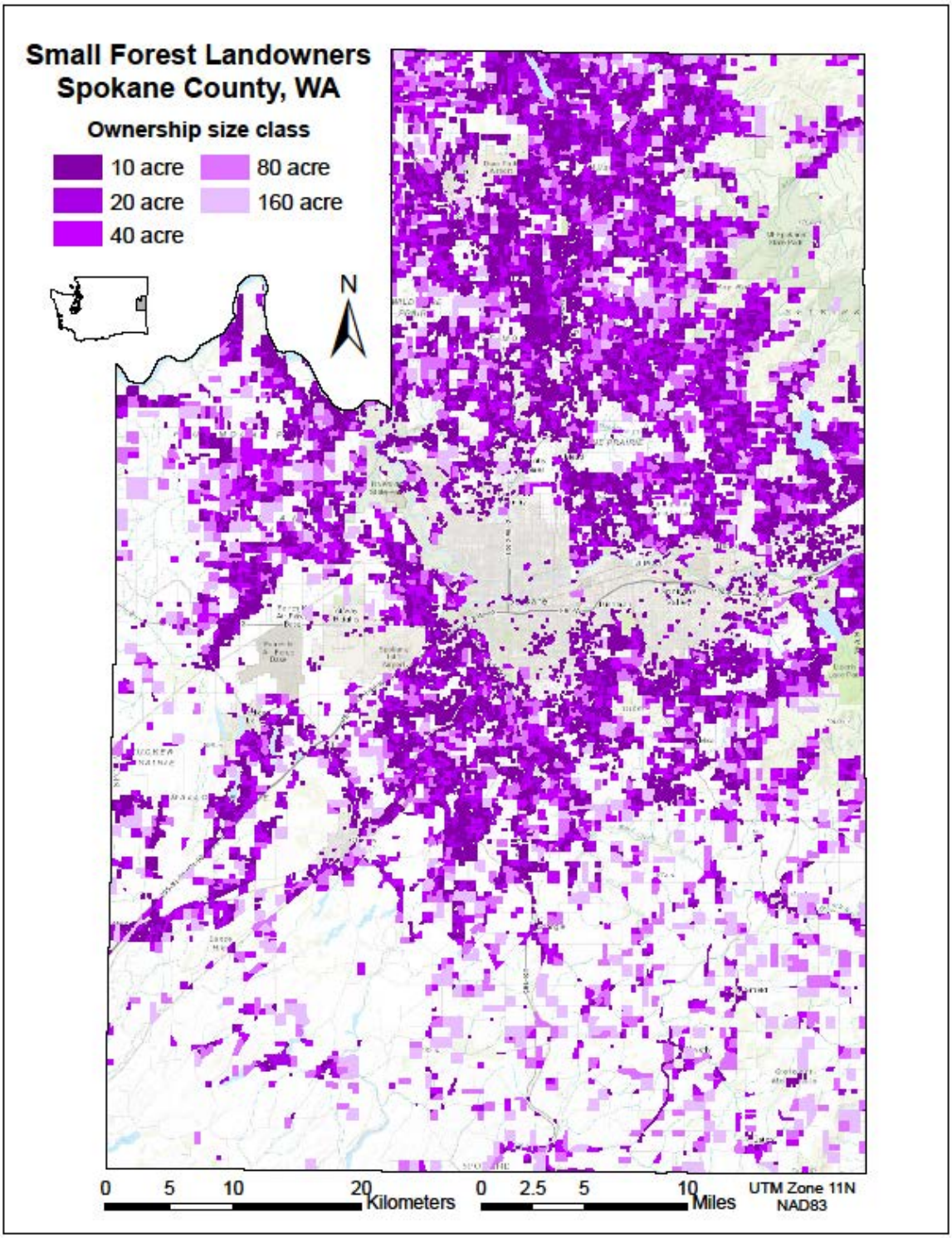

Figure 8 - Small forest landowners in Spokane County, Washington. Small size classes are concentrated in northern portions of the county and immediately south of the city of Spokane. Large size classes in the southeastern portion of the county are primarily agricultural lands with a minor forest component.

these properties were located in the southeastern portion of the county where the primary land use is agriculture and forests are mostly limited to riparian corridors.

Small forest landownership was lowest in the northeastern and southwestern corners of the county. In the northeast, most excluded forests are either state owned (Mt. Spokane State Park) or industrial timberland owned by Inland Paper Company. In the southwest, most excluded forests are either federally owned (Turnbull National Wildlife Refuge) or owned by individuals with more than 180 acres.

Compared to the 2007 Washington State Forestland Database, the number of small forest landowners increased considerably between 2007 and 2014. Even though this project used a more restrictive acreage limit (180 versus 9,990 acres), the number of owners increased more than 28% from 16,378 to 21,045. Total acreage decreased compared to the 2007 database, but most if not all of the reduction can likely be attributed to the difference in acreage limits.

Small forest landowner size class statistics

Class	Median acres	Mean acres	Std Dev
10 acre	6.70	7.14	3.07
20 acre	19.81	20.14	3.99
40 acre	39.86	41.18	7.57
80 acre	79.66	82.92	16.01
160 acre	154.74	148.76	15.33

Table 5 - SFLO size class statistics. Most classes showed relatively normal distribution with median and mean closely matching class title, but the 10 acre class showed a bimodal distribution with 5 and 10 acre parcel clusters.

Statistically, size classes accurately reflected their class title with the exception of the 10 acre class. Table 5 summarizes size class statistics, showing the 10 acre class with median and mean ownerships of 6.70 and 7.14 acres, respectively. This is because the 10 acre class had a bimodal distribution with 5 and 10 acre parcel clusters. If these clusters were subdivided into individual classes, the resulting 5 acre class (2-7 acres) would have 7,918 owners with median

and mean of 4.82 and 4.46 acres; the 10 acre class (7.0001-14 acres) would have 7,455 owners with median and mean of 9.97 and 9.99 acres, respectively.

Although the upper acreage limit was set somewhat arbitrarily, it accurately reflected ownership patterns. In the 160 acre class, 64% of owners (242) were concentrated between 140-170 acres, 32% (119) owned 120-140 acres, and only 4% (15) owned 170-180 acres. Expanding the upper limit to 200 acres would have a marginal impact on total results, adding 24 owners and 4,629 total acres. This would increase median and mean size in the 160 acre class to 155.86 and 151.40 acres, respectively.

Landsat-identified changes in forest condition

Remotely sensed vegetation indices can quickly estimate forest conditions. However, without calibration and ground verification they cannot effectively measure forest health. Because this project lacked ground verification, analysis was thus limited to changes in forest conditions, which may or may not correspond with changes in health.

Between 1991 and 2011, NDVI and NBR indices reflected widespread forest changes throughout Spokane County. Figures 9 and 10 display the respective spatial distributions of NDVI and NBR change in forested areas (see Appendix C for additional change detection figures). Overall, mean index values increased slightly, with mean NDVI increasing 1.2 points and mean NBR increasing 5.2 points. However, as shown in the figures isolated patches throughout the county changed dramatically.

Table 6 summarizes NDVI and NBR change detection statistics. From 1991 to 2011, NDVI increased at least 10 points in 9% (26,811 acres), and decreased at least 10 points in 6% (19,470 acres) of forested land. During the same time period, NBR increased at least 10 points in 33% (105,032 acres), and decreased at least 10 points in 12% (36,717 acres) of forested land.

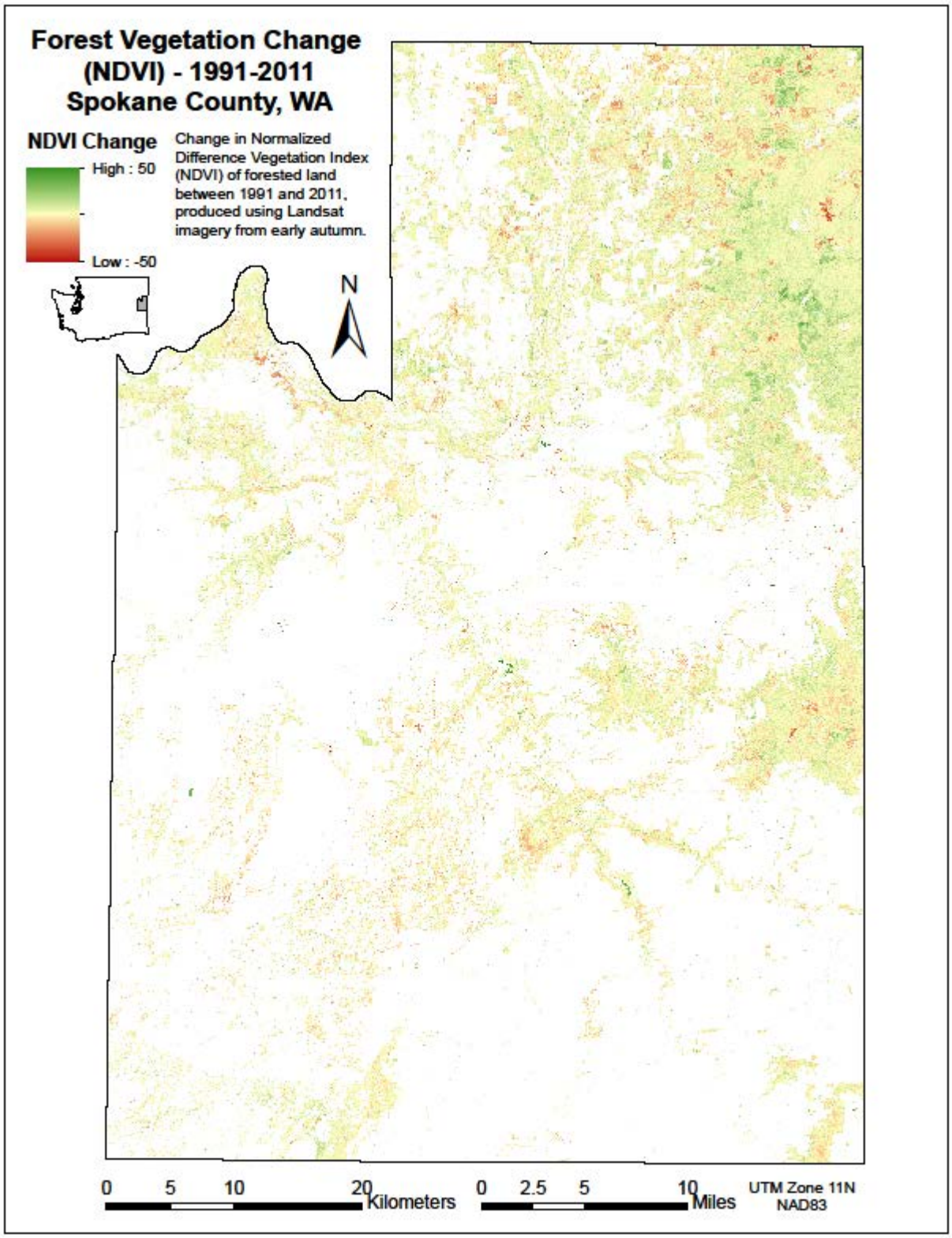

Figure 9 - NDVI change in forest condition, 1991-2011. The mean index increased 1.2 points with a maximum increase of 66 points and maximum decrease of 74 points. NDVI increased at least 20 points in 3,270 acres, and decreased at least 20 points in 2,499 acres.

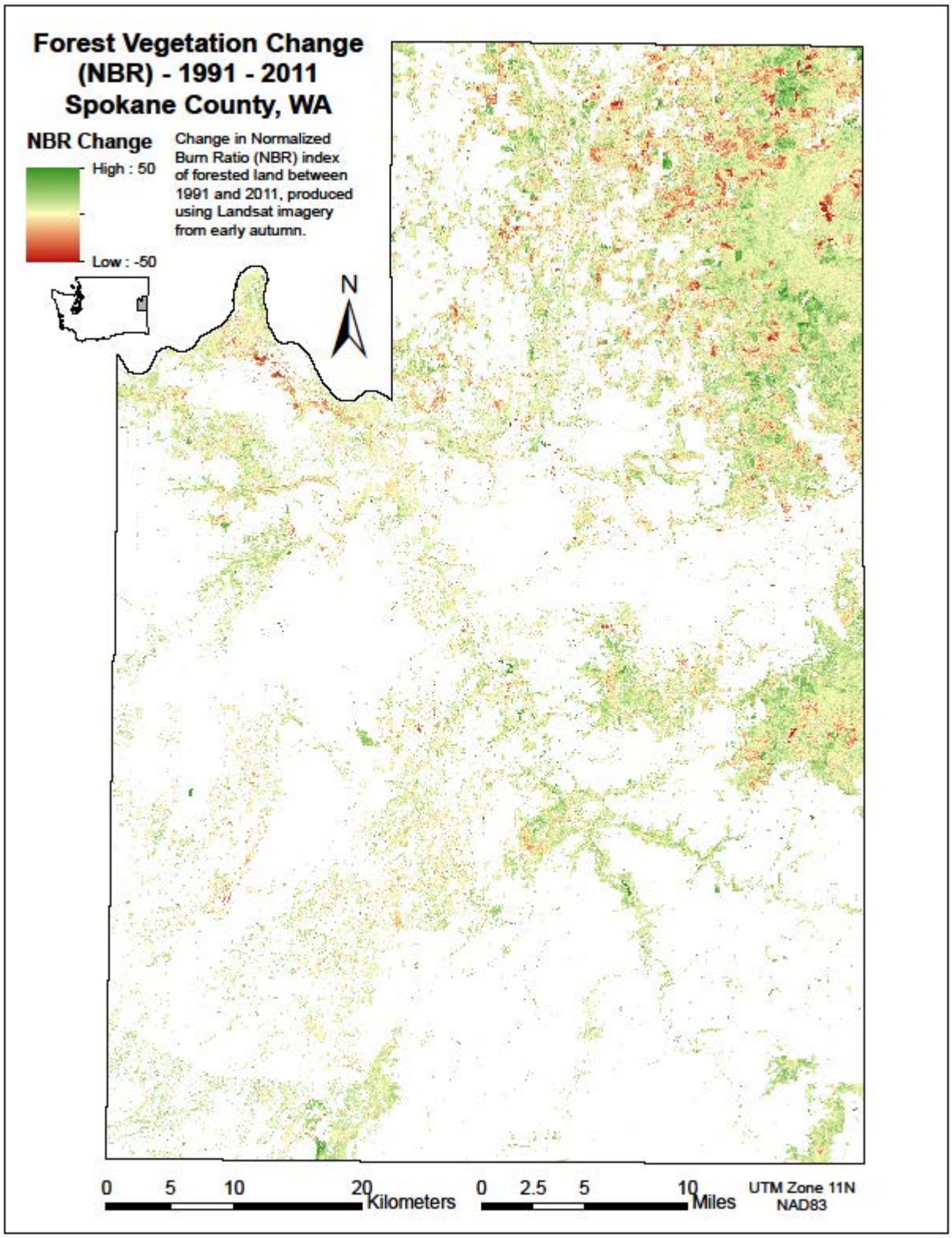

Figure 10 - NBR change in forest condition, 1991-2011. The mean ratio increased 5.2 points with a maximum increase of 89 and maximum decrease of 80. NBR increased at least 20 points in 30,196 acres, and decreased at least 20 points in 14,246 acres.

Of note, mean NDVI increased (+0.83) between 1991 and 1998, but mean NBR decreased (-2.68) during the same time period. From 1998 to 2011 mean NDVI showed a smaller increase (+0.36) while mean NBR grew substantially (+7.91).

Landsat NDVI/NBR change detection statistics

	Summary statistics				Acres with significant index change			
Change Series	**Mean**	**Min**	**Max**	**Std Dev**	**- > 20**	**- > 10**	**+ > 10**	**+ > 20**
NDVI 1991-2011	1.19	-74	66	7.40	2,499	19,470	26,881	3,270
NDVI 1991-1998	0.83	-67	72	6.97	4,206	23,826	12,391	862
NDVI 1998-2011	0.36	-76	72	7.43	2,872	21,236	23,244	2,526
NBR 1991-2011	5.23	-80	89	13.29	14,246	36,717	105,032	30,196
NBR 1991-1998	-2.68	-74	81	12.11	29,287	68,117	25,473	2,709
NBR 1998-2011	7.91	-84	94	11.75	7,489	19,574	129,710	36,081
SFLO NDVI 1991-2011	0.99	-61	64	7.08	907	8,728	10,678	821
SFLO NBR 1991-2011	4.84	-71	88	13.09	6,038	17,195	45,193	13,029

Table 6 - Landsat NDVI/NBR change detection statistics. Although average change was minimal, NDVI changed at least 10 points in 15% of forests (9% increased, 6% decreased). NBR changed at least 10 points in 45% of forests (33% increased, 12% decreased).

Small forest landowners were slightly less likely to see significant change in their forests. Mean NDVI increased at least 10 points in 7% (10,678 acres), and decreased at least 10 points in 6% (8,728 acres) of SFLO forests. Mean NBR increased at least 10 points in 30% (45,193 acres) and decreased at least 10 points in 12% (17,195 acres) of SFLO forests.

Figures 11 and 12 compare change detection results with aerial imagery for selected areas in Spokane County. As mentioned above, changes in forest condition may or may not indicate changes in forest health, but aerial imagery yields some clues as to possible causes. In northern portions of the county (Figure 11), NDVI and NBR tended to reinforce each other with both indices increasing or decreasing in the same pixels. Increased values frequently corresponded with visible forest regeneration or growth, while decreased values frequently corresponded with visible development, timber harvest, or other reductions in forest cover.

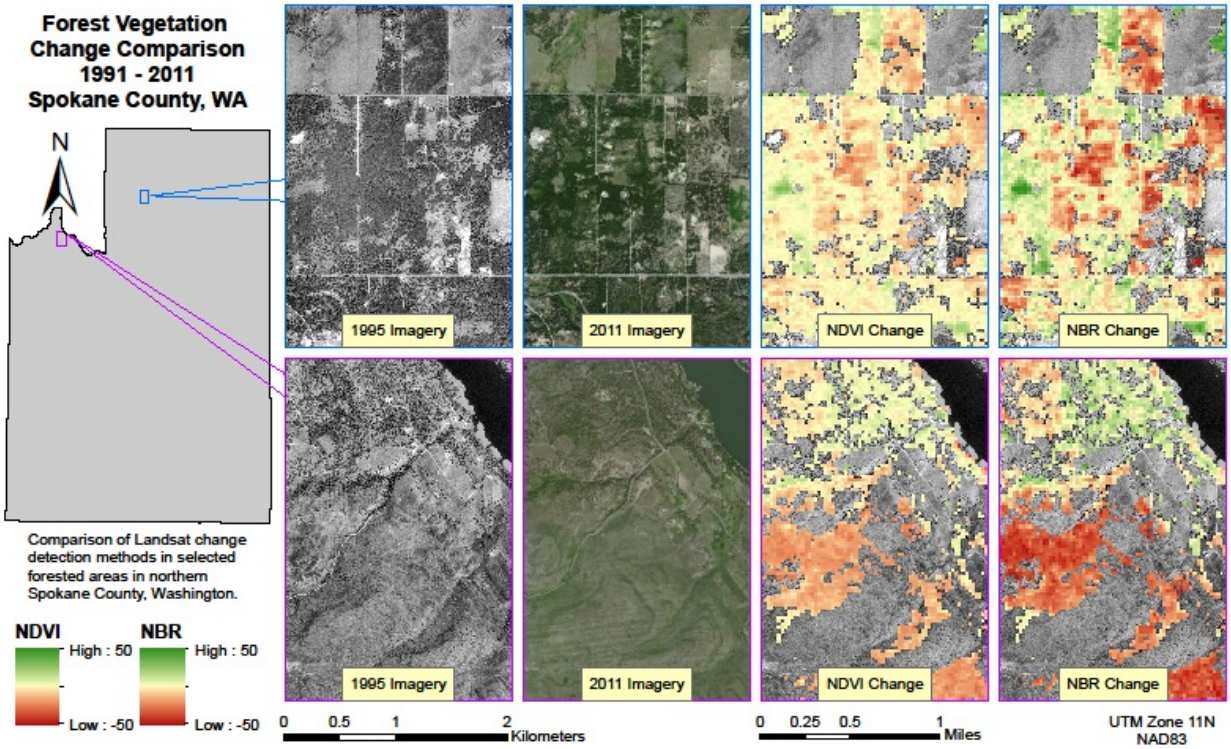

Figure 11 - Change detection comparison in northern Spokane County, Washington. Selected areas show similar changes in NDVI and NBR. Decreased values potentially indicate development or timber harvest, while increased values potentially indicate forest growth or regeneration.

In southern portions of the county (Figure 12), NDVI and NBR were less likely to increase or decrease in unison. In particular, several areas were identified where NDVI decreased but NBR increased in the same pixels. This most often occurred in ponderosa pine forests, and might indicate decreased density leading to improved forest health. As noted earlier, NDVI estimates live vegetation density by comparing light reflectance in the red and NIR bands, and NBR estimates live vegetation and moisture content by comparing reflectance in the SWIR and NIR bands. Decreased NDVI would therefore indicate less total vegetation in the 900 m^2 (30 x 30 m) pixel, while increased NBR would indicate more total moisture in the pixel. Aerial imagery also appears to confirm LANDFIRE's underestimation of forest cover in southwestern

Spokane County.

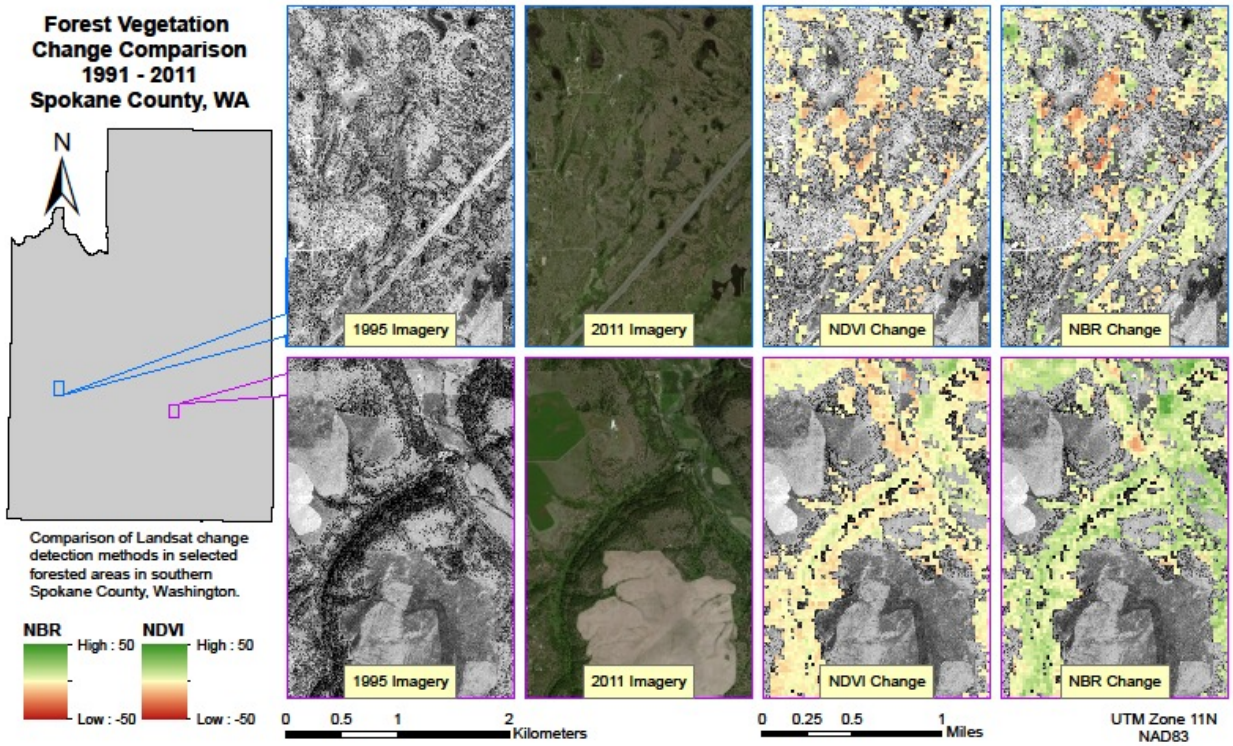

Figure 12 - Change detection comparison in southern Spokane County, Washington. Compared to northern portions of the county, there is less consistency between NDVI and NBR change. Decreased NDVI combined with increased NBR potentially indicates a less-dense, healthier forest canopy. Aerial imagery also appears to confirm LANDFIRE's underestimation of forest cover in southwestern Spokane County.

Discussion of natural resource management implications

Ecology

To quote the Washington Department of Natural Resources: "Forests in Eastern Washington are out of balance... Current conditions of altered forest structure and composition have contributed to damaging insect infestations and wildfires that are often more severe and extensive than would have occurred historically" (Washington DNR 2014a). Most of Spokane County's remaining forests are dangerously outside their historic range of variability, and

projected climate change impacts will threaten the ability of these ecosystems to persist in a forested state (Littell et al 2009).

Active restoration of Spokane County's forests is essential to improve health and resilience now and in the future. Current conditions are untenable, and natural disturbance (e.g., frequent low-intensity wildfire) is no longer a feasible management option due to forest density and human proximity. This project did not consider specific management prescriptions, but its results can potentially assist in identifying restoration priorities. For example, forest administrators can combine change detection analysis with local knowledge to better assess forest health, highlighting areas potentially at risk before conducting qualitative surveys. Ground verification would affirm or disprove forest health assumptions, with small forest landowner information facilitating rapid communication and response.

Human dimensions

The human dimensions of forest management are somewhat unique in Spokane County, where so many small acreage owners control such a large proportion of total forestland. While some might consider such fragmented ownership akin to 'the inmates taking over the asylum,' small forest management is not necessarily any better or worse than public or industrial forest management. It is, however, more difficult. In particular, two human variables complicate small forest management in Spokane County: population density and landowner autonomy.

Whereas most public and industrial forests are relatively isolated, more than 100,000 people live among the small private forests in Spokane County's wildland-urban interface. For these stakeholders, healthy forests are important to their safety and livelihood. Private forest owners rightly have broad authority to manage their land in accordance with their individual goals and objectives. At the same time, they have an obligation to ensure such management does

not adversely impact adjacent landowners or the public at large. Successful restoration will require careful balancing of individual and collective rights, protecting the general public without unduly restricting landowner autonomy.

Density and autonomy provide management opportunities as well. If owners personally manage their land, those with fewer acres can restore forests more easily than those owning large properties. Small forest landowners can also respond more rapidly to emerging problems. Public forest administrators cannot undertake management activities without environmental analysis and public input, which can take months or years. In contrast, private landowners can act immediately in most situations to reduce wildfire hazards, mitigate insect infestations, and generally promote forest health.

If small forest landowners possess the authority and capability to take action, why are so many of these forests still in need of restoration? This project did not involve landowner interaction, and therefore any attempt to understand or explain individual attitudes and objectives would be purely speculative. Instead, this project endeavored to quantify the human dimension, identifying who owns forested land, how much they own, and where they live. Further study is recommended in order to understand the goals and motivations of Spokane County's private forest owners.

Economics

The economic impacts of forest health in the wildland-urban interface are substantial, especially when unhealthy conditions lead to catastrophic wildfire. In 2014, Washington State experienced record wildfire severity with 425,136 acres burned and more than $180 million in direct firefighting costs (Northwest Interagency Coordination Center 2015). Reliable estimates of total property loss are unavailable but likely exceed firefighting costs. Without restoration, the

economic costs of wildfire and other disturbance will likely continue to grow (Littell et al 2009).

Because private forest owners can directly benefit from the use of their land, they should conceivably bear the economic costs of management activities. However, this simplified view does not account for economic externalities, which are third-party costs or benefits not directly reflected in market interactions between buyer and seller. For example, if a poorly managed private forest contributes to the growth and spread of catastrophic wildfire, the landowner does not bear the cost of damage to adjacent properties (assuming he or she did not ignite the fire). Similarly, if a landowner undertakes costly conservation and/or restoration activities to promote wildfire resilience and provide wildlife habitat, the public at large benefits freely.

External impacts justify public investments in private forest management. The legislation establishing Washington's small forest landowner office cited the influence of externalities, stating, "as the benefits of the proposed revisions to the forest practices rules will benefit the general public … (this act) suggests that some of these costs be shared with the general public" (Washington ESHB 2091 Sec. 101(4)). Several federal, state, and local agencies offer assistance to small forest landowners in Spokane County, including free or subsidized technical advice, cost-sharing for management activities, and property tax exemptions for forest stewardship. Some programs – including forest stewardship plan cost-sharing and designated forest property taxation – require minimum ownership of 20 forested acres, which limits potential economic assistance in Spokane County where 79% (16,665) of small forest landowners own less than 20 acres. However, these restrictions might have marginal impact because landowners with less than 20 acres can still request cost-sharing assistance without an approved stewardship plan or current-use forest designation (Washington DNR 2014b).

Conclusion

The first objective of this project, quantification of small forest landownership in Spokane County, Washington, was successful. Forests currently cover nearly one-third (28%) of Spokane County, and nearly half (47%) of these forests are owned by 21,045 private landowners with an average of 7 forested acres. As a reminder, this project defined the term 'small forest landowner' more narrowly than Washington State, in an effort to identify those most likely to live and recreate in the wildland-urban interface, rather than those in more isolated areas who manage their land for resource production.

The second objective, detection of long-term changes in forest condition, yielded mixed results. Analysis of Landsat imagery effectively measured changes in vegetation indices between 1991 and 2011, but without additional context this information is of limited utility in measuring forest health or prioritizing restoration efforts. Ground verification and calibration would have provided more accurate information, and the inclusion of imagery from additional Landsat satellites would have increased the monitoring period.

Geographic information systems can be a tremendous asset in natural resource management. In this project, existing data sets were combined, processed, and analyzed to produce useful information regarding private forest ownership in Spokane County's wildland-urban interface. Local administrators can apply these results immediately to promote forest restoration, or refine the methods as appropriate to support their objectives. Administrators elsewhere can adapt these methods with relative ease to produce similar results in their area of interest.

Caution must be exercised, however, with GIS. The popular admonition, 'with great power comes great responsibility,' certainly applies to GIS analysis in the 21st century. More information is not necessarily better, and this project carefully considered data sources and

methods of analysis to provide accurate and meaningful information. In determining the best method of delineating forest cover, the relative strengths and weaknesses of several land cover databases were compared. The Spokane County assessor maintains a comprehensive GIS-compatible property database, but individual parcels only tell a partial story of land ownership. An understanding of survey history, zoning regulations, land use classifications, and common ownership patterns enabled processing of property information to better reflect small forest landownership. Change detection analysis is highly sensitive to variations in both the environment and method of data collection. Careful screening of available Landsat scenes was essential to minimize interference from instrument malfunction, cloud cover, sun elevation, and drought.

Further research is recommended to better identify and understand small forest landowners. Specifically, the author suggests the following:

- Broader forest classification – As noted earlier, LANDFIRE and the National Land Cover Database differed considerably in their delineation of forest cover. Combining both classification systems for maximum forest cover would produce a larger list of small forest landowners. This method would be more inclusive but not necessarily more accurate.

- Improved forest classification – Local land cover classification using high-resolution aerial imagery or lidar data would provide a more accurate representation of Spokane County's diverse forests. However, this method would require considerable resources to collect and interpret high-resolution data.

- Small forest landowner survey – For local administrators, a targeted survey would provide critical insight into small forest landowners' goals and objectives. Given the somewhat unique nature of private forest ownership and population density in Spokane County's fire-prone wildland-urban interface, such a survey could also provide meaningful insight for researchers and administrators elsewhere.

- Combined forest health monitoring – Schroeder et al (2014) combined multi-temporal Landsat change detection analysis with existing forest health monitoring programs (aerial surveys, FIA) in Eastern Utah. Their methods were resource-intensive and require further refinement before widespread application, but preliminary results show great promise to improve forest disturbance detection and response.

Appendix A – Literature cited

Blatner, KA, CE Keegan III, J O'Laughlin, and DL Adams. 1994. Forest health management policy: a case study in Southwestern Idaho. *Journal of Sustainable Forestry* 2(3-4):317-337.

Collins, JB, and CE Woodcock. 1996. An assessment of several linear change detection techniques for mapping forest mortality using multitemporal Landsat TM data. *Remote Sensing of Environment* 56:66-77.

Creighton, JH, DM Baumgartner, and KA Blatner. 2002. Ecosystem management and nonindustrial private forest landowners in Washington State, USA. *Small-scale Forest Economics, Management and Policy* 1(1):55-69.

Hessburg, PF, RG Mitchell, and GM Filip. 1994. *Historical and current roles of insects and pathogens in Eastern Oregon and Washington forested landscapes*. USDA Forest Service: PNW-GTR-327.

Hessburg, PF, BG Smith, SD Kreiter, CA Miller, RB Salter, CH McNicoll, WJ Hann. 1999. *Historical and current forest and range landscapes in the interior Columbia River basin and portions of the Klamath and Great Basins*. USDA Forest Service: PNW-GTR-458.

Hessburg, PF, and JK Agee. 2003. An environmental narrative of Inland Northwest United States forests, 1800-2000. *Forest Ecology and Management* 178:23-59.

Jin, S, L Yang, P Danielson, C Homer, J Fry, and G Xian. 2013. A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sensing of Environment* 132:159-175.

Johnson, CG, RR Clausnitzer, PJ Mehringer, and CD Oliver. 1994. *Biotic and abiotic processes of Eastside ecosystems: the effects of management on plant and community ecology, and stand and landscape vegetation dynamics*. USDA Forest Service: PNW-GTR-322.

Lehmkuhl, JF, PF Hessburg, RL Everett, MH Huff, and RD Ottmar. 1994. *Historical and current forest landscapes of Eastern Oregon and Washington*. USDA Forest Service: PNW-GTR-328.

Leopold, AS. 1949. *A Sand County Almanac, and Sketches Here and There*. New York: Oxford University Press.

Littell, JS, EE Oneil, D McKenzie, JA Hicke, JA Lutz, RA Norheim, and MM Elsner. 2009. Chapter 7: Forest ecosystems, disturbance, and climatic change in Washington State, USA. Climate Impacts Group (eds): *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*.

Long, JN. 2009. Emulating natural disturbance regimes as a basis for forest management: A North American view. *Forest Ecology and Management* 257: 1868-1873.

Miller, JD, and AE Thode. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment* 109:66-80.

O'Laughlin, J, RL Livingston, R Thier, J Thornton, DE Toweill, L Morelan. 1994. Defining and measuring forest health. *Journal of Sustainable Forestry* 2(1-2):65-85.

Palmer, WC. 1965. *Meteorological drought*. United States Department of Commerce, Weather Bureau: Research Paper No. 45.

Provencher, L, K Blankenship, J Smith, J Campbell, and M Polly. 2009. Comparing locally derived and LANDFIRE geo-layers in the Great Basin, USA. *Fire Ecology* 5(2):126-132.

Rogers, LW, and AG Cooke. 2010. *The 2007 Washington State Forestland Database*. University of Washington – College of Forest Resources. http://www.ruraltech.org/projects/wrl/fldb, accessed 15 January 2015.

Schroeder, TA, SP Healey, GG Moisen, TS Frescino, WB Cohen, C Huang, RE Kennedy, and Z Yang. 2014. Improving estimates of forest disturbance by combining observations from Landsat time series with U.S. Forest Service Forest Inventory and Analysis data. *Remote Sensing of Environment* 154:61-73.

Spokane County, Washington, Board of County Commissioners. 2014. *Community Wildfire Protection Plan*. Adopted 8 April 2014.

Spokane County, Washington, Division of Building and Planning. 2004. *Zoning Code, Spokane County, Washington*. http://www.spokanecounty.org/data/buildingandplanning/lud/documents/Zone%20Code%202008%20for%20internet.pdf, accessed 05 April 2014.

Spokane County, Washington, Division of Building and Planning. 2007. *Spokane County Comprehensive Plan*. http://www.spokanecounty.org/BP/data/Documents/CompPlan/TOC.pdf, accessed 05 April 2014.

United States Department of Agriculture, Forest Service. 2009. Forest Health Monitoring – Detection Monitoring [Fact Sheet]. http://fhm.fs.fed.us/fact/pdf_files/fhm_dm_2009.pdf, accessed 01 February 2015.

United States, Northwest Interagency Coordination Center. 2015. 2014 Northwest large fire statistics. http://www.nwccinfo.blogspot.com/2015/02/1262015-2014-northwest-large-fire.html, accessed 05 February 2015.

Vogelmann, JE, Z Zhu, J Kost, B Tolk, and D Ohlen. 2006. Chapter 13: Perspectives on LANDFIRE prototype project accuracy assessment. USDA Forest Service: RMRS-GTR-175: *The LANDFIRE prototype project: nationally consistent and locally relevant geospatial data for wildland fire management*.

Vogelmann, JE, B Tolk, and Z Zhu. 2009. Monitoring forest changes in the southwestern United States using multitemporal Landsat data. *Remote Sensing of Environment* 113:1739-1748.

Wang, J, TW Sammis, VP Gutschick, M Gebremichael, SO Dennis, and RE Harrison. 2010. Review of satellite remote sensing use in forest health studies. *The Open Geography Journal* 3:28-42.

Washington State. 1999. *Engrossed Substitute House Bill 2091: An Act relating to forest practices as they affect the recovery of salmon and other aquatic resources.* 56th Legislature, 1999 1st Special Session.

Washington State. Revised Code of Washington, Title 76: Forests and Forest Products. http://apps.leg.wa.gov/rcw/default.aspx?Cite=76, accessed 01 February 2015.

Washington State, Department of Natural Resources. 2014a. *Eastern Washington Forest Health: Hazards, Accomplishments and Restoration Strategy*. A report to the Washington State Legislature. http://www.dnr.wa.gov/Publications/rp_fh_leg_report_2014.pdf, accessed 01 February 2015.

Washington State, Department of Natural Resources. 2014b. Eastern Washington forest landowner cost-share information. http://www.dnr.wa.gov/Publications/fp_sflo_fs_ewcostshareinstructions.pdf, accessed 01 February 2015.

Washington State, Office of Financial Management. 2013. *Washington State Data Book: Spokane County Profile*. http://www.ofm.wa.gov/databook/pdf/53063.pdf, accessed 04 January 2015.

Appendix B – GIS datasets used

Esri. "Basemaps." http://www.esri.com/data/basemaps (accessed 21 January 2015).

Spokane County, Washington, Assessor. "Download Assessment Data." http://www.spokanecounty.org/assessor/content.aspx?c=1388 (accessed 10 December 2014).

Spokane County, Washington, GIS. "GIS Data [county boundary]." http://www.spokanecounty.org/gis/content.aspx?c=1156 (accessed 10 December 2014).

United States Geological Survey. "Earth Explorer [Landsat imagery]." http://earthexplorer.usgs.gov (accessed 02 January 2015).

United States Geological Survey. "LANDFIRE Data Distribution Site [existing vegetation type]." http://landfire.cr.usgs.gov/viewer/ (accessed 10 December 2014).

United States Geological Survey. "National Land Cover Database 2011 (NLCD2011)." http://www.mrlc.gov/nlcd11_data.php (accessed 10 January 2015).

University of Washington. "Digital ortho quads and quarter-quads for Washington State [1995 aerial imagery]." http://gis.ess.washington.edu/data/raster/doqs/index.html (accessed 20 January 2015).

University of Washington, Rural Technology Initiative. "Forestland Database Downloads." http://www.ruraltech.org/projects/wrl/fldb/data.asp (accessed 02 January 2015).

Appendix C – Additional change detection figures

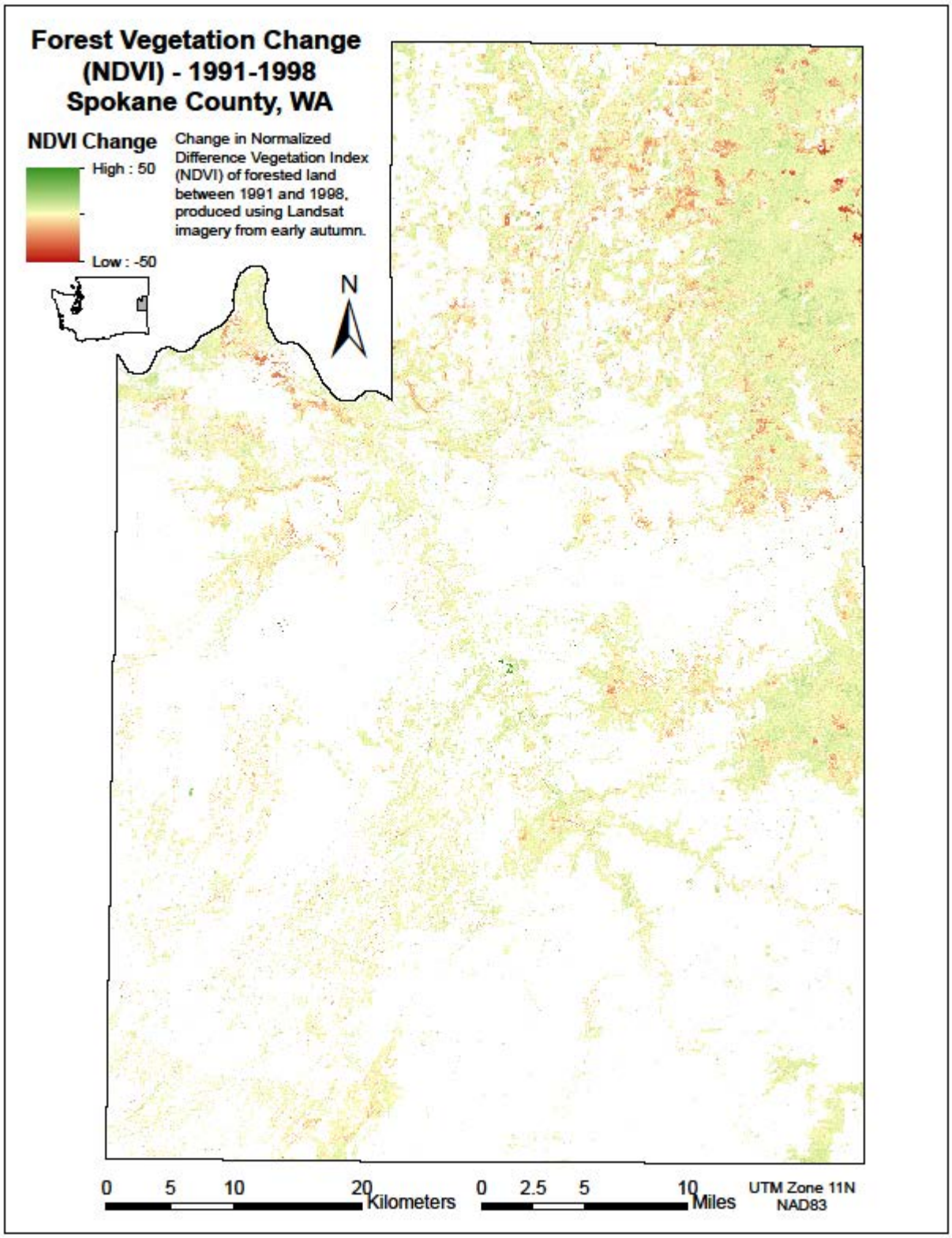

Figure 13 - NDVI change in forest condition, 1991-1998.

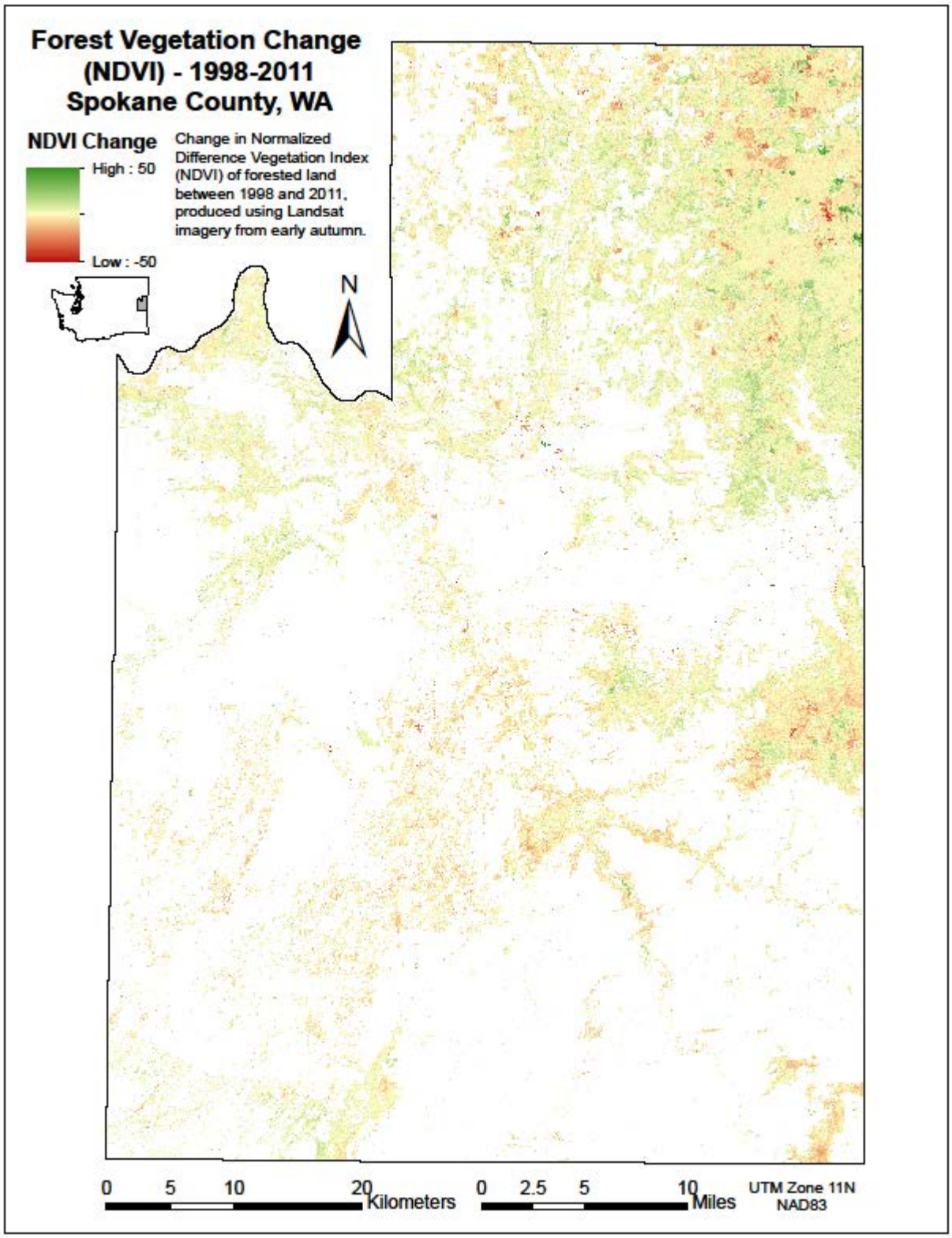

Figure 14 - NDVI change in forest condition, 1998-2011.

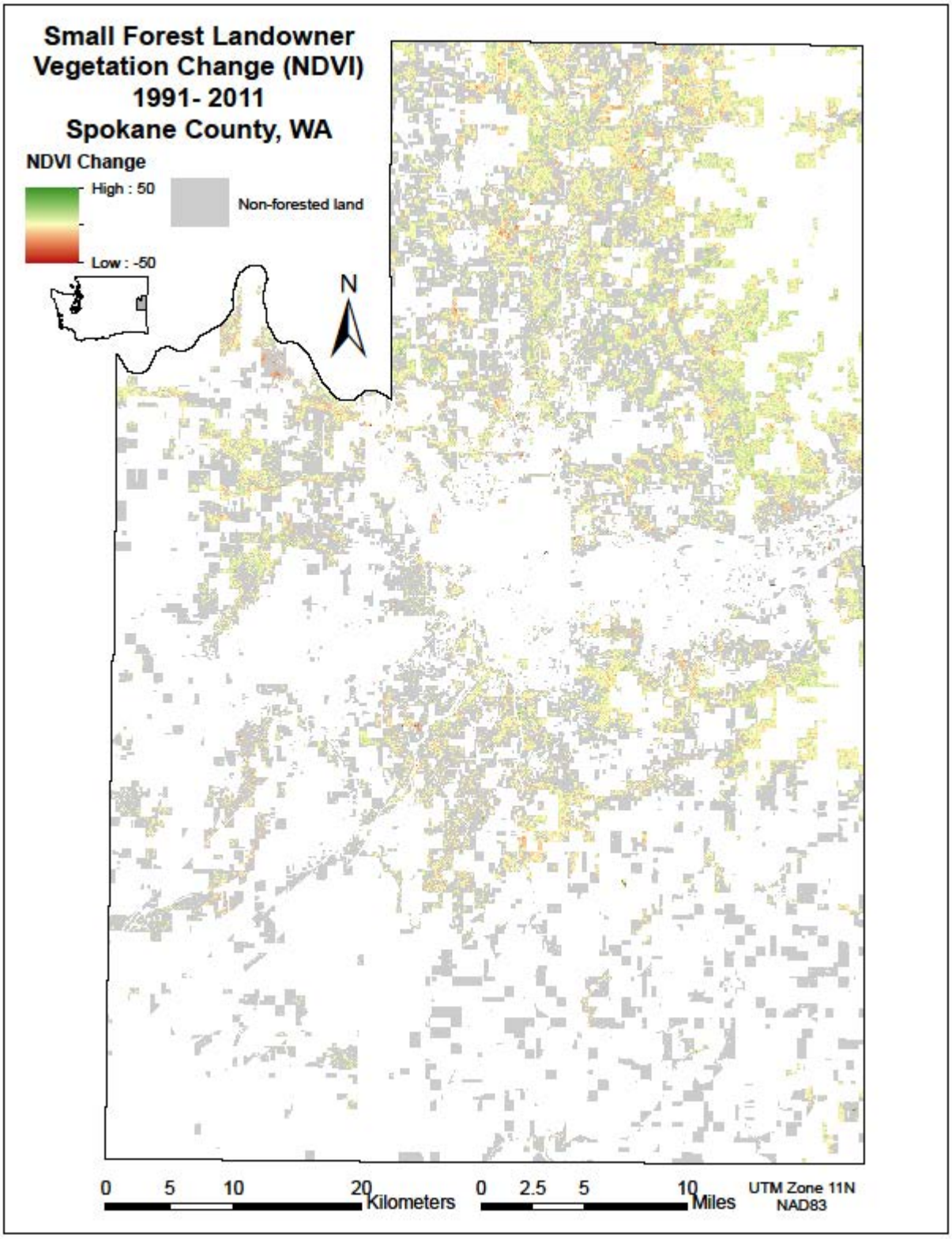

Figure 15 - NDVI change in SFLO forest condition, 1991-2011.

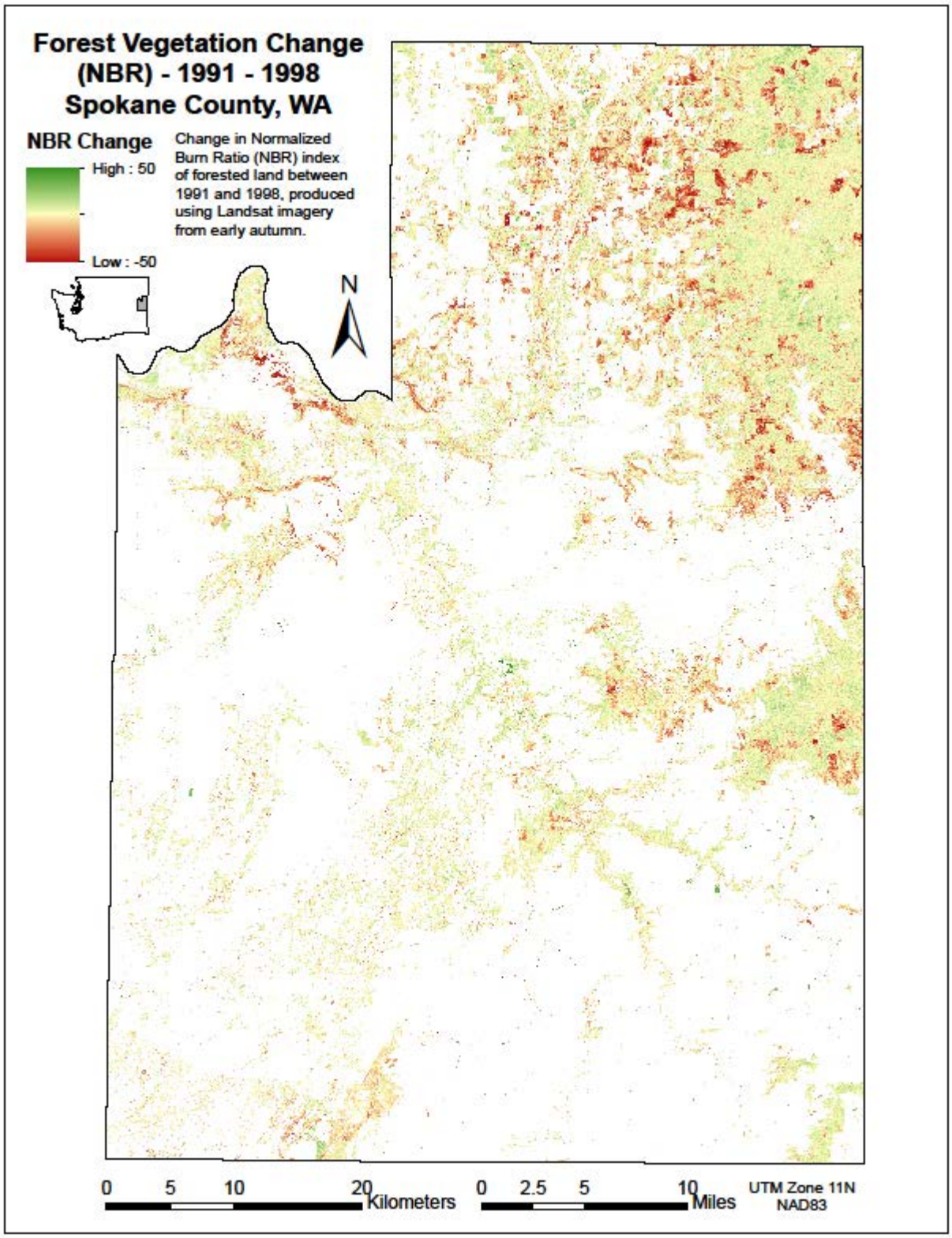

Figure 16 - NBR change in forest condition, 1991-1998.

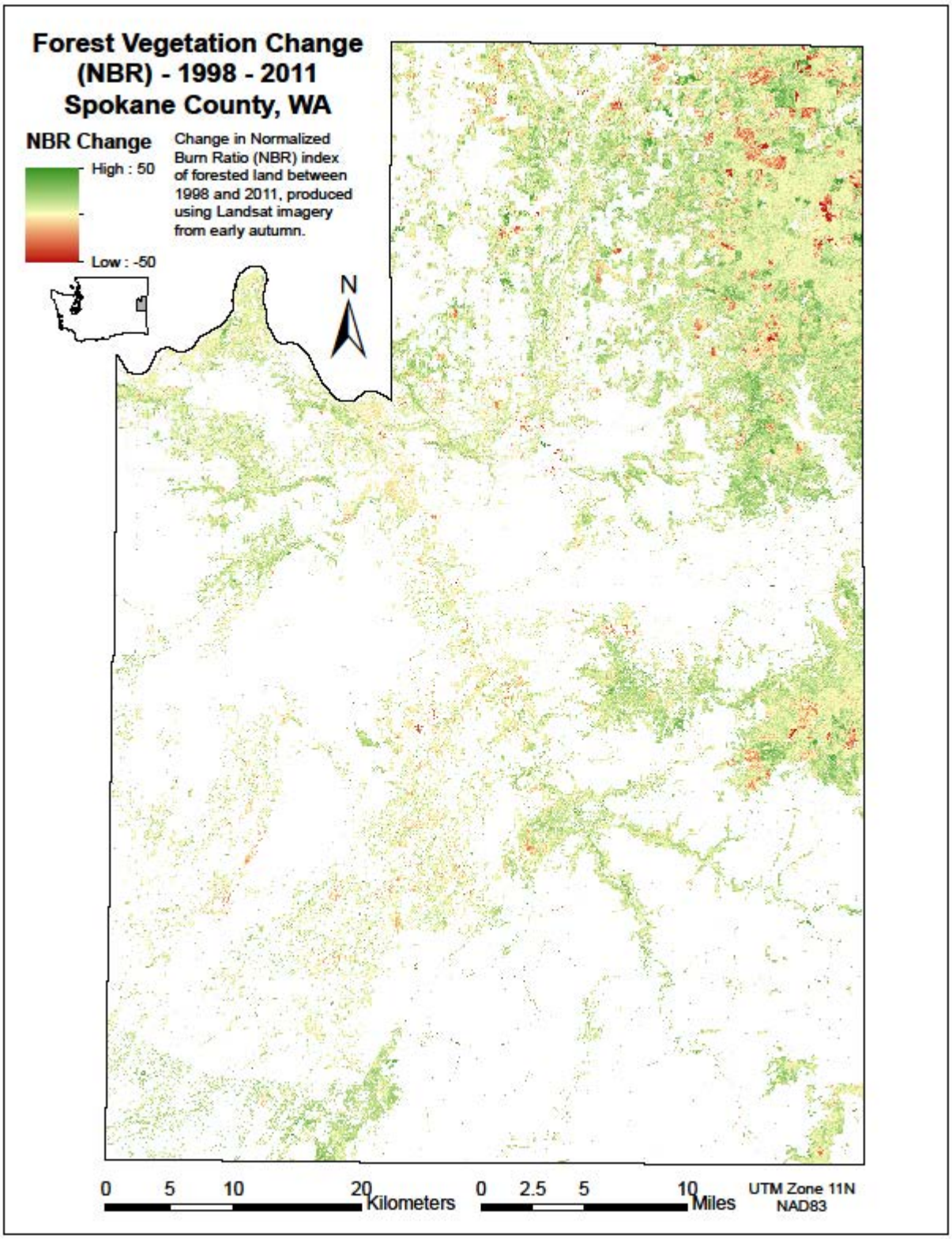

Figure 17 - NBR change in forest condition, 1998-2011.

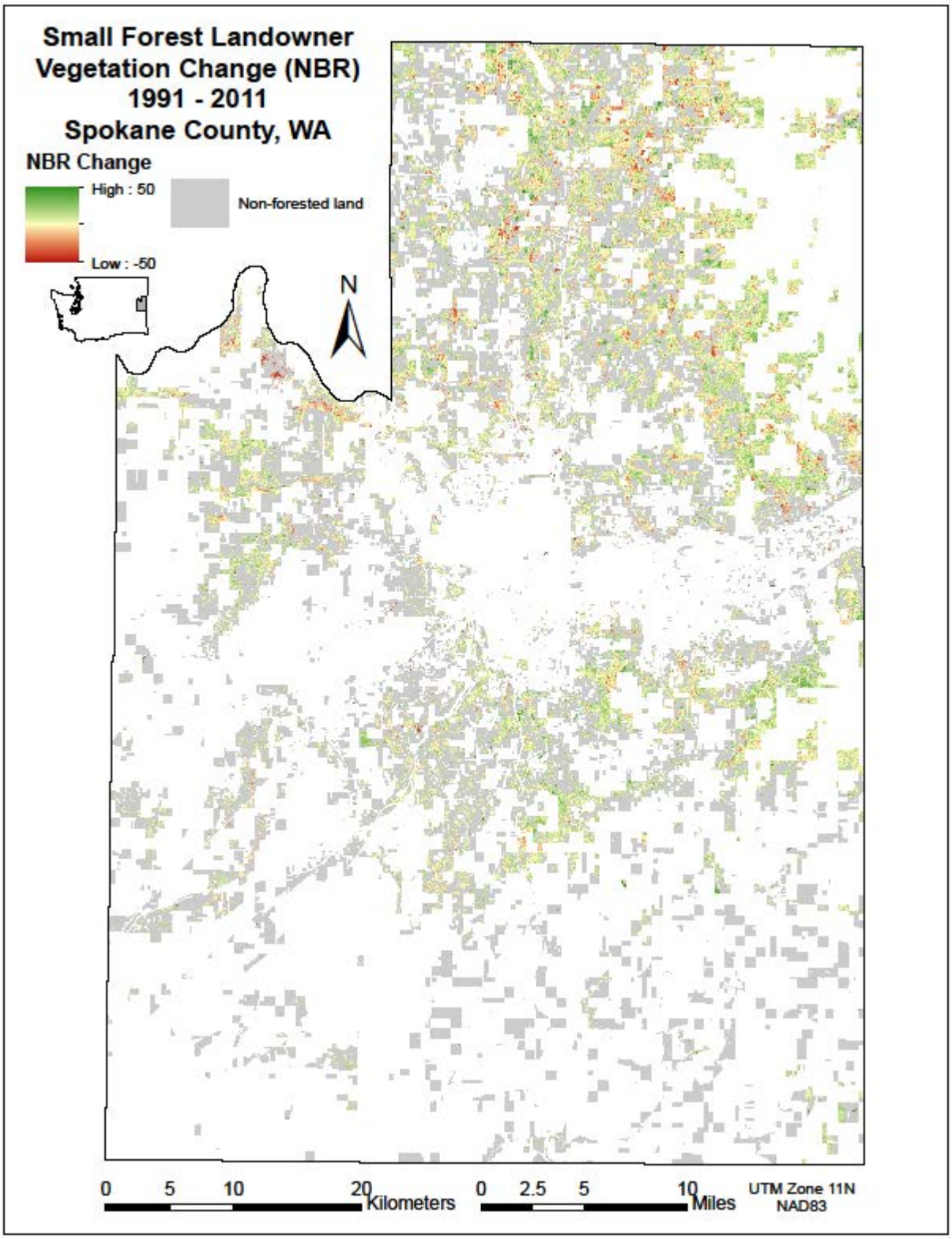

Figure 18 - NBR change in SFLO forest condition, 1991-2011.