FIFTEEN YEARS OF LAND COVER CHANGE IN OREGON: A CASE STUDY OF CLIMATIC IMPACTS, DISTURBANCE, AND OTHER POTENTIAL DRIVERS

by

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THESIS ABSTRACT

Weicheng Wang

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The national land cover data has covered the past 15 years. Land cover types of Oregon were reclassified into seven categories and assigned with different codes. The trend of each land cover type was calculated. A new coding system was applied to study the temporal and spatial distribution of the shifts between different ecosystems. Two case studies were introduced to analyze the tree cover gain and loss on different aspects in either fire burnt and unburnt areas. Lastly, the observed changing trends of tree cover extent in Oregon were discussed and partially explained by other related researches. The methodology revealed that tree cover loss on public land had exceeded the gain significantly. Tree cover gain on dry and hot south-facing slopes was detected in the unburnt study site. Surprisingly, the fire damage and severity were quantified accurately by the applied method.

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CHAPTER I

INTRODUCTION

The increasing global temperature has an impact on global ecosystems (Dillon, Wang, & Huey, 2010). Since the last century, the global mean surface air temperature has increased at a rate of 0.12°C every ten years (Huang et al., 2017). Over the past two hundred years, the average global temperatures have increased by 0.85°C (IPCC, 2012). According to instrumental records, 2015 and 2016 were obviously two warmest years in history (Kennedy, Dunn, McCarthy, Titchner, & Morice, 2017). Besides global warming, soil moisture may also have a significant impact on temperature anomalies in Oregon. A shift from wet to dry regime was suggested (Philip et al., 2018).

This thesis has two goals. First, it provides a quantitative characterization of changes in land cover across the state of Oregon over the past two decades. Second, it explores potential mechanisms driving changes in land cover with a specific focus on forest ecosystems. By definition, land cover can be understood as the physical cover of the surface of the Earth, such as water, vegetation, and developed areas (Sheffield, Morse-McNabb, Clark, Robson, & Lewis, 2015). The Food and Agriculture Organization (FAO) has traditionally classified the surface of the Earth using a Land Cover Classification System (LCCS) inferred from satellite data (Gregorio, 2005). Land cover change has closely related to climate change (Song et al., 2018), rising atmospheric carbon dioxide (CO_2) concentration (Silva & Lambers 2017), and changes in management, ownership, or land use policy closely (FAO, 2018). When viewed from a large-scale perspective, land cover change can be understood as a proxy for natural as well as human-induced changes in biophysical and biogeochemical cycles that govern the energy balance of the Earth and its climate (Bonan, 2016; Mancino, Nolè, Ripullone, & Ferrara, 2014). Accordingly, understanding whether and how dominant trends in land cover have occurred will be important to predict a plethora of environmental factors that affect the sustainability of ecosystems and society (Seddon, Macias-Fauria, Long, Benz, & Willis, 2016). Here, significant shifts in tree cover are used as a proxy for forest expansion or decline in relation to other land cover categories, which are important for land conservation and management efforts.

As technology progresses, it is now possible to have a long term monitoring of land cover change using remote sensing techniques and satellite data (Sexton, Urban, Donohue, & Song, 2013). Here, data from the National Land Cover Database (NLCD) are used to determine changes in tree cover in relation to other ecosystems in response to climate and land use across the state of Oregon. For the first part of the study, the land cover analysis will encompass the entire state to provide an overview of land cover change with a focus on forests. For the second part of the study, the emphasis is placed on mountain landscapes where divergent trends in tree cover (e.g., forest expansion or decline) have occurred in response to major shifts in climate or disturbance regime. According to the FAO report from 2011, mountains encompass about 23% of the Earth's forests and function as a carbon sink and water source for millions of people (Price et al., 2011). Some of Oregon's iconic forest landscapes have been well studied and managed for long periods (Littell, Peterson, & Tjoelker, 2008). Indeed, it is well known that Oregon forests are important for timber production, carbon sequestration, water conservation, and wildlife habitat (Kline et al., 2016). However, there is considerable disagreement regarding how changes in climate, disturbance regime, and land use will affect the distribution of forests in relation to other dominant managed and unmanaged ecosystems (Hessburg et al., 2019). This thesis was designed to improve basic understanding that will foster applied knowledge of land cover change across the state with implications for other Pacific Northwest (PNW) regions or montane regions more broadly.

The following sections of the thesis provide a brief introduction of the physiography of Oregon, including climate types, vegetation types, and a discussion of natural resources-related policies. The results of the study are displayed by tables, and maps derived from Landsat-based NLCD data ranged from 2001 to 2016. The quality and the authority of NLCD data are discussed and employed to reclassify land cover trends in both public and private lands across the state. The methods for displaying and analyzing patterns, differentiating land ownership, checking the occurrence time of events (e.g., wildfires), quantifying different types of vegetation gain or loss are also introduced in the following sections. Specifically, by comparing land cover data from different years, the spatial and temporal distribution of dominant land cover types and trends are quantified. Two case studies are provided in order to show the details of the trend of the change.

CHAPTER II

STUDY REGION

Oregon has a surface area of 254,800 km^2 (U.S. Census Bureau, 2018). It ranges from 42° N to 46°18′ N and from 116°28′ W to 124°38′ W. The total population of Oregon is around 4 million (U.S. Census Bureau, 2018). Oregon has lots of different landforms and climate types. The Coast Range and the Cascade Range stretch across Oregon from north to south, and vegetation density decreases from west to east (Smith, Barstad, & Bonneau, 2005). In the eastern part of the Cascade Range, Oregon high desert covers vast areas. Annual precipitation decreases from the coast to inland, as well as temperature (Smith, Barstad, & Bonneau, 2005). The primary goal of the thesis focuses on land cover change that occurred over the past 16 years in the state of Oregon. By using land ownership data created by Oregon the Bureau of Land Management (BLM) and acquired from Oregon Spatial Data Library, the thesis has divided land parcels in Oregon into private and public lands. Throughout the thesis, land cover change in private and public lands has been studied separately based on their coverage extent. The reason for doing so is that private lands usually undergo a high density of management activities (e.g., thinning, logging, clearcutting) while public lands usually experience fewer disturbances. The total area of different land cover types is calculated by using a new classification system. The overall gain and loss of tree cover in both private and public lands are reported for the entire state. Typical trends of tree cover change are detected and studied.

Oregon, just like other regions of the PNW, has abundant forest resources. Forests play important roles in enhancing carbon sequestration, maintaining water balance, and mitigating temperature through evaporation and transpiration (Baldocchi & Penuelas, 2019, Ellison et al., 2017). Due to longer growing seasons and a higher transpiration rates, montane forests have higher demand for water compared to other ecosystems, including food crops (Baldocchi, Dralle, Jiang, & Ryu, 2019). A 10-60% increase in transpiration has been attributed to recent changes in tree cover in PNW montane landscapes (Maxwell, Silva, & Horwath, 2018). As a result, changes in tree cover can be used to understand changes in forest carbon and water balance, as shown in Oregon's long-term paired watershed experiments (Perry & Jones, 2017).

In dry PNW landscapes, such as those dominated by Ponderosa Pine trees, intensive forest management can under certain conditions reduce competition for water, leading to enhanced growth and water-use efficiency (WUE) of trees – i.e., the amount of carbon assimilated per unit of water transpired (Liles, Maxwell, Silva, Zhang, & Horwath, 2019). Elevated CO_2 levels increase tree and forest WUE, an effect that is most pronounced in dry environments (Keenan et al., 2013; Castruita-Esparza et al., 2019). However, in historically wet Douglas-fir forests such as those of western Oregon, raising air temperature and increasing drought frequency have brought forests to "the verge of switching from being carbon sinks to carbon sources," despite rising CO_2 levels (Baldocchi, Chu, & Reichstein, 2018). Drought stress hotspots can be identified from PRISM-derived a combination of temperature and water input data from Remote Automatic Weather Stations (RAWS), which allows for the calculation of a moisture index interpolated across the state (Figure 1).

In addition to statewide trends, two specific case studies are considered in landscapes that have experienced major drought stress areas: (i) tree cover loss and partial recovery following the 2002 Biscuit Fire in southwest Oregon and (ii) the expansion of forests into previously open montane systems of the Eagle Cap Wilderness in eastern Oregon. Land cover can vary strongly with topographic gradients typical of montane landscapes (Hahm et al., 2014); therefore, an analysis of landscape position (e.g., south vs. north-facing slopes) is used to better constrain the regional trend in each of the case studies. To this end, fire disturbance and land cover history are integrated with Digital Elevation Models (DEMs) to investigate the modulating effect of local landscape features on the impacts of regional climate and disturbance regimes (e.g., the rate of loss and gain based on landscape position).

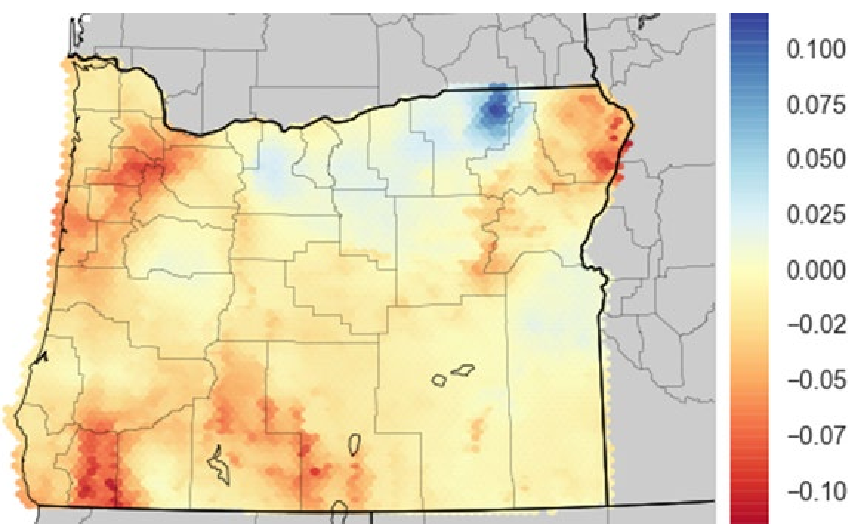


Figure 1: Moisture index differences 1980-2010 vs. 1950-1980 normals. Decreasing moisture (red) or increasing moisture (blue) calculated from PRISM data based on temperature and water inputs as in (Willmott & Feddema, 1992)

CHAPTER III

METHODS

Data Source

This thesis has mainly used the National Land Cover Database (NLCD) data for analyzing and studying. NLCD data is a part of the Multi-Resolution Land Characteristics (MRLC). NLCD data derives from Landsat images, which covers all the fifty states of the US. The resolution of the NLCD product is 30 meters by 30 meters (Wickham et al., 2013). NLCD data has been used to detect the change between different land cover types (Shi et al., 2018). In order to create a database with high-quality data, scientists searched and selected low cloud cover (< 20%) Landsat images (Yang et al., 2018). Missing values in the cloud/shadow masks can be estimated and filled (Yang et al., 2018). Training data and a decision-tree classifier were used for mapping land cover and changes (Yang et al., 2018). After that, an integration of all intermediate datasets was made to complete a final product (Yang et al., 2018). The land cover data updates every five years. The earliest data was from 2001, and the next available data was from 2006 and 2011. The latest 2016 land cover data was published in May 2019 and was added to the analysis immediately after the releasing.

In order to study the trend of vegetation change in Oregon comprehensively, the land management ownership information from the Oregon Bureau of Land Management (BLM) was applied in the study. By separating different land ownership, it is possible to differentiate between management effects on vegetation and other changes, such as those induced by climate.

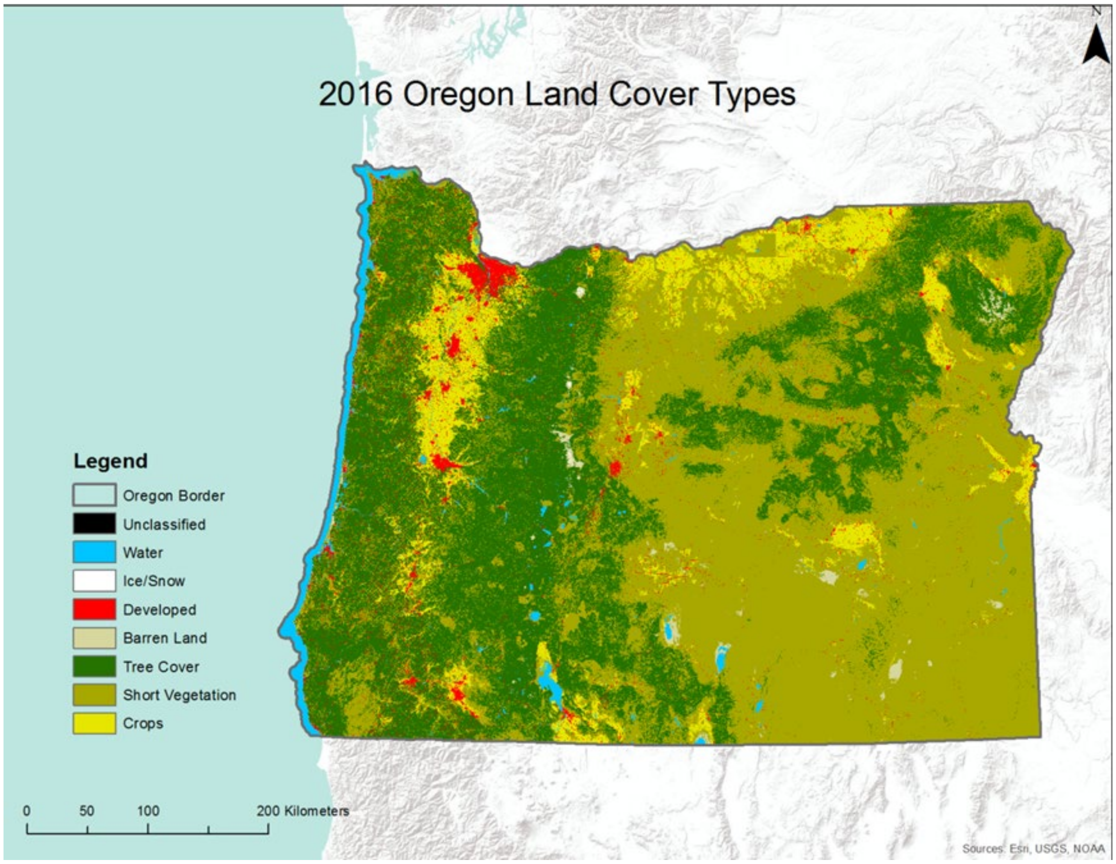


Figure 2: Current Oregon Land Cover (2016) and major land cover categories

Data Analysis

Landsat-derived NLCD data was used to classify land cover types into eight categories with twenty subdivisions (MRLC, 2019). Data from 2001, 2006, 2011, and 2016 were acquired from the MRLC website. After downloading NLCD data, the original classification system was simplified by merging all urban areas into a single category. All woody vegetation areas where trees were taller than 5 meters were considered to be under tree cover. Short vegetation includes shrubland and herbaceous plants, which is shorter than 5 meters. Planted and cultivated vegetation such as pasture or crops was not considered as natural vegetation (Table 1). Woody but human-related crops such as vineyards or orchards were not studied primarily as well. This new classification system is useful for studying major shifts in tree cover distribution in responding to climate and other forms of environmental change. Each land cover type has been assigned with a unique code: 1 (Water Bodies), 2 (Ice/Snow), 3 (Urban), 4 (Barren Land), 5 (Tree Cover), 6 (Short Vegetation), 7 (Crops) (Table 1). NLCD data are in raster forms; thus, the total number of 30 x 30 meters pixels were counted, and the area of each land cover type was calculated (900 m^2 multiplied by the number of pixels). By dividing the number of pixels of certain land cover type by the total pixels of all seven land cover types, the percentage of each land cover type from different years can be calculated (Table 2 & Appendix 1). The dynamic of the percentage of different land cover types, in other word, the trend of changing, can be quantified. Spatial and temporal transitions from open vegetation physiognomies, which include Barren Land (BL) and Short Vegetation (SV), to forested areas (e.g., Tree Cover - TC) and vice versa, are the primary focus of the analysis.

Table 1: The new classification system used in the thesis

Name Used by NLCD	Name Used by Thesis	Code
Open Water	Water	1
Perennial Ice/Snow	Ice/Snow	2
Developed, Open Space	Urban	3
Developed, Low Intensity	Urban	3
Developed, Medium Intensity	Urban	3
Developed High Intensity	Urban	3
Barren Land	Barren Land	4
Deciduous Forest	Tree Cover	5
Evergreen Forest	Tree Cover	5
Mixed Forest	Tree Cover	5

Shrub/Scrub	Short Vegetation	6
Grassland/Herbaceous	Short Vegetation	6
Woody Wetlands	Short Vegetation	6
Emergent Herbaceous Wetlands	Short Vegetation	6
Pasture/Hay	Crops	7
Cultivated Crops	Crops	7

In order to specify and study the details of the land cover change, the value of the earliest data (2001) was multiplied by 1000, which ranges from 1000 to 7000. Similarly, the data value from 2006 was multiplied by 100, which ranges from 100 to 700. The data value from 2011 was multiplied by 10, and the latest data from 2016 can remain its value unchanged. After coding, the Raster Calculator tool from ArcMap was used to stack and analyze the data layers. Thus, the coded pixel data values for all years ranged from 1111 to 7777. For instance, if a certain area in Oregon was assigned with code 4455, which means that it was barren ground before 2001 and remained unchanged in 2006, but shifted to forest between 2006 and 2011. Similarly, code 4555 indicates that the change happened between 2001 and 2006. In this case, both code 4455 and 4555 represent forest expansion. On the other hand, code 5544 and 5554 both represent deforestation. The only difference between 5544 and 5554 was the time of the occurrence. For areas that have been altered but restored (e.g., code 5445, 6566, etc.) will not be studied in this thesis. The following chart explains the meaning of different codes that will be used in this article. All transitions between 4, 5, and 6 (4xx5 tree growth, 5xx4 deforestation, 4xx6 short vegetation growth, 6xx4 desertification, 5xx6 vegetation degradation, 6xx5 forest expansion) were selected resulting in 54 possible combinations of codes. The thesis set up a threshold and focused on patterns that had an extent greater than 10 km^2 (10000 pixels) to avoid extracting insignificant vegetation changes. The selected land cover codes are listed in the appendix (Appendix 2). A breakdown analysis of tree cover gain and loss is also provided (Table 3).

Table 2: Net area change for 7 major land cover categories in the state of Oregon from 2001 to 2016

Code	Land Cover Types	2001 (km²)	2006 (km²)	2011 (km²)	2016 (km²)	Net Area Change from 2001 to 2016 (km²)	Net Percentage of Change from 2001 to 2016 (%)
1	Water	5692.96	5856.71	6302.36	5546.51	-146.45	-2.57
2	Ice/Snow	31.09	31.09	29.99	29.99	-1.1	-3.54
3	Urban	6708.5	6779.11	6754.04	6780.2	71.7	1.07
4	Barren Land	3677.43	3866.67	1519.4	1729.18	-1948.25	-52.98
5	Tree Cover	94207.07	91476.13	88700.96	89130.17	-5076.9	-5.39
6	Short Vegetation	124511.45	126794.52	131676.91	131667.58	7156.13	5.75
7	Crops	19971.51	19995.78	19816.34	19916.37	-55.14	-0.28

Table 3: Major changes in tree cover as a result of expansion or decline in the state of Oregon from 2001 to 2016

Categories of Shifts	Land Cover Change Description	Period of Shifts	Change on Private Land (km²)	Change on Public Land	Change Area in Total (km²)
5566	Tree Cover to Open Vegetation	2006-2011	1002.65	5144.90	6147.55
5556	Tree Cover to Open Vegetation	2011-2016	603.48	3149.42	3752.90
5666	Tree Cover to Open Vegetation	2001-2006	376.87	1050.78	1427.65

5466	Tree Cover to Barren Land, then to Open Vegetation	2001-2011	198.72	277.65	476.37
5544	Tree Cover to Barren Land	2006-2011	6.17	25.51	31.68
5656	Tree Cover to Open Vegetation (Periodically)	2001-2016	9.47	11.94	21.41
Total	**Tree Cover Loss**	**2001-2016**	**2197.36**	**9660.20**	**11857.56**
6655	Open Vegetation to Tree Cover	2006-2011	1227.78	2625.34	3853.12
6665	Open Vegetation to Tree Cover	2011-2016	673.71	1690.42	2364.13
4665	Barren Land to Short Vegetation, then to Tree Cover	2001-2016	111.43	138.87	250.30
6555	Open Vegetation to Tree Cover	2001-2006	23.56	36.71	60.27
4465	Barren Land to Short Vegetation, then to Tree Cover	2006-2016	25.38	16.60	41.98
4455	Barren Land to Tree Cover	2006-2011	5.53	32.40	37.93
6565	Open Vegetation to Tree Cover (Periodically)	2001-2016	22.96	17.11	40.07
4655	Barren Land to Short Vegetation, then to Tree Cover	2001-2011	7.78	3.58	11.36
Total	**Tree Cover Gain**	**2001-2016**	**2098.13**	**4561.03**	**6659.16**

Visualization

Land cover change codes for all relevant categories are stored in raster form, which can be visualized as described in Appendix 2. For the analysis of tree cover gain and loss, we focus on those land cover change categories described in Table 3. Briefly, the selected meaningful codes were converted into polygons. There were 14 categories of codes with their polygons converted for further selection and analysis (Table 3). All the polygons start with 5 and end with 6 (e.g., 5566) are classified as tree cover loss because tree cover was replaced by short vegetation such as shrubs. They are marked with red color on maps (Figure 5, 6, and 7). Polygons start with 6 and end with 5 (e.g., 6655) will be classified into tree cover gain because the code indicates shifts from short vegetation to tree cover. These polygons are labeled with blue (Figure 5) and green (Figure 6, 7) on maps. The growth of short vegetation on barren lands is represented by codes start with 4 and end with 6 (e.g., 4466), but it was not displayed on maps. The transition between short vegetation and barren lands usually indicate losses of shrubs or herbaceous vegetation. These polygons start with 6 and end with 4 (e.g., 6644), but they were not displayed on maps as well. Polygons start with 5 and end with 4 (e.g., 5544) imply loss of tree cover. In these areas, tree cover was replaced by barren lands directly without being in the stage of short vegetation. They are labeled with red color on maps (Figure 5, 6, and 7). On the other hand, polygons start with 4 and end with 5 (e.g., 4465, 4455) indicate tree cover growth over bare lands, and they are marked with blue (Figure 5) and green color (Figure 6, 7) on maps.

One added benefit of converting raster into polygon is that polygons can be turned on and off to display different vegetation distribution patterns. For example, in order to show areas experiencing tree cover gain over barren land specifically, all the layers can be turned off except layers start with 4 and ends with 5. In this case, four layers (4665, 4465, 4455, and 4655) will be displayed on the map. Any pattern observed on the map indicates the growth of tree cover over vegetationless barren land, with references to the time of the occurrence. In addition, all fourteen categories of land cover change (Table 3) can be grouped into larger categories. For example, the thesis has merged all the polygons which indicated tree cover gain over barren land (4XX5) into one large polygon and named it 4to5polygon. The same procedure has been applied to all the tree cover gain/loss polygons. Polygons indicated short vegetation gain/loss were not merged yet because the thesis mainly focused on gain and loss of tree cover on Oregon. However, the merging of polygons can be executed easily in case of future studies.

The next step of the visualization is to differentiate all land cover change categories based on ownership and divide them into two categories: Private and Public lands. There were in total 27 types of land ownership in Oregon (Appendix 4) and they had different levels of human activities ranged from high to none. In fact, there was no official document describing the intensity of human activities in each ownership. The division between private and public lands has to be done manually. Thus, the thesis has overlaid the land ownership polygon with an imagery base map to find patterns. For example, the checkerboard patterns of forest in western Oregon indicate the coexistence of both private and public lands. In other word, every parcel of private lands is surrounded by public lands, and vice versa. After overlaying and observing, the thesis concluded that land parcels that have experienced intensive management activities were classified as pv and pvi (private and private industrial). By using the Query Builder from ArcMap, all land parcels with pv and pvi attributes are grouped into private lands, and they have covered an area of 107455 km^2, which is equivalent to 42.2% of Oregon's land surface area. Public lands, including all the land ownership left (e.g., National Park Service, US Forest Service), occupied 57.8% of the surface area of Oregon (Figure 3).

Finally, after the separation of land ownership, it is possible to exclude changes in tree cover driven by climate or natural disturbances (e.g., forest expansion into alpine meadows; or fire-induced transition from forests to open vegetation) from those caused directly by management actions (e.g., logging, clearcutting, or agricultural activities). For example, previously produced polygons that reflect tree loss or gain (e.g., polygon5566, polygon6655) will be clipped with the extent of public lands throughout the state. The outcome polygons will be named as public5566 or public6655 etc. The final result of this effort is reflected in a new map of tree cover gain and loss in private and public lands across the state (Figure 5, 6, and 7).

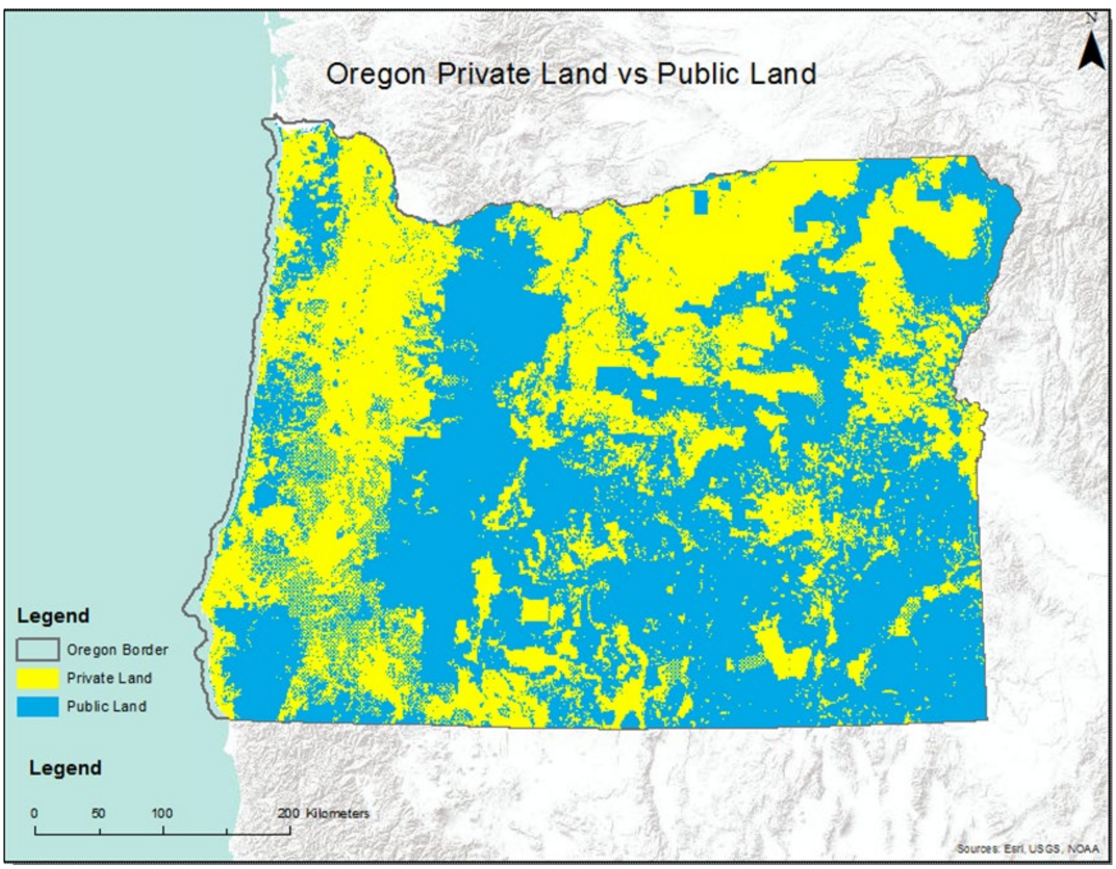


Figure 3: Oregon Land Ownership Distribution Map Private 42.2% vs. Public 57.8%

Analysis of Landscape Position

As mentioned above, two specific case studies were designed to examine the modulating effect of landscapes on regional changes in climate and disturbance. Specifically, this analysis aims at determining (i) how does landscape position (e.g., aspect) affect tree cover response to major drought-induced fires, and (ii) how does landscape position influence changes in tree cover driven by climate warming in montane landscapes? In order to address these questions, historical fire polygons of Oregon were downloaded from the Oregon Spatial Data Library. The data included all the fire extent polygons since 1900, and the polygon of the 2002 Biscuit Fire was selected and extracted as the study boundary for case study (i). The extent of this polygon corresponds approximately to a hotspot of drought stress (Figure 1) and the large area of short vegetation observed in the forests of the southwestern corner of Oregon (Figure 2). For case study (ii), the polygon of Eagle Cap Wilderness in Northeastern Oregon was acquired from the Wilderness Connect. It is also a drought hotspot although without major stand-replacing fire. For those two locations, DEMs were downloaded from the Oregon Geospatial Enterprise Office. Each DEM was clipped to the extent of the two moisture deficiency hotspots, corresponding roughly to the same total area each (1906.99 km^2 vs. 1463.34 km^2). Each resulting land cover and DEM layer contains topographic information such as elevation and slope position and therefore allows for the comparison of tree cover change for different aspects. By using the aspect tool from ArcMap, the aspect raster of both the Biscuit Fire Polygon and the Eagle Cap Wilderness were calculated and added to the analysis.

In total, nine directions will be identified (Flat, N-, NE-, E-, SE-, S-, SW-, W-, and NW-facing slopes; Figure 4). The result produced was a raster file that generally contrasts N- and S-facing slopes. In this thesis, however, N- and S-facing is not identical to compass N and S. Specifically, all slopes whose values ranged from 0 to 67.5 degrees or 292.5 to 360 degrees were classified as N-facing and values ranging from 112.5 to 247.5 degrees were classified as S-facing. East-facing slopes (67.5 to 112.5 degrees) and west-facing slopes (247.5 to 292.5 degrees) were excluded from the study. However, because the values contain float numbers with decimal points, the original raster file will be multiplied by 10 and converted to an integer for the final selection criteria (Table 4).

Table 4: Aspect Selection Criteria

Aspect Directions	Value Before	Value After	Comment
Flat	-1	-10	Not Selected
N	0-22.5	0-225	Selected
NE	22.5-67.5	225-675	Selected
E	67.5-112.5	675-1125	Not Selected
SE	112.5-157.5	1125-1575	Selected
S	157.5-202.5	1575-2025	Selected
SW	202.5-247.5	2025-2475	Selected
W	247.5-292.5	2475-2925	Not Selected
NW	292.5-337.5	2925-3375	Selected
N	337.5-360	3375-3600	Selected

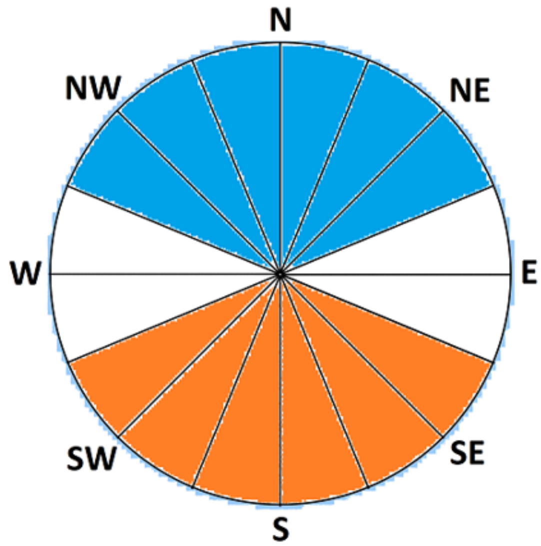


Figure 4: Aspect selection criteria shown on compass

Selected Directions Are Marked in blue and orange

The thesis studied the land cover change from 2001 to 2016 on both north and south facing slopes of two case studies sites. The detailed numeric data table and visualized changing trend are provided in the result section and the appendix (Appendix 9, 10).

CHAPTER IV

RESULTS

Land Cover across the State

From the latest 2016 NLCD data, the thesis has classified Oregon into seven land cover types. From Figure 2, we can identify large water bodies such as Upper Klamath Lake or Lake Abert. Perennial ice or snow is rare, but it exists around the summit of Mount Hood or Three Sisters. Developed urban areas located in the Willamette Valley. Large urban areas such as Portland or Eugene are labeled as red on the map. Crops and pastures can be found near cities or Columbia River in the north. Barren ground mainly exists in alpine regions such as the Wallowa Mountains or arid regions such as the Alvord Desert. Forest resources can be found in the Coast Range and the Cascade Range as well as some national forests in the Eastern Oregon. Short vegetation such as shrubs is ubiquitous in Oregon. They cover most parts of Eastern Oregon.

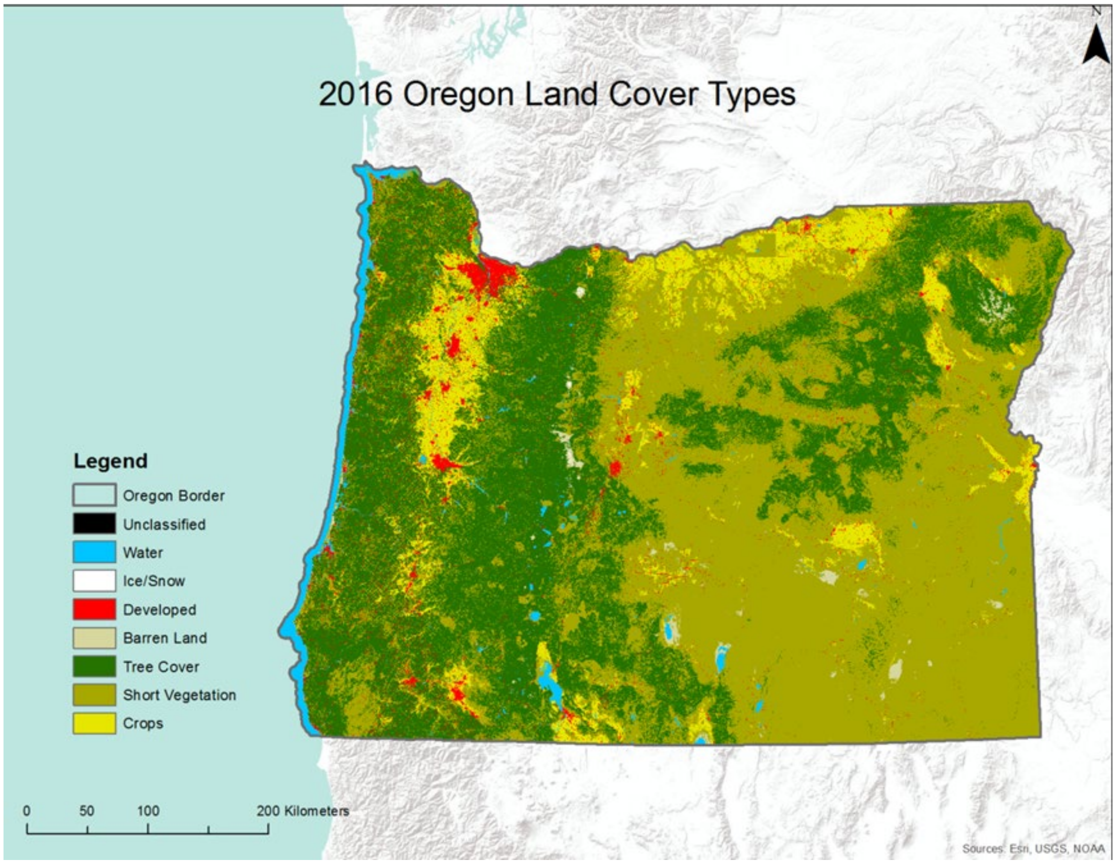


Figure 2: Current Oregon Land Cover (2016) and major land cover categories

After quantification (Table 2), the thesis detected that Water Bodies occupied 5546.5 km^2 of land surfaces, which is equivalent to 2.18% of Oregon's total area. However, compared to the data value in 2001, 146.5 km^2 or 2.57% of the water bodies disappeared or converted to other land cover types. Ice and snow only occupy 0.01% of Oregon's total area. After 16 years, glaciers in Oregon decreased by 3.5% (1.1 km^2) and were 30 km^2 in 2016. Developed lands such as urban areas keep increasing. In 2016, 6780.2 km^2, or 2.7% of Oregon's total area were used as constructed areas. Compared to the value from 2001, developed lands increased by 1.1% (71.7 km^2). Natural land cover types (Barren Ground, Tree Cover, and Short Vegetation) have more dramatic fluctuations. Barren ground once covered 1.44% (3677.43 km^2) of Oregon's surface area in 2001. However, this number decreased by 53%. In 2016, barren ground had coverage of 1729.2 km^2 and it only covered 0.68% of Oregon's total area. In 2016, tree cover occupied 35% of Oregon's surface area, which was 89130.2 km^2. In 2001, however, the numbers were 94207.07 km^2 and 40%. Tree cover decreased by 5.4% after 16 years. Short vegetation such as shrubs or herbaceous plants covered more than half of the surface in Oregon. In 2001, 124511.45 km^2, or 48.9% of the total land area. After 16 years, the number increased by 5.7% to 131667.58 km^2, or 51.67% of the total land area. Crops, hay, and pasture stayed stable between 2001 and 2016. In 2001, crops covered 7.84% of Oregon's surface area, which was 19971.51 km^2. In 2016, crops only decreased by 0.28% to 19916.37 km^2, which occupied 7.82% of the total surface area of Oregon. Before the separation of vegetation change on private or public lands, the thesis studied tree cover in Oregon from 2001 to 2016 (Figure 5). Red areas indicate tree cover loss (shifted to barren land or short vegetation) and blue areas indicate tree cover gain (shifted from barren land or short vegetation). The total vegetation change areas are 18860.89 km^2. Within the areas where experienced vegetation change, 63.3% (11938.94 km^2) were tree cover loss and 36.7% (6921.95 km^2) were tree cover gain. In the western side of the Cascade Range, tree cover gain and loss both exist and they often surround each other like checkerboards. However, there is more tree cover loss in the eastern side of the Cascade Range.

In order to separate vegetation change caused by anthropogenic factors such as logging with vegetation change caused by non-anthropogenic factors, the thesis investigated land ownership in Oregon and has divided land parcels into private and public lands. By the definition of the thesis, private lands are usually owned by timberlands companies such as Weyerhaeuser. They usually experience high-intensity logging like clearcutting. On the other hand, "public" lands in the thesis does not mean 100% owned by the public. Public lands can be owned by the Bureau of Land Management (BLM) or the US Forest Service or even tribes, and they usually experience very low to none logging activities. From Figure 3, we can see that public lands mainly located in the Cascade Range and its eastern side. On the western side of the Cascade; however, public lands and private lands surrounding each other produce checkerboard patterns. These patterns widely exist in the western part of Oregon.

Table 2: Net area change for 7 major land cover categories in the state of Oregon from 2001 to 2016

Code	Land Cover Types	2001 (km^2)	2006 (km^2)	2011 (km^2)	2016 (km^2)	Net Area Change from 2001 to 2016 (km^2)	Net Percentage of Change from 2001 to 2016 (%)
1	Water	5692.96	5856.71	6302.36	5546.51	-146.45	-2.57
2	Ice/Snow	31.09	31.09	29.99	29.99	-1.1	-3.54
3	Urban	6708.5	6779.11	6754.04	6780.2	71.7	1.07
4	Barren Land	3677.43	3866.67	1519.4	1729.18	-1948.25	-52.98
5	Tree Cover	94207.07	91476.13	88700.96	89130.17	-5076.9	-5.39
6	Short Vegetation	124511.45	126794.52	131676.91	131667.58	7156.13	5.75
7	Crops	19971.51	19995.78	19816.34	19916.37	-55.14	-0.28

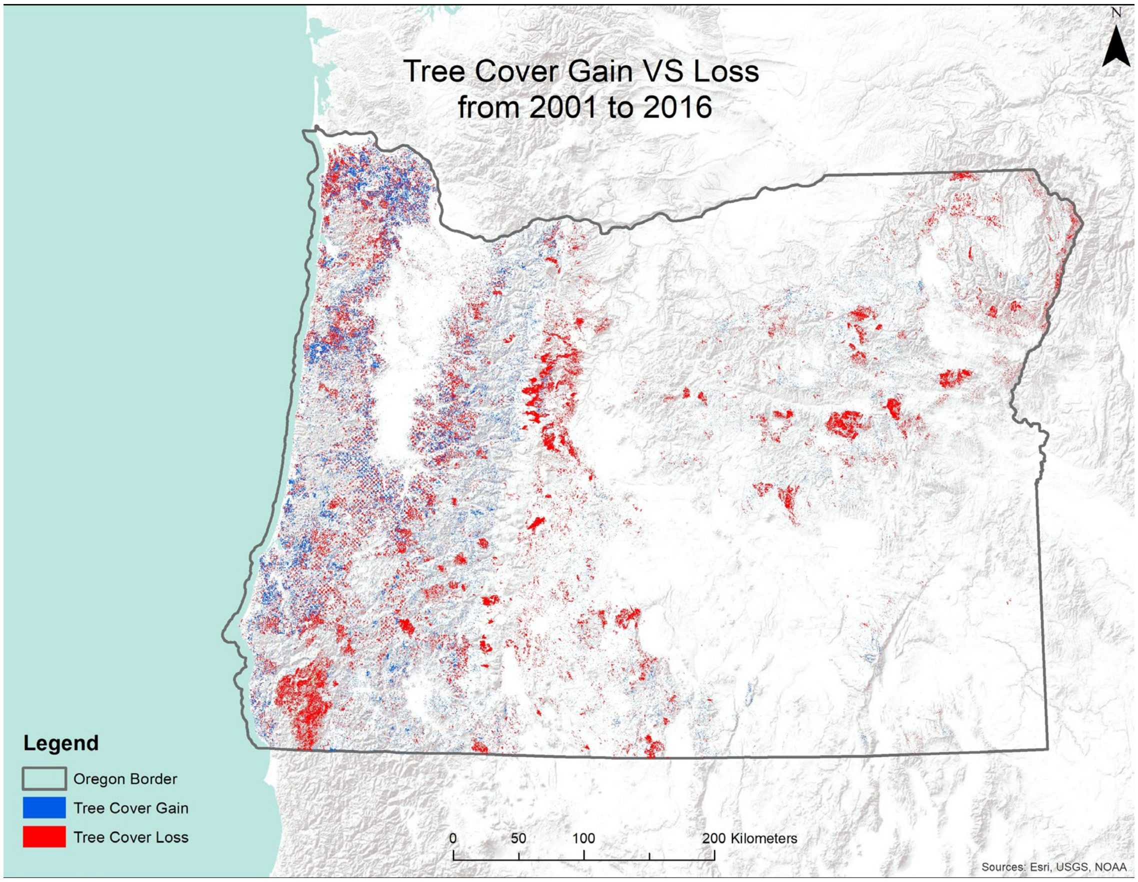


Figure 5: Tree Cover Gain (36.7%) vs. Tree Cover Loss (63.3%) as a proportion of the total change in tree cover across the state of Oregon from 2001 to 2016 (The same map with outlined pixels is provided in Appendix 13)

Trends in Public vs. Private Land

After separating land ownership into private and public lands, the thesis has produced two new maps (Figure 6 and 7). Figure 6 shows the tree cover gain and loss over Oregon's private lands. Either gain or loss is not very dramatic. According to the statistics of the data, the total tree cover change areas on private lands were 4295.22 km^2. Tree cover gain on private lands covered 2097.85 km^2, which took up 48.8% of the total changed area. Tree cover loss on private lands took up 51.2%, which equals to 2197.37 km^2.

Public lands have more dramatic tree cover changes (Figure 7). In total, 14221.23 km^2 of Oregon's public lands have experienced tree cover change. Tree cover loss is more noticeable than gain. The total area of tree cover gain on public lands was 4561.03 km^2 (32.1% of the total area) while tree cover loss was 9660.2 km^2 (67.9% of the total area). After knowing where the change happened, the thesis also studied when the change happened (Appendix 5, 6). Zoomed in case studies will be added in the end of this chapter (Figure 8, 9, 11, 12).

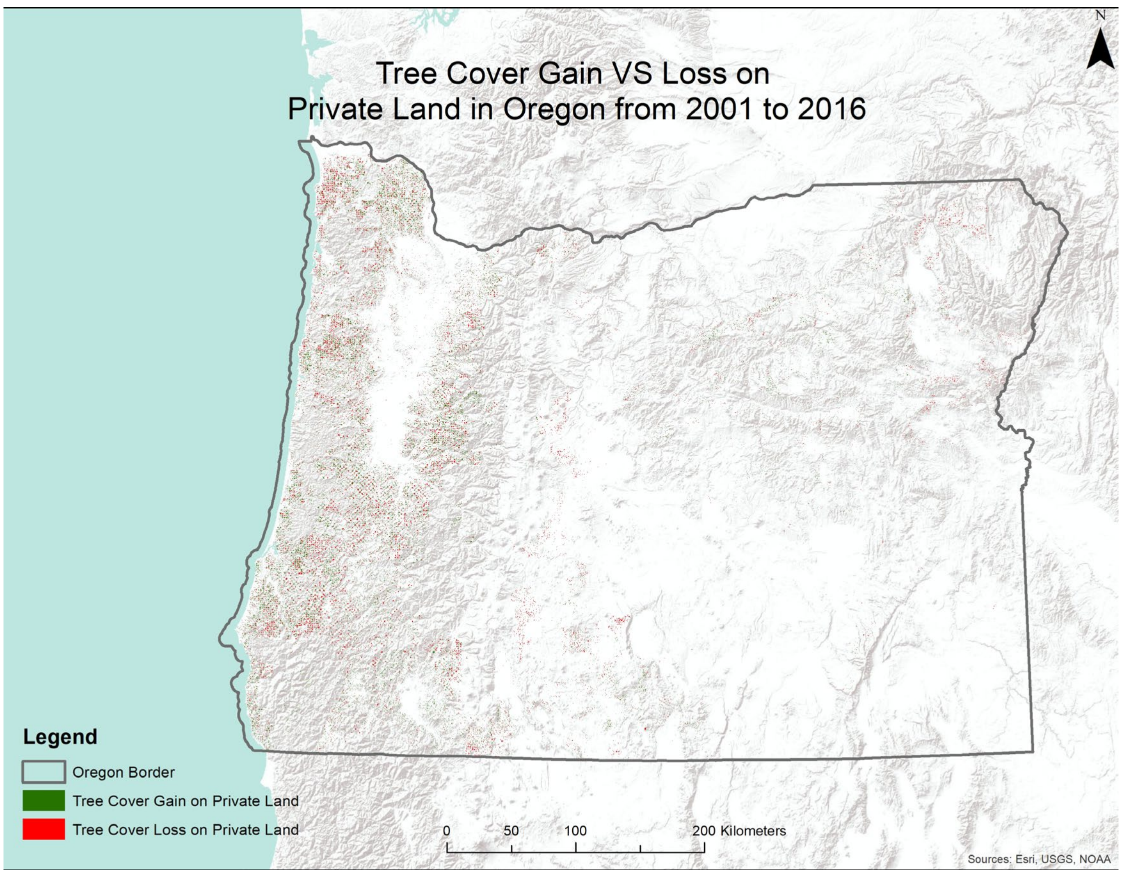


Figure 6: Tree Cover Gain and Tree Cover Loss on Private Land in Oregon from 2001 to 2016

Gain 2097.85 km^2 vs. Loss 2197.37 km^2 (The same map with outlined pixels is provided in Appendix 14)

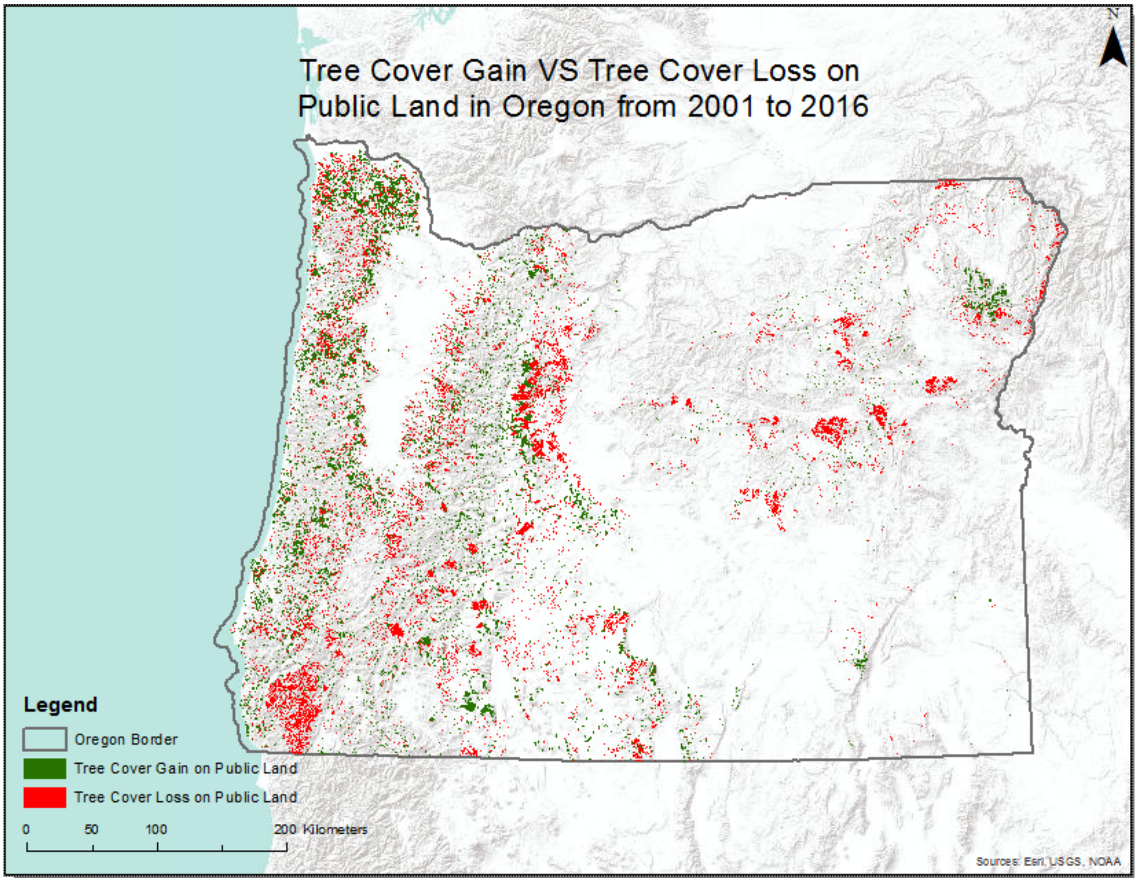


Figure 7: Tree Cover Gain and Tree Cover Loss on Public Land in Oregon from 2001 to 2016 Gain 4561.03 km^2 vs. Loss 9660.2 km^2 (The same map with outlined pixels is provided in Appendix 15)

The thesis has also analyzed the tree cover gain and loss over public land based on their temporal distribution. The spatial distribution of tree cover gain over public land in Oregon from different periods between 2001 and 2016 is displayed in the appendix (Appendix 5). Blue areas represent tree cover gain which occurred before 2006. They are rare, but they can be found near the Paulina Peak in Central Oregon. These changes occupy 36.71 km^2, which is only 0.8% of overall tree cover gain on public land. Tree cover gain happened more frequently between 2006 and 2011. It covered 2661.32 km^2, which took up 58.35% of total tree cover gain on public land. It was labeled in fir green color and most of them exist in the Cascade Range and the Wallowa Mountains. The latest tree cover gain, which happened between 2011 and 2016, located in the western part of Oregon. It was marked in light green color and covered an area of 1863.0 km^2, which took up 40.85% of overall tree cover gain on public land.

Tree cover loss over public land in Oregon usually associates with wildfires or other natural disasters. The thesis indicated that the tree cover loss which happened before 2006 (Red) is located in the Coast Range (Appendix 6). Between 2006 and 2011, tree cover loss occurred sporadically in the Cascade Range and its eastern side (Orange). However, there is a large and continuous polygon in the southwestern corner of the map and it will be studied separately. The latest tree cover loss, which happened after 2011, can be found in forests in the east part of the state (Yellow). Early tree cover loss (between 2001 and 2006) covered 1328.43 km^2, which is 13.75% of the total overall tree cover loss. Recent tree cover loss (between 2006 and 2011) covered 5170.41 km^2, which is 53.52% of the total tree cover loss. The latest tree cover loss (between 2011 and 2016) took up 32.72% of the total tree cover loss, which is equivalent to 3161.36 km^2.

Case Studies

The 2002 Biscuit Fire Extent

In 2002, the Biscuit Fire destroyed almost 2000 km^2 forests in the southwestern part of Oregon (Sessions, Bettinger, Buckman, Newton, & Hamann, 2004). The climate within the fire polygon can be classified as dry warm summers and wet cool winters (Halofsky & Hibbs, 2008). The thesis has downloaded the Biscuit Fire polygon created by the BLM and stacked and compared it with the extent of tree cover loss on public land. Figure 8 shows that fire-related tree cover loss mostly happened between 2001 and 2011. Damage of the fire is detected accurately both by time and location.

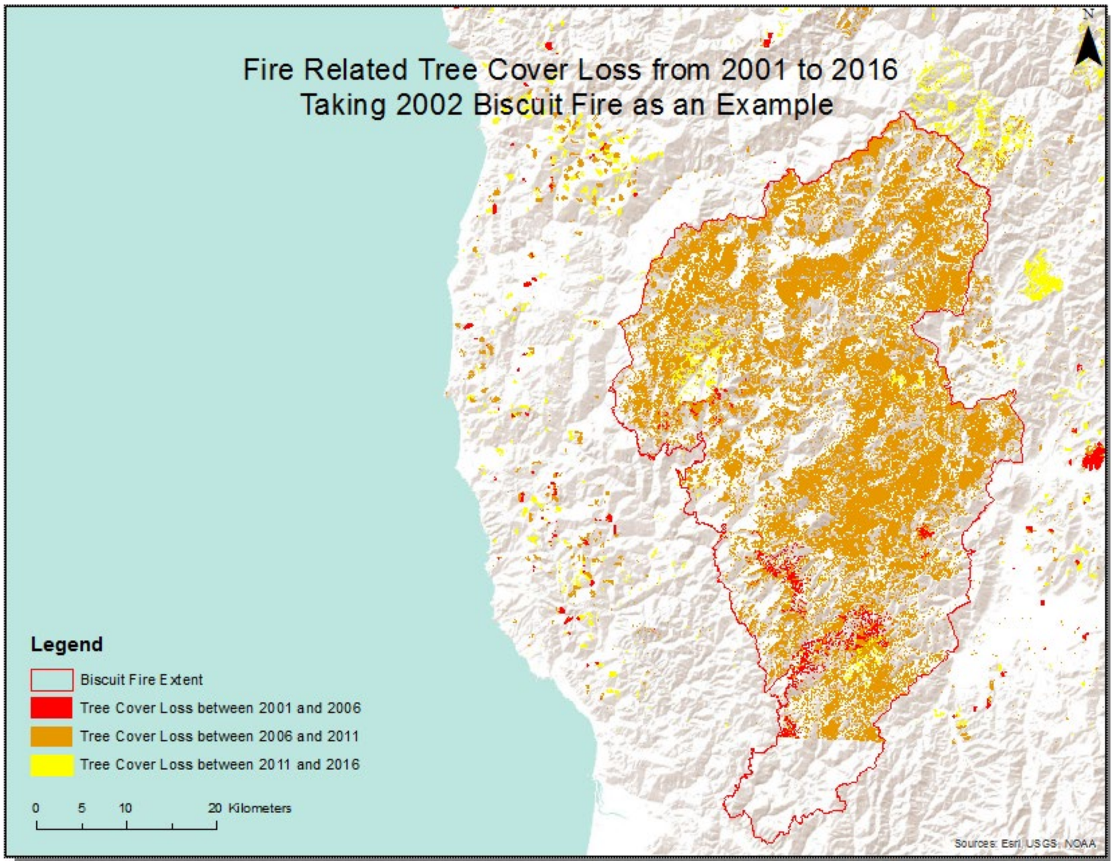


Figure 8: Tree Cover Loss in Biscuit Fire Extent. The fire occurred in 2002, but the majority of the tree cover loss was detected a few years later.

Loss between 2001 and 2006: 25.13 km^2

Loss between 2006 and 2011: 697.81 km^2

Loss between 2011 and 2016: 19.86 km^2

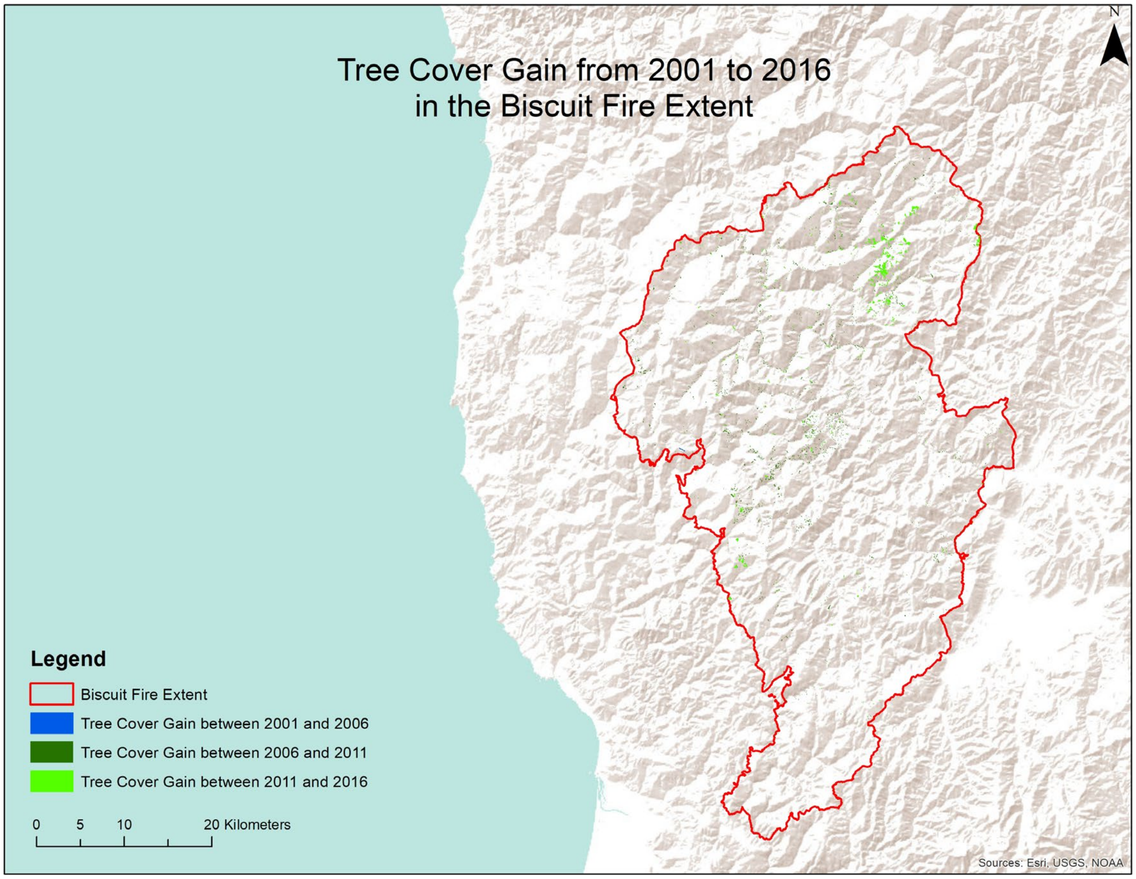


Figure 9: Tree Cover Gain in Biscuit Fire Extent

Gain between 2001 and 2006: 0.024 km^2

Gain between 2006 and 2011: 11.17 km^2

Gain between 2011 and 2016: 3.909 km^2

(The same map with outlined pixels is provided in Appendix 11)

From Figure 8, we can see the tree cover loss history between 2001 and 2016. Between 2001 and 2006 or 2011 and 2016, tree cover loss was maintained at a relatively low scale. However, almost 94% of the tree cover loss happened during 2006 and 2011, which implied large scale natural disturbance (Figure 8, Appendix 7). Most of the tree cover loss happened inside of the fire extent in 2002. On the contrary, outside of the fire polygon, tree cover loss happened randomly and sporadically in Southeastern Oregon. Although the fire occurred in 2002, the majority of the tree cover loss was detected between 2006 and 2011. One possible explanation is that dead trees still covered the ground and Landsat satellite failed to reclassify them until the next available data was collected. Although fire-related tree cover loss dominated the case study area, tree cover gain from different periods are detected (Figure 9). The detailed change of tree cover area and the percentage is shown in the appendix (Appendix 7).

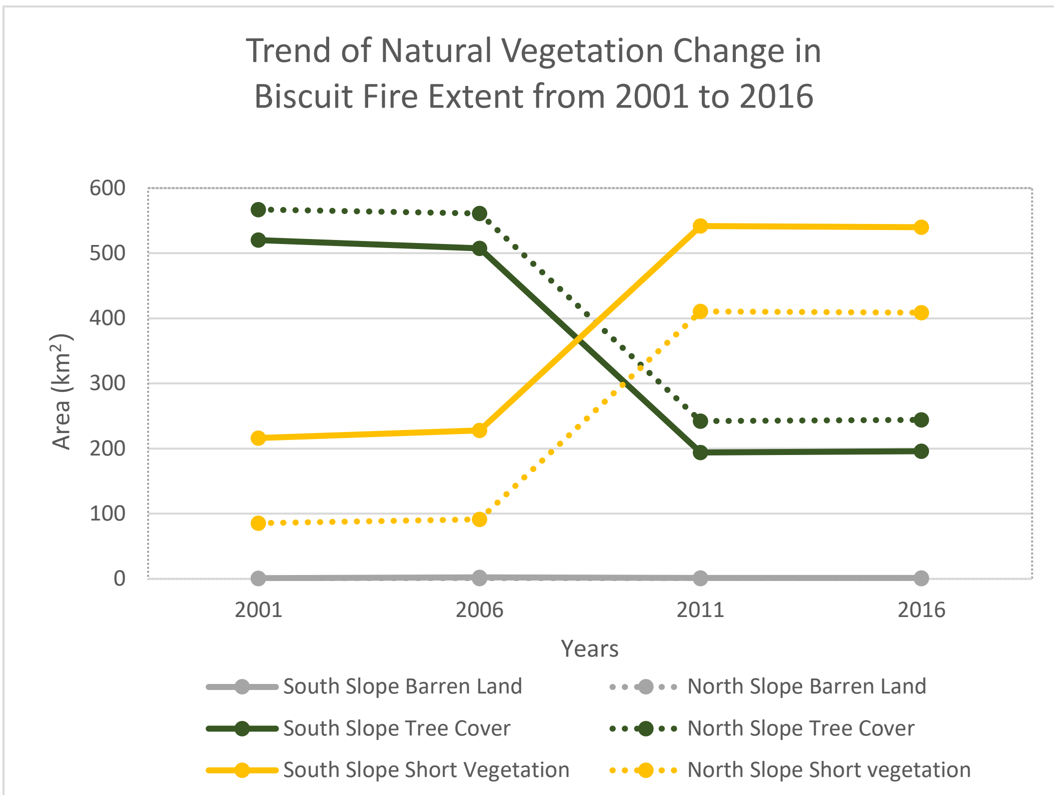


Figure 10: The Changing Trend of Natural Vegetation inside the 2002 Biscuit Fire Extent South vs. North Slopes

During the 16 years period, the conversion between tree cover and short vegetation was obviously observed. Before 2011, tree cover was the dominant land cover type on both south and north-facing slopes in the fire polygon. For example, in 2001, tree cover on north slopes covered an area of 567.09 km^2, which was equivalent to 85.88% of the total area of all north-facing slopes of the fire extent. Tree cover on south slopes also occupied an area of 520.09 km^2 in 2001, which took up 69.6% of the total area of all south-facing slopes. The area and percentage of short vegetation and barren land remained low and stable until 2006. However, the Biscuit Fire totally switched the position. After the fire, short vegetation became the most dominant land cover type in both south and north slopes. In 2011, short vegetation on south-facing slopes had an area of 541.73 km^2, which covered 72.5% of the total area of all south-facing slopes. Similarly, there were 410.66 km^2 of short vegetation on north-facing slopes and it took up 62.19% of the total area of all north-facing slopes. However, tree cover on both south and north-facing slopes inside the fire extent is recovering slowly. In 2016, tree cover gained its area by 1.92 km^2 on the south and 1.82 km^2 on north-facing slopes. In the meanwhile, the extent of short vegetation is shrinking slowly. In 2016, the area of short vegetation on south and north-facing slopes had decreased by 1.97 km^2 and 1.85 km^2 respectively. The gain of the tree cover almost equals the loss of the short vegetation. One possible explanation can be the regrowth of tree cover after the fire. In 2011, some recently regrew trees were not tall enough to be detected as tree cover. However, they have grown tall enough to be recognized as tree cover in the data from 2016. A detailed raw data table is provided in Appendix 9.

Eagle Cap Wilderness

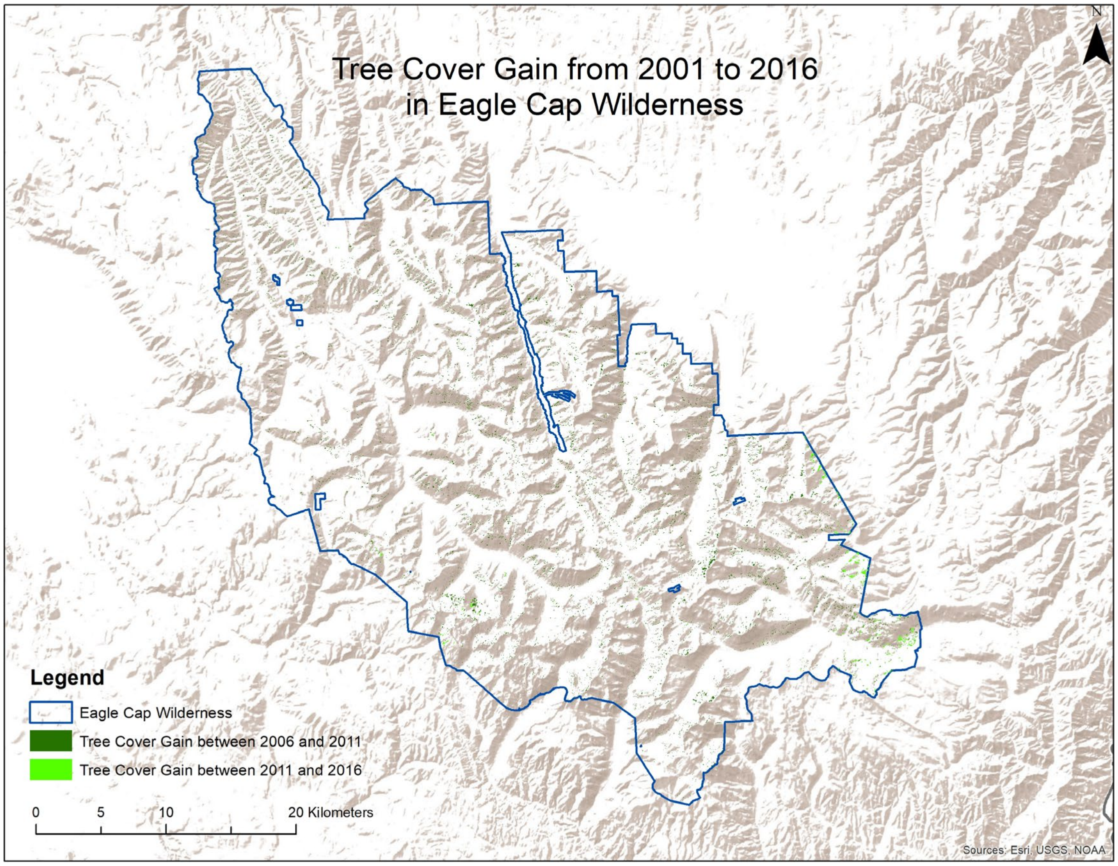


Figure 11: Net Tree Cover Gain in Eagle Cap Wilderness. No tree cover gain was detected between 2001 and 2006

Gain between 2006 and 2011: 19.27 km^2

Gain between 2011 and 2016: 1.95 km^2

(The same map with outline pixels is provided in Appendix 12)

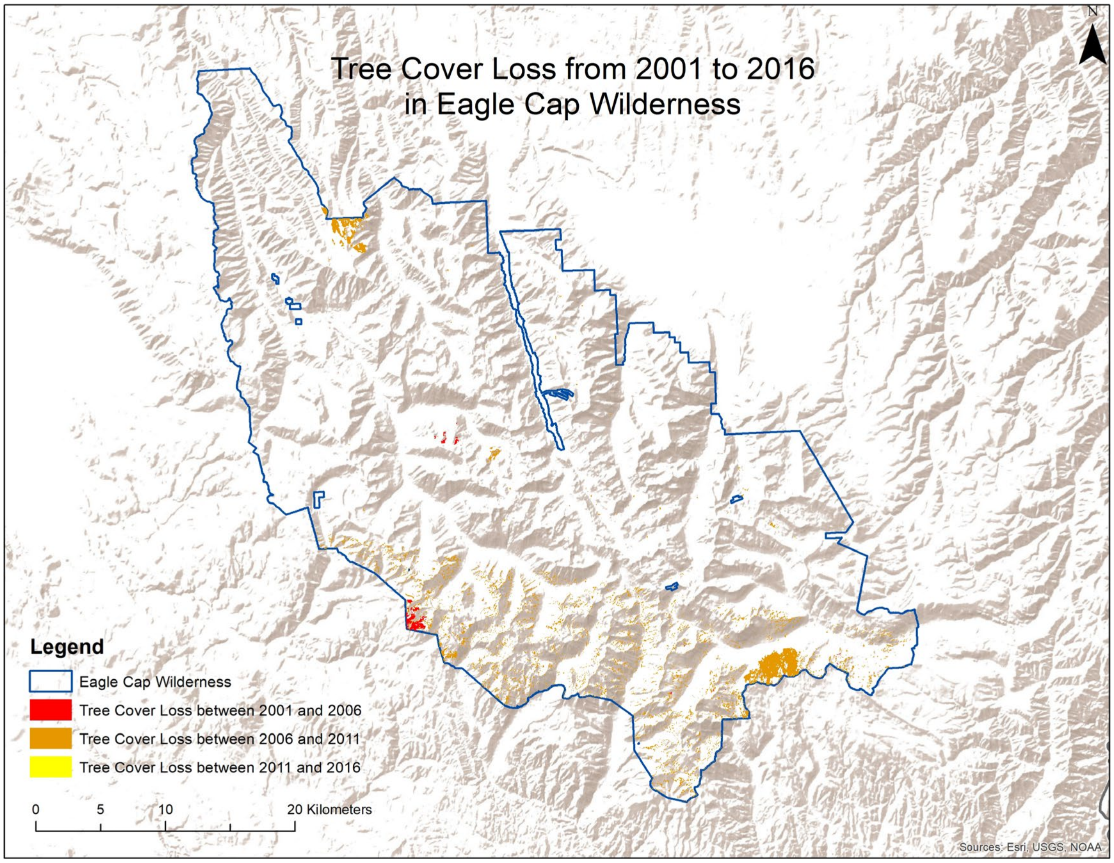


Figure 12: Net Tree Cover Loss in Eagle Cap Wilderness

Loss between 2001 and 2006: 1.555 km^2

Loss between 2006 and 2011: 33.06 km^2

Loss between 2011 and 2016: 9.60 km^2

(The same map with dark basemap is provided in Appendix 16)

In a region without frequent and severe fire activities, such as Eagle Cap Wilderness in northeast Oregon, vegetation growth has demonstrated different patterns. The climate of Eagle Cap Wilderness is characterized by cold winter and warm summer and most of the precipitation occurs during winter months (Rheinheimer, 2007). The average low temperature of January is -3.9 °C (25 °F) and the average high temperature of July is 28.9 °C (84 °F) (Rheinheimer, 2007). Figure 11 showed that the growth of tree cover mainly happened between 2006 and 2011. Tree cover growth existed in mountainous regions ubiquitously. No noticeable tree cover gain has been detected between 2001 and 2006. However, among the total increased tree cover, about 91% of them happened between 2006 and 2011 (Appendix 8). But surprisingly, the area of tree cover loss has exceeded the area of gain (Figure 12). From 2001 to 2016, about 44.21 km^2 of tree cover has been converted into either short vegetation or barren land. However, only 21.22 km^2 of barren land and short vegetation has shifted to tree cover (Appendix 8). Both tree cover gain and loss occurred dramatically between 2006 and 2011. The detailed change of tree cover area and the percentage is shown in the appendix.

Although forest expansion was common in Eagle Cap Wilderness area, tree cover only gained an area by 0.63 km^2 on south slopes and even decreased by 14.17 km^2 on north slopes since 2001. The extent of short vegetation such as shrubs decreased by 15.93 km^2 on south slopes since 2001, but it increased by 7.421 km^2 on north-facing slopes. The extent of the barren land on both south and north-facing slopes had increased since 2001. Especially between 2006 and 2011, barren land expanded substantially in the area. At the same time, the extent of north-facing tree cover and south-facing short vegetation have both shrunk. Figure 13 has reflected the changing trend of natural vegetation in the Eagle Cap Wilderness. It is not as dramatic as the fire polygon in Southeastern Oregon, but the causes of shifts between different land cover types will be needed to discover in further studies. Detailed raw data is provided in the appendix (Appendix 10).

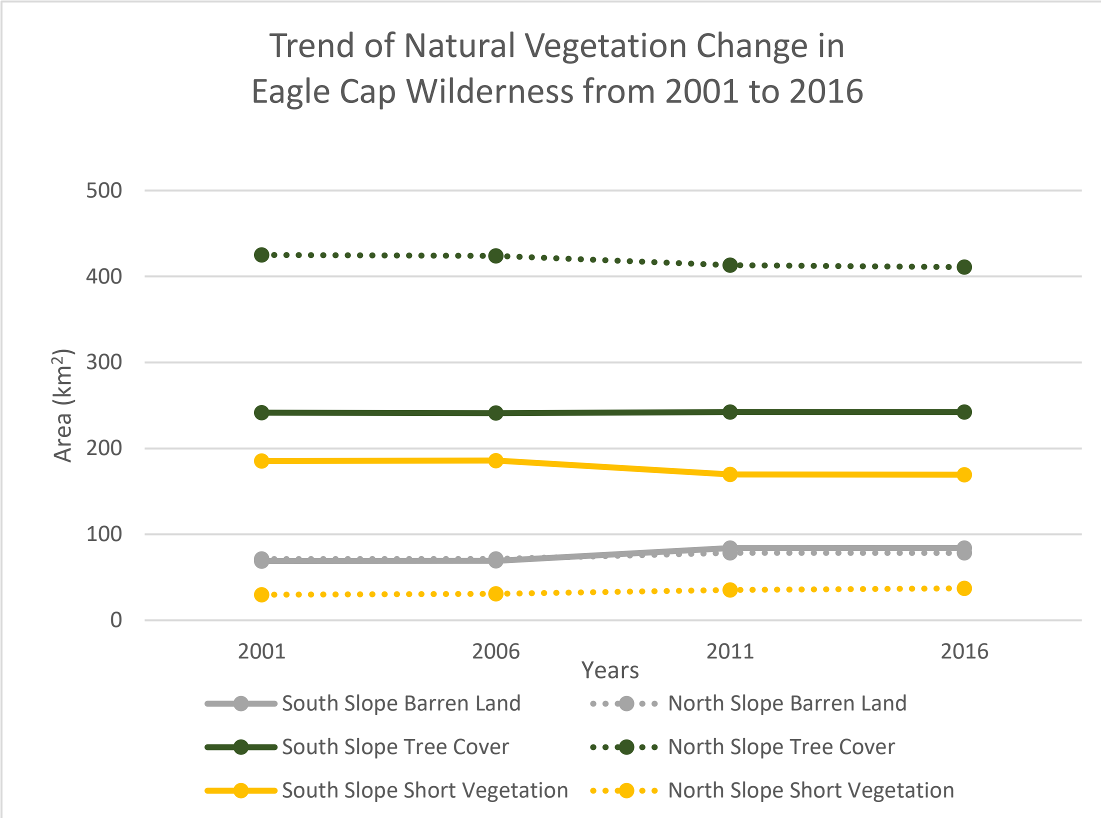


Figure 13: The Changing Trend of Natural Vegetation inside Eagle Cap Wilderness South vs. North Slopes

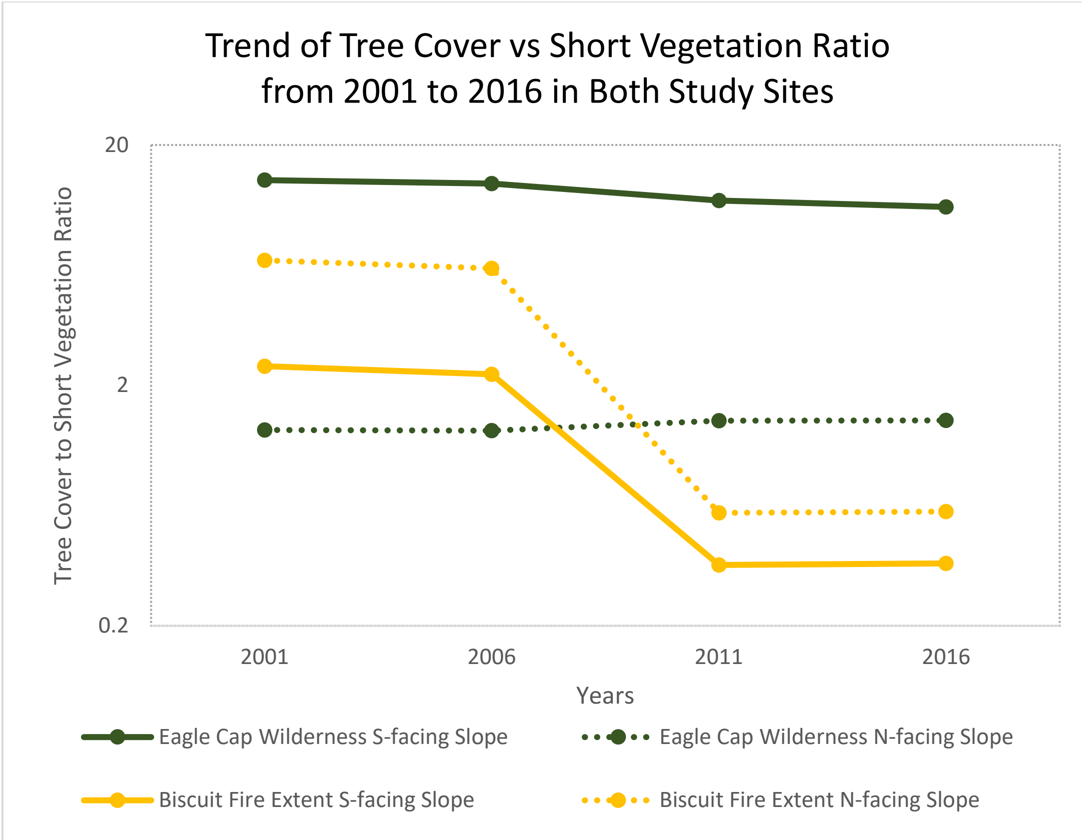


Figure 14: Tree Cover vs. Short Vegetation Ratio, Biscuit Fire Extent vs. Eagle Cap Wilderness

Figure 14 shows the ratio between tree cover and short vegetation extent based on the data collected through the study. This figure indicated that tree cover gain on N-facing slopes of Eagle Cap Wilderness had exceeded the short vegetation gain by the end of the 16 years period (Dashed green line). Also, this figure showed a steady decline in tree cover relative to short vegetation in S-facing slopes of Eagle Cap Wilderness (solid green line). The gain of short vegetation has exceeded the gain of tree cover by the end of the 16 years period. Lastly, this figure indicated that the major decline of tree cover has occurred on both S and N-facing slopes in the Biscuit Fire impacted area. But warmer S-facings slopes had more intense tree cover loss relative to short vegetation loss.

CHAPTER V

DISCUSSION OF RESULTS

Land Cover across the State

This thesis has established a novel workflow to quantify and classify land cover change in Oregon from 2001 to 2016. Both the spatial distribution and the rough occurrence time of land cover change can be identified. The method introduced in previous sections can be applied to different study areas or disciplines with different time span or type of data. By quantifying and classifying land cover change from 2001 to 2016 in Oregon, the thesis has assigned codes to each detected land cover change category and discovered the declining trend of tree cover extent and the increasing trend of short vegetation coverage. The 2002 Biscuit Fire impacted area overlaid with the moisture deficiency in southwestern Oregon (Figure 1) and provided the thesis with a great example to study the tree cover loss caused by natural disturbances and its recovery. The Eagle Cap Wilderness has also corresponded with the observed decreasing moisture hotspot in northeastern Oregon (Figure 1). The expansion of the tree cover and their interactions with the environment in Oregon high elevation regions was also studied and discussed.

Tree Cover Change Trends in Public Land

Viewing from Figure 2, extensive coverage of forests can be observed. According to table 2, forests covered a large percentage of Oregon's total land area. However, the percentage declined continuously since 2001. The tree cover loss can be examined in two ways: private land and public land. The tree cover gain/loss on private land was stable and stayed close. From 2001 to 2016, 2197.37 km^2 of forests on private land has shifted to other land cover categories while 2097.85 km^2 of other land cover categories shifted back to forests. The loss has only exceeded the gain of about 100 km^2. The relatively small difference between tree cover gain and loss on private land stays consistent with the findings from the Oregon Department of Forestry (ODF). A report from ODF which published in 2016 indicated that tree cover area owned by forest industry stayed nearly the same since 1974. From 1974 to 2014, non-Federal owned forest only declined by 2% (Gray, Hubner, Lettman, McKay, & Thompson, 2016), which supported the statistic from this thesis (Figure 6). Also, Oregon laws require forests restoration after commercial timber harvests (Cathcart, 2000). Thus, it explained why tree cover on private land did not change dramatically. However, the changing trend of tree cover on public land have demonstrated a different pattern. Comparing to the 100 km^2 difference between loss and gain on private land, tree cover loss on public land has exceeded the gain by more than 5000 km^2. Among all the areas which have experienced categories shifts between barren land, tree cover, and short vegetation, 32% of them were classified as tree cover gain and 68% of them were detected as tree cover loss.

The 2002 Biscuit Fire

The notable imbalance between tree cover gain and loss on public land can be partially explained by the history of wildfires in Oregon. In 2002, the Biscuit Fire, one of the largest wildfires in Oregon history, destroyed almost 500,000 acres (2023 km^2) of forests and caused a loss of 154 million dollars (Sessions, Bettinger, Buckman, Newton,

& Hamann, 2004; Azuma, Donnegan, & Gedney, 2004). Other wildfires may also play roles to exacerbate the tree cover loss on public land. For example, the 2003 B&B Complex Fire, which happened on the eastern side of the Cascade Range, burned around 37000 ha (370 km^2) of tree cover (Halofsky & Hibbs, 2008). It is hard to determine the exact relationship between tree cover loss and fire activities. But major and sporadic fire disturbances obviously associated with land cover categories shifts (especially from 5 to 6). Other potential causes of tree cover loss, such as climate factors will require further study to discover and prove.

The impact of the 2002 Biscuit Fire and following forest recovery in the area were studied in the thesis. As one of the biggest wildfires in Oregon's history, the impact and the post-fire recovery of the fire have been studied by scholars and researchers broadly. By using the method mentioned above, the thesis has visualized the shifts between tree cover and short vegetation within the fire polygon (Figure 10). Also, the trend line of tree cover loss and gain since 2001 were made based on the observed data. Comparing to other studies related to the Biscuit Fire, the thesis has visualized the tree mortality accurately. The orange area in Figure 8 matched closely with the canopy mortality map from USDA (Azuma, Donnegan, & Gedney, 2004). Although the fire perimeter was notable, the fire severity was not always the same within the fire polygon. According to USDA, about 37% of tree cover within the fire perimeter has experienced moderate or severe damage (Azuma, Donnegan, & Gedney, 2004). Compared to the low burn severity area, the stand-replacing fire was relatively uncommon. But it explained why the observed tree cover loss area (code 5566, 5666, and 5556) were much smaller than the burnt area reported by other studies. The small difference between calculated tree cover loss and reported tree cover loss provided the thesis with credibility.

$$USDA: 499{,}000\ acres * 37\% = 184630\ acres\ (747.2\ km^2)$$
$$Thesis: 5566\ (697.66\ km^2) + 5666\ (24.61\ km^2) + 5556\ (19.8\ km^2) = 742.7\ km^2$$

In early successional stages after a fire, short vegetation such as shrub can be abundant and dominant (Halofsky et al., 2011). However, it may take more than a century for forests to fully recover (Adámek, Hadincová, & Wild, 2016). The 2002 Biscuit Fire has created a "scar" in the southwestern corner of Oregon, which was observed in the thesis (Figure 2). Figure 2 showed that after 14 years of regrowth, short vegetation was still the dominant land cover type within the fire polygon in 2002. Forest restoration after the fire was observable (Figure 9), but the rate of recovery was relatively slow (Appendix 7). The full recovery of forests may take several decades or even longer to finish under the current rate. The observed and calculated tree loss and gain stayed consistent with related studies.

Eagle Cap Wilderness

In areas with relatively low fire frequencies, such as the Eagle Cap Wilderness, the gain and loss of tree cover were also observed and studied by the thesis. Viewing historically, fire activities happened in the area over the past 15 years sporadically, but they were not as severe as the 2002 Biscuit Fire. Both tree cover gain and loss were detected throughout the Eagle Cap Wilderness area (Figure 11 & 12). Historical fire polygon data can be found on the website of the Bureau of Land Management (BLM). In order to study tree cover gain and loss without fire disturbances, the thesis has removed fire related loss. After exclusion, the tree cover gain and loss in the Eagle Cap Wilderness were 21.22 km^2 and 32.52 km^2 respectively. Generally, south-facing slopes in the North-Hemisphere usually receive more solar radiation than other slopes, causing relatively higher temperatures and lower moisture for vegetation growth (Hu, Ma, Shugart, & Yan, 2018). Consequently, north-facing slopes are more favorable for tree cover growth considering thermal and hydrological requirements. Related studies have also concluded that tree cover growth was mostly detected on north-facing slopes and low altitude regions (Améztegui, Brotons, & Coll, 2010). The research results of this thesis stayed partially consistent with the conclusion from similar studies. Figure 13 and appendix 10 both showed that there was far more tree cover extent in the north-facing slopes than in the south-facing slopes. Both the extent and the density of the tree cover were more noticeable on the north-facing slopes. However, comparing to other similar studies focusing on tree cover expansions, the expansion of the tree cover in the Eagle Cap Wilderness has demonstrated different or even opposite patterns. Among all the areas which have experienced tree cover gain, 34.2% (7.26 km^2) of the change happened below 2000 m (6561 ft) while 65.8% (13.96 km^2) of the change happened above 2000 m. 38.5% (8.17 km^2) of the total change happened on north facing slopes while 61.5% (13.05 km^2) of the change happened on south facing slopes. South-facing slopes and high altitude usually have less favorable growing conditions (Améztegui, Brotons, & Coll, 2010), but they supported more than 60% of the total tree cover gain. Under the background of global warming and climate change, the average annual temperature of the PNW region has increased by 0.72°C over the past century (Mote et al., 2014). The correlation and causation between higher temperature and abnormal tree cover gain observed on south-facing slopes worth further research.

Limitations and Further Studies

Although the thesis has designed new methods to qualify and quantify long-term land cover change, there are some limitations. Currently there are four time periods and seven land cover types in the thesis study. But if the number of time periods and/or land cover types increase, the workload of calculation and coding will increase significantly, even exponentially. Thus three to four time periods will be ideal for applying this method, and this method is not ideal for studying yearly changes unless the total time span is short as well.

To recap, this thesis has studied the land cover change trend in Oregon since 2001, and it has broken down the change into details to study the time of the occurrence and spatial distribution over both private and public lands. It has quantified the rate of vegetation change under different topographic gradients in local scales. Most of the findings in the thesis were supported and explained by previous studies. However, the declining trend of tree cover in Oregon since 2001 has not been addressed by any publication perfectly. Fire disturbances and mountain pine beetle (MPB) outbreaks are two possible causes, but it will require future studies to verify. In the Eagle Cap Wilderness, tree cover loss has exceeded the gain. However, more tree cover gain was detected on hotter and drier south-facing slopes, which was unexpected in the North-Hemisphere. The intrinsic connection between temperature anomalies and forest expansion in the Eagle Cap

Wilderness will await further research to analyze. Lastly, both large and small scales studies in the thesis have revealed the increasing trend of short vegetation. Further studies may use historical aerial photos and remote sensing techniques to study the starting year of this trend and determine whether it is a long and stable trend, or it is a fluctuation stage of ecosystem shifts.

APPENDIX

Land Cover Categories	Number of Pixels (2001)	Number of Pixels (2006)	Number of Pixels (2011)	Number of Pixels (2016)
Water	6325510	6507456	7002626	6162790
Ice/Snow	34545	34545	33321	33321
Urban	7453885	7532342	7504491	7533556
Barren Land	4086033	4296297	1688224	1921311
Tree Cover	104674523	101640141	98556620	99033523
Short Vegetation	138346051	140882799	146307678	146297310
Crops	22190565	22217532	22018152	22129301
Land Cover Categories	Area in 2001 (sq km)	Area in 2006 (sq km)	Area in 2011 (sq km)	Area in 2016 (sq km)
Water	5692.959	5856.7104	6302.3634	5546.511
Ice/Snow	31.0905	31.0905	29.9889	29.9889
Urban	6708.4965	6779.1078	6754.0419	6780.2004
Barren Land	3677.4297	3866.6673	1519.4016	1729.1799
Tree Cover	94207.0707	91476.1269	88700.958	89130.1707
Short Vegetation	124511.4459	126794.5191	131676.9102	131667.579
Crops	19971.5085	19995.7788	19816.3368	19916.3709

Appendix 1: Raw data of number of pixels and area of each land cover category for each year

Code	Number of Pixels	Description
5566	6920682	Recent Tree Cover Loss
6655	4543478	Recent Tree Cover Gain
5556	4180536	Latest Tree Cover Loss
6665	2640221	Latest Tree Cover Gain
4466	1623070	Recent Short Vegetation Growth over Barren Land
5666	1585272	Early Tree Cover Loss
5466	527750	Recent Short vegetation Growth over Barren Land and Tree Cover
4665	278022	Latest Tree Cover Gain over Short Vegetation and Barren Land
4666	149686	Early Short Vegetation Growth over Barren Land
6644	88893	Recent Short Vegetation Loss over Barren Land
6555	67749	Early Tree Cover Gain

4465	47465	Latest Tree Cover Gain over Barren Land and Short Vegetation
4455	46074	Recent Tree Cover Gain over Barren Land
6565	45508	Shifts between Short Vegetation and Tree Cover
5544	36288	Recent Tree Cover Loss Over Barren Land
5656	24450	Shifts between Tree Cover and Short Vegetation
4655	13041	Recent Tree Cover Gain over Barren Land and Short Vegetation

Appendix 2: Typical vegetation change patterns and their codes. Number 4, 5, and 6 refer to barren land, tree cover, and short vegetation respectively.

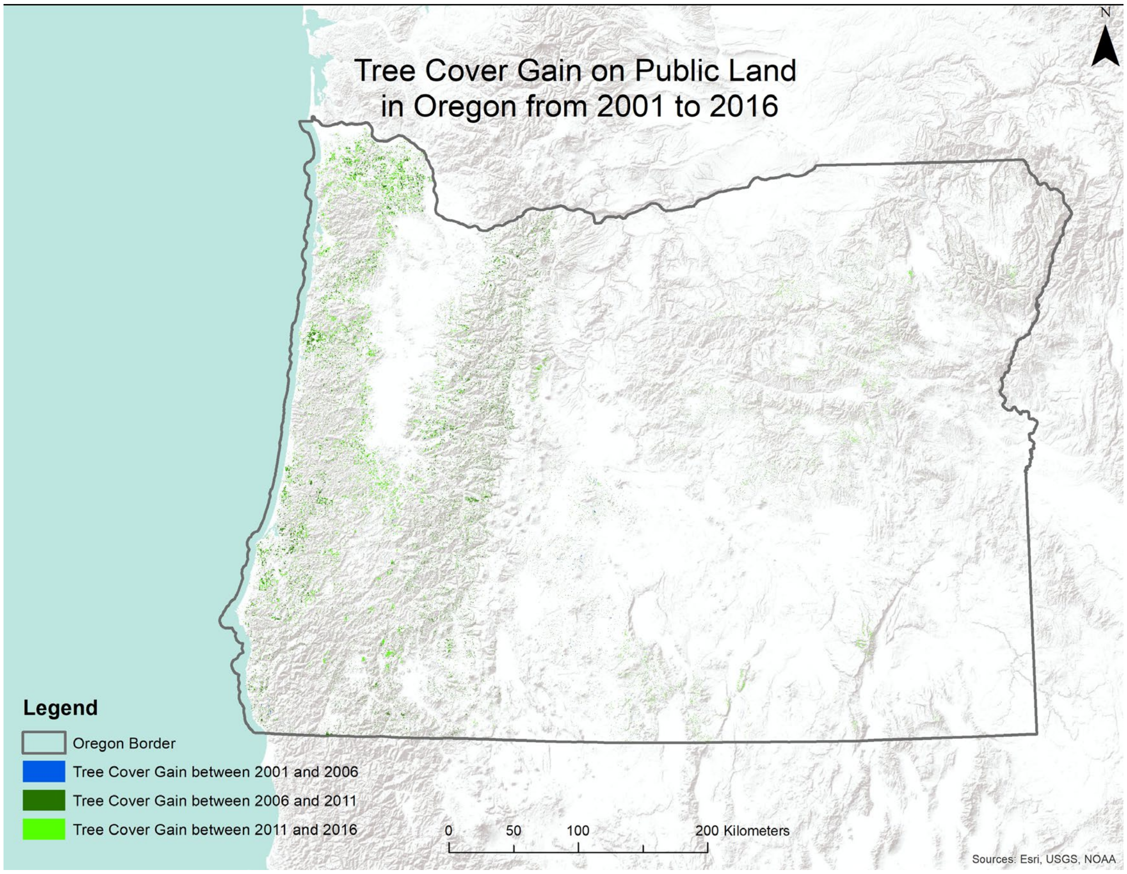
Code	Number of Pixels	Area (sq km)
7766	2083191	1874.8719
6677	1928983	1736.0847
5533	1106383	995.7447
6633	1068751	961.8759
3355	1006656	905.9904
3366	951399	856.2591
3377	606861	546.1749
7733	444082	399.6738
1116	249314	224.3826
4411	144518	130.0662

Appendix 3: Codes for land cover change types which were not discussed in the thesis

Land Manager Name	Description
BIA	Bureau of Indian Affairs
BLM	USDI Bureau of Land Management
BPA	Bonneville Power Administration
DOD	US Department of Defense
DOE	US Department of Energy
FAA	Federal Aviation Administration
FWS	US Fish and Wildlife Service
GSA	General Services Administration
LG	Local Government
NPS	National Park Service

ODF	Oregon Board of Forestry
ODFW	Oregon Dept. of Fish and Wildlife
ODOT	Oregon Dept. of Transportation
ODSL	Oregon State Land Board
OPRD	Oregon Dept. of Parks and Recreation
OR	State of Oregon
OSU	Oregon State University
OUS	Board of Higher Education
PV	**Private**
PVI	**Private Industrial**
TRIBAL	Tribes
USACE	Us Army Corps of Engineers
USBR	US Bureau of Reclamation
USCG	US Coast Guard
USDA	US Department of Agriculture
USFS	US Forest Service
WATER	Water

Appendix 4: A list of 27 kinds of land management ownership in Oregon. Ownerships considered as private land are bolded



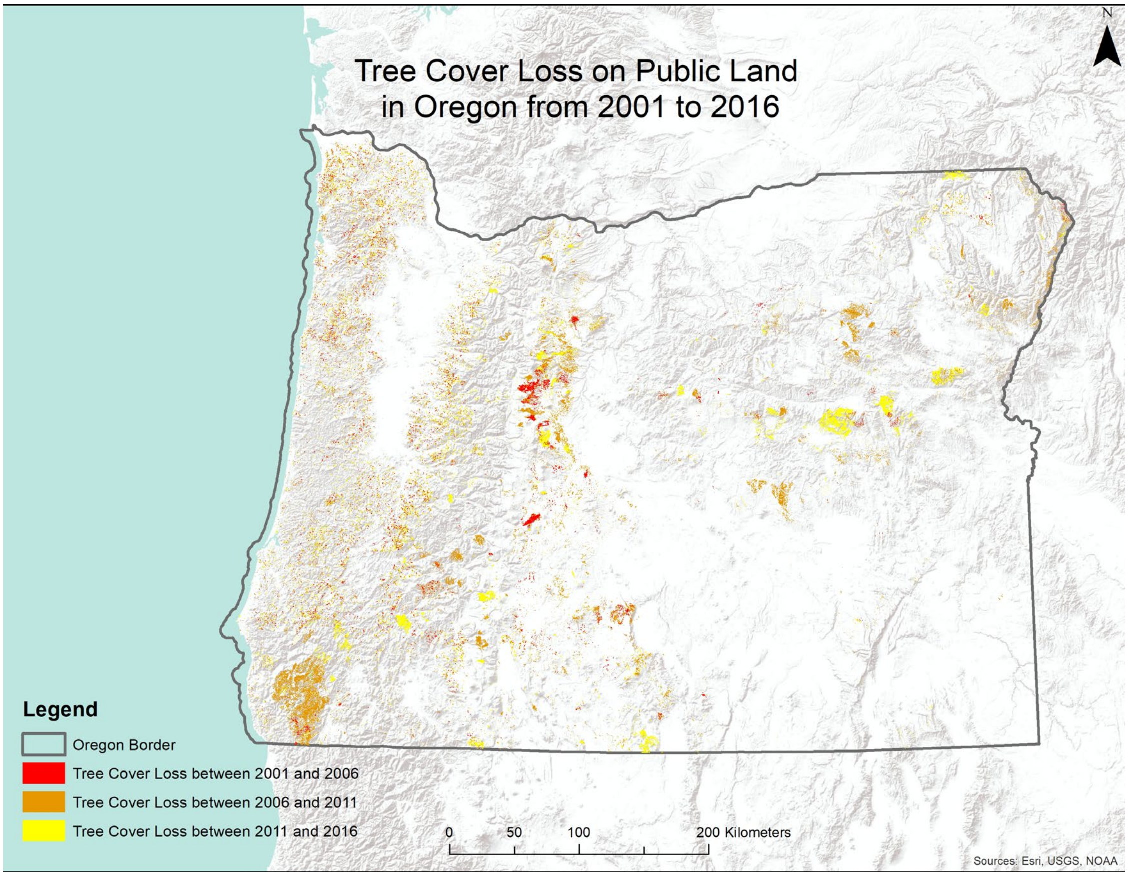
Appendix 5: Tree Cover Gain on Public Land from 2001 to 2016

Gain between 2001 and 2006: 0.8%

Gain between 2006 and 2011: 58.35%

Gain between 2011 and 2016: 40.85%

(The same map with outlined pixels is provided in Appendix 17)



Appendix 6: Tree Cover Loss on Public Land from 2001 to 2016

Loss between 2001 and 2006: 13.75%

Loss between 2006 and 2011: 53.52%

Loss between 2011 and 2016: 32.72%

(The same map with outlined pixels is provided in Appendix 18)

Land Cover Change Code	Description	Period of Shift	Area (sq km)
6655	Recent Tree Cover Gain	2006-2011	11.06
6665	Latest Tree Cover Gain	2011-2016	3.89
4455	Recent Tree Cover Gain	2006-2011	0.11
6555	Early Tree Cover Gain	2001-2006	0.024
6565	Latest Tree Cover Gain	2011-2016	0.019
4655	Recent Tree Cover Gain	2006-2011	0
4465	Latest Tree Cover Gain	2011-2016	0
5566	Recent Tree Cover Loss	2006-2011	697.66
5666	Early Tree Cover Loss	2001-2006	24.61
5556	Latest Tree Cover Loss	2011-2016	19.8
5466	Early Tree Cover Loss	2001-2006	0.52
5544	Recent Tree Cover Loss	2006-2011	0.15
5656	Latest Tree Cover Loss	2011-2016	0.06

Appendix 7: Tree Cover Gain and Loss in the Biscuit Fire extent

Land Cover Change Code	Description	Period of Shift	Area (sq km)
6655	Recent Tree Cover Gain	2006-2011	16.15
4455	Recent Tree Cover Gain	2006-2011	3.12
6665	Latest Tree Cover Gain	2011-2016	1.56
4465	Latest Tree Cover Gain	2011-2016	0.39
5566	Recent Tree Cover Loss	2006-2011	32.45
5556	Latest Tree Cover Loss	2011-2016	9.59
5666	Early Tree Cover Loss	2001-2006	1.52
5544	Recent Tree Cover Loss	2006-2011	0.61
5466	Early Tree Cover Loss	2001-2006	0.035
5656	Latest Tree Cover Loss	2011-2016	0.01

Appendix 8: Tree Cover Gain and Loss in the Eagle Cap Wilderness

Biscuit Fire Extent	2001	2006	2011	2016
South Slope Barren Land	1.13 km^2	2.32 km^2	1.49 km^2	1.5 km^2
North Slope Barren Land	0.54 km^2	0.56 km^2	0.53 km^2	0.54 km^2
South Slope Tree Cover	520.09 km^2	507.3 km^2	194.06 km^2	195.98 km^2
North Slope Tree Cover	567.09 km^2	561.11 km^2	242.3 km^2	244.12 km^2
South Slope Short Vegetation	216.31 km^2	227.92 km^2	541.73 km^2	539.76 km^2
North Slope Short Vegetation	85.59 km^2	91.55 km^2	410.66 km^2	408.81 km^2

Biscuit Fire Extent	2001	2006	2011	2016
South Slope Barren Land	0.15%	0.31%	0.2%	0.2%
North Slope Barren Land	0.08%	0.08%	0.08%	0.08%
South Slope Tree Cover	69.6%	67.89%	25.97%	26.23%
North Slope Tree Cover	85.88%	84.97%	36.69%	36.97%
South Slope Short Vegetation	28.95%	30.5%	72.5%	72.23%
North Slope Short Vegetation	12.96%	13.86%	62.19%	61.9%

Appendix 9: Natural Vegetation Changing Trend in 2002 Biscuit Fire Extent (Area in km^2 and Percentage)

South vs. North Slopes

Percentage are calculated by dividing area values with the total area of N or S facing slope

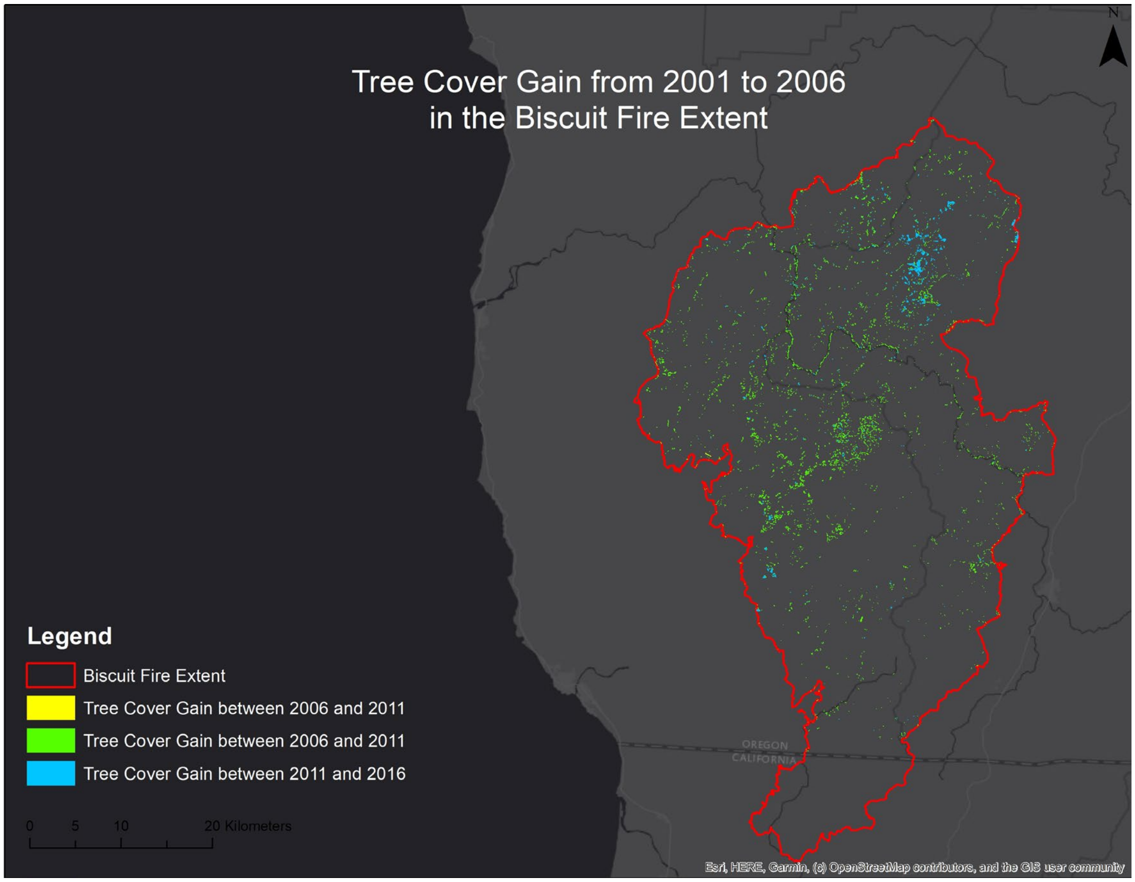
Eagle Cap Wilderness	2001	2006	2011	2016
South Slope Barren Land	68.95 km^2	69.03 km^2	84.15 km^2	84.16 km^2
North Slope Barren Land	71.25 km^2	71.53 km^2	78.27 km^2	78.31 km^2
South Slope Tree Cover	241.63 km^2	240.99 km^2	242.1 km^2	242.26 km^2
North Slope Tree Cover	425.06 km^2	423.84 km^2	413 km^2	410.89 km^2
South Slope Short Vegetation	185.3 km^2	185.86 km^2	169.54 km^2	169.37 km^2
North Slope Short Vegetation	29.759 km^2	30.7 km^2	35.15 km^2	37.18 km^2

Eagle Cap Wilderness	2001	2006	2011	2016
South Slope Barren Land	13.84%	13.85%	16.89%	16.89%
North Slope Barren Land	13.48%	13.53%	14.8%	14.81%
South Slope Tree Cover	48.49%	48.36%	48.59%	48.62%
North Slope Tree Cover	80.41%	80.18%	78.13%	77.73%
South Slope Short Vegetation	37.19%	37.3%	34.02%	33.99%
North Slope Short Vegetation	5.63%	5.81%	6.65%	7.03%

Appendix 10: Natural Vegetation Changing Trend in Eagle Cap Wilderness (Area in km^2 and Percentage)

South vs. North Slopes

Percentage are calculated by dividing area values with the total area of N or S facing slope



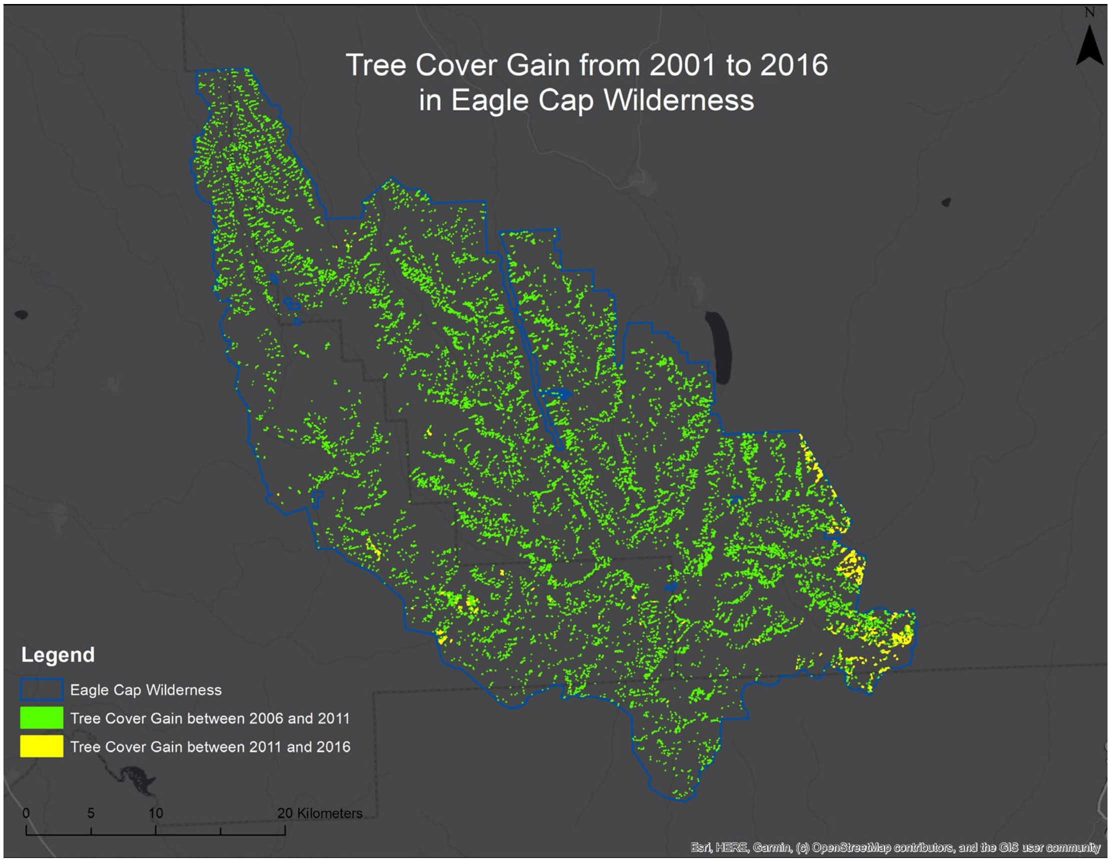
Appendix 11 (with outlined pixels): Tree Cover Gain in Biscuit Fire Extent

Gain between 2001 and 2006: 0.16%

Gain between 2006 and 2011: 74.00%

Gain between 2011 and 2016: 25.84%

(Supplementary for Figure 9)

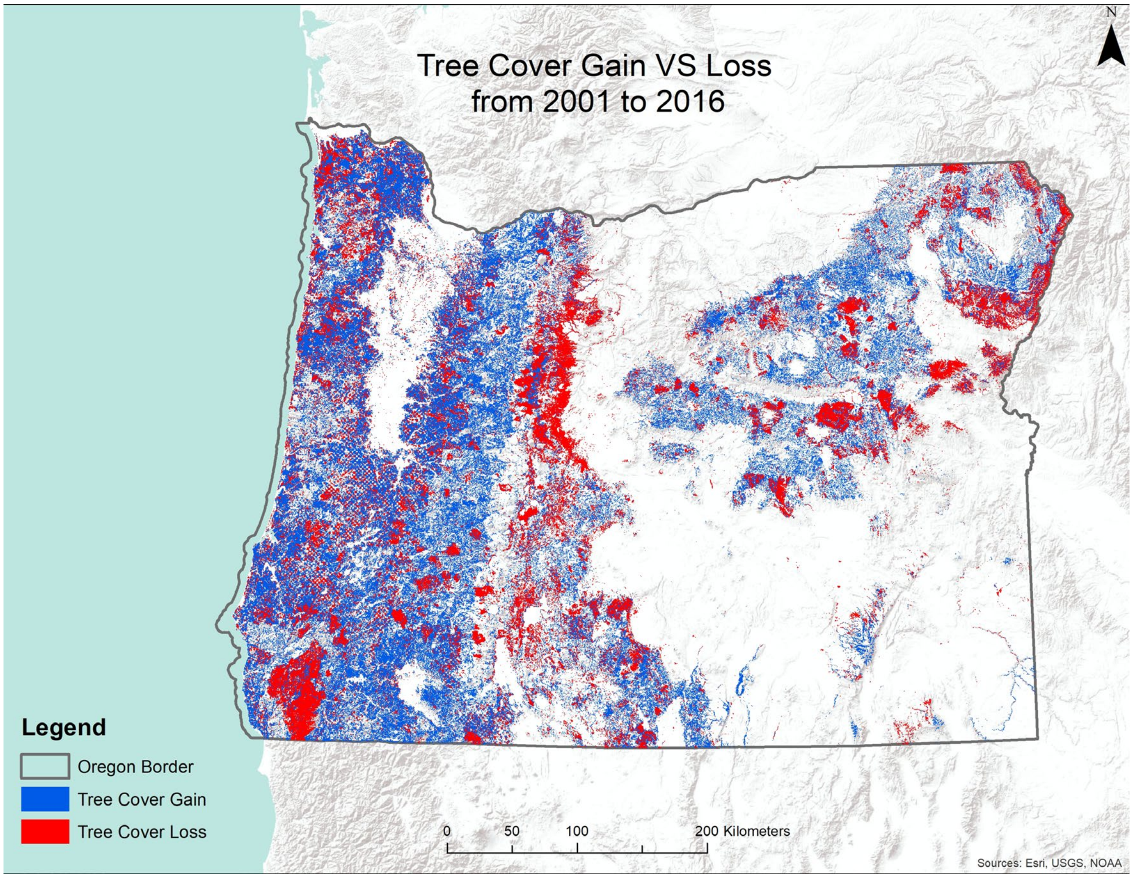


Appendix 12 (with outlined pixels): Net Tree Cover Gain in Eagle Cap Wilderness. No tree cover gain was detected between 2001 and 2006

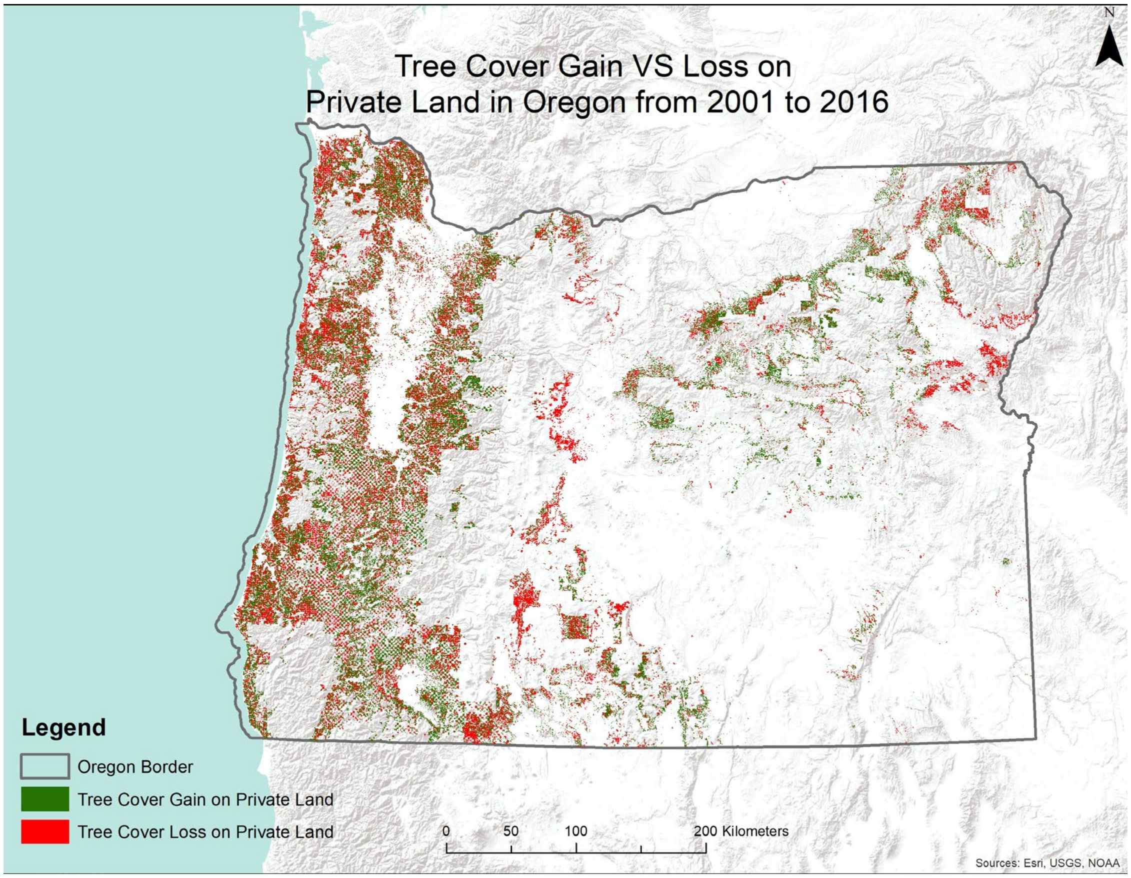
Gain between 2006 and 2011: 90.81%

Gain between 2011 and 2016: 9.19%

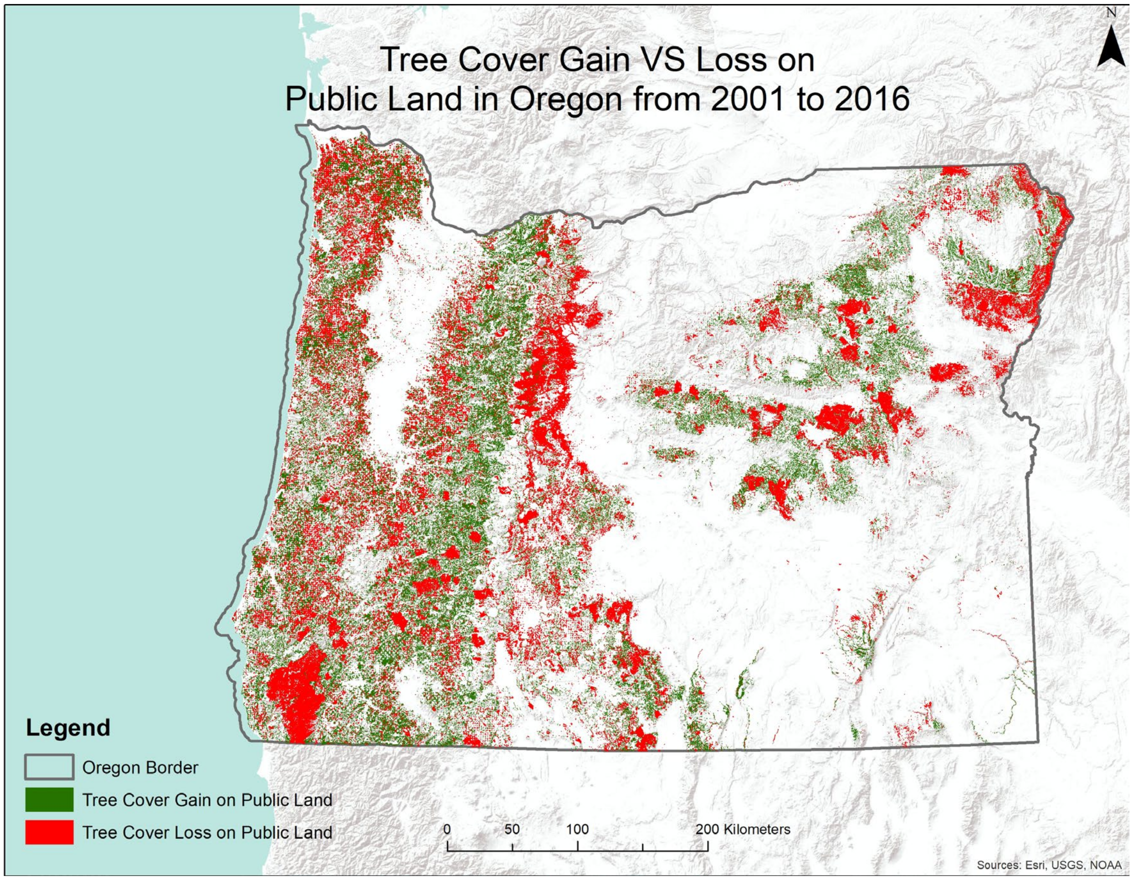
(Supplementary for Figure 11)



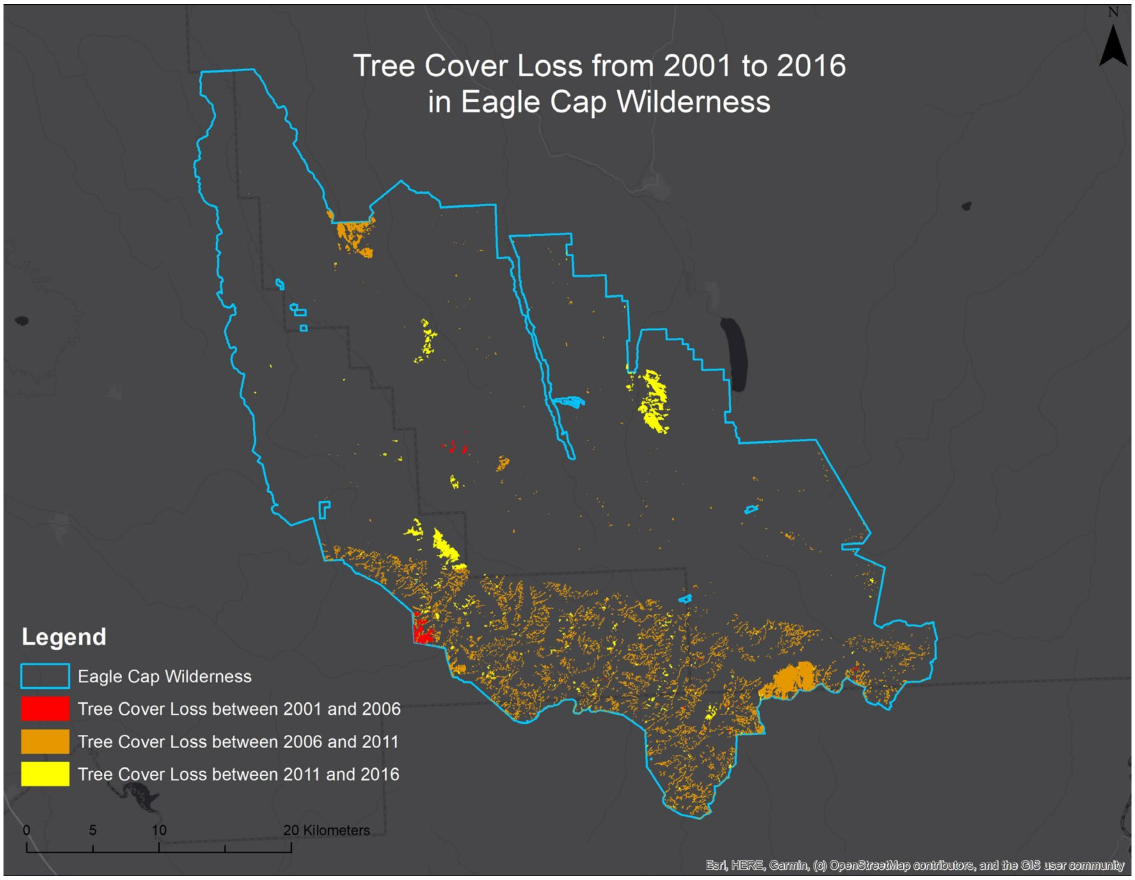
Appendix 13 (with outlined pixels): Tree cover gain vs. loss (Supplementary for Figure 5)



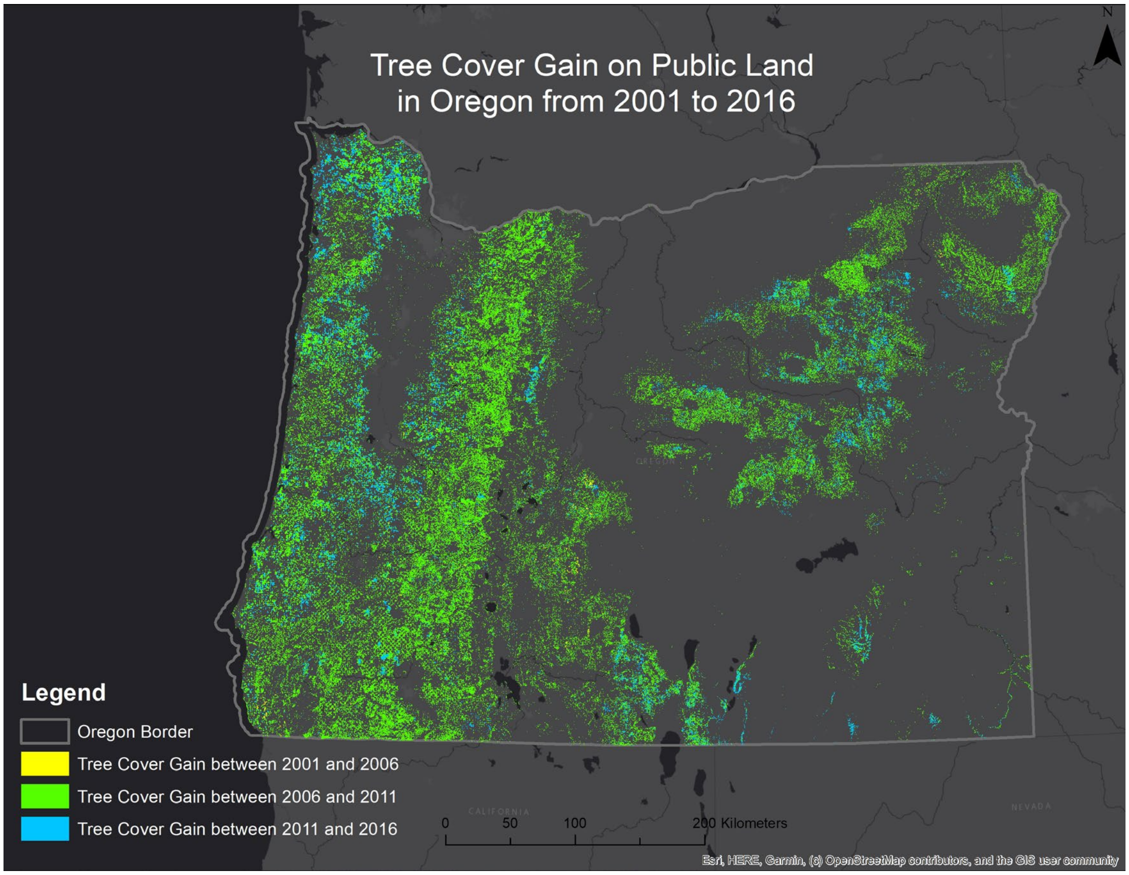
Appendix 14 (with outlined pixels): Tree cover gain vs. loss on private land in Oregon from 2001 to 2016 (Supplementary for Figure 6)



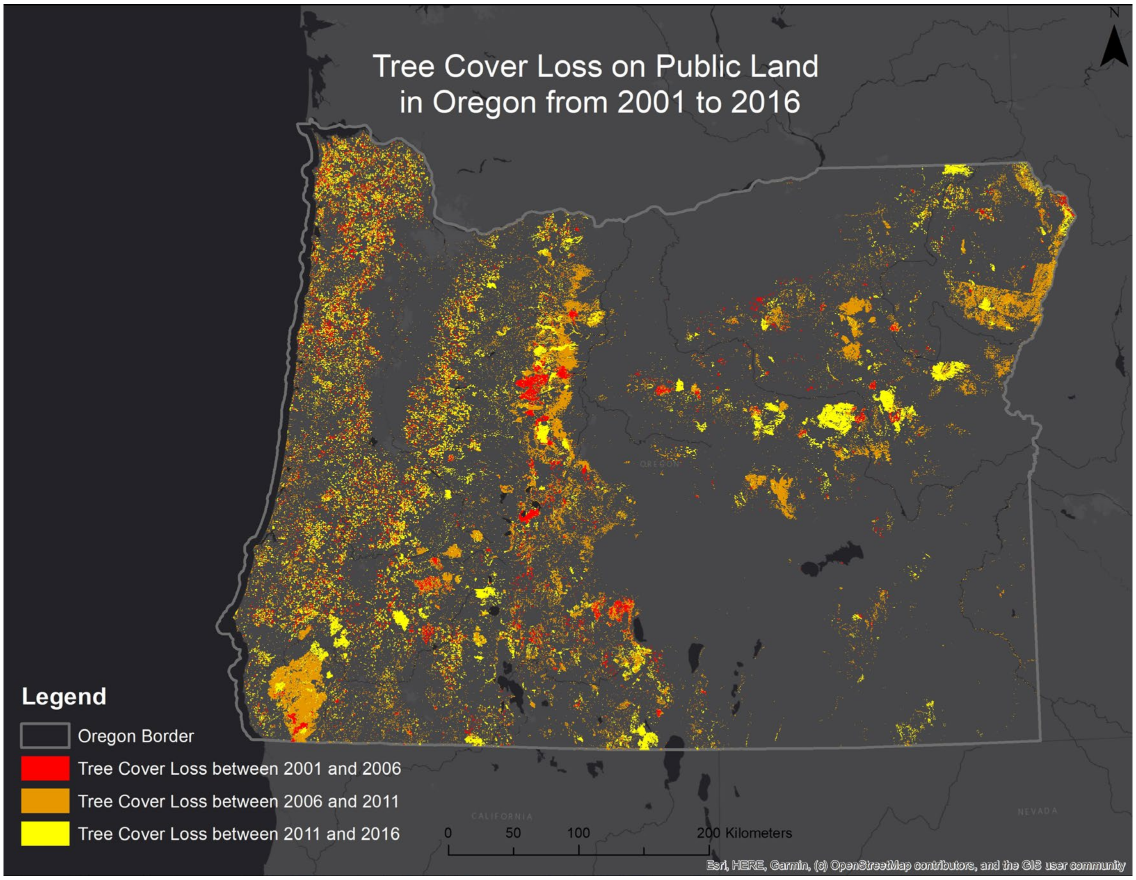
Appendix 15 (with outlined pixels): Tree cover gain vs. loss on public land in Oregon from 2001 to 2016 (Supplementary for Figure 7)



Appendix 16 (with outlined pixels): Net tree cover loss in Eagle Cap Wilderness (Supplementary for Figure 12)



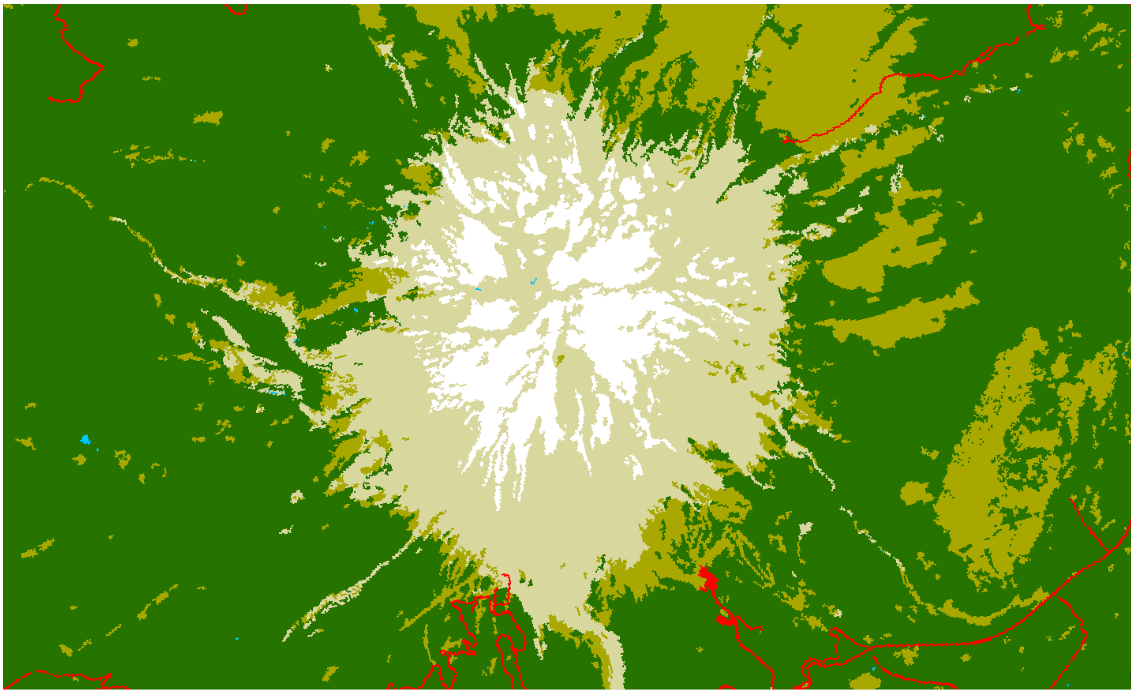
Appendix 17 (with outlined pixels): Tree cover gain on public land from 2001 to 2016 (Supplementary for Appendix 5)



Appendix 18 (with outlined pixels): Tree cover loss on public land from 2001 to 2016 (Supplementary for Appendix 6)

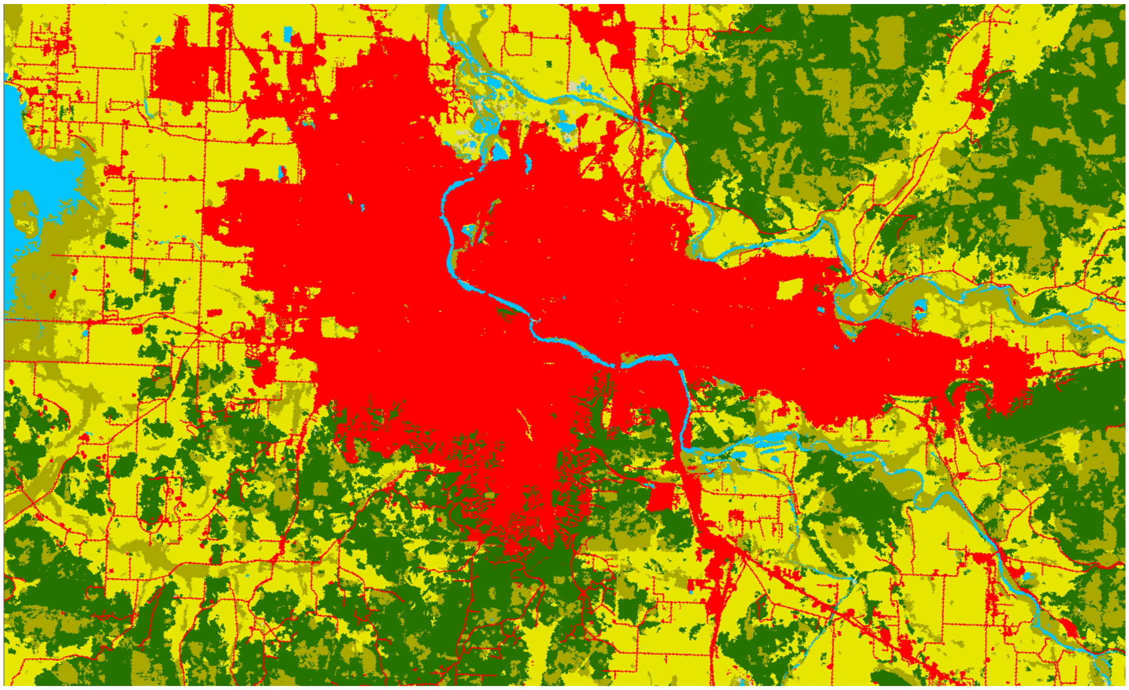
Appendix 19: Water Bodies

Satellite Imagery vs. Reclassified



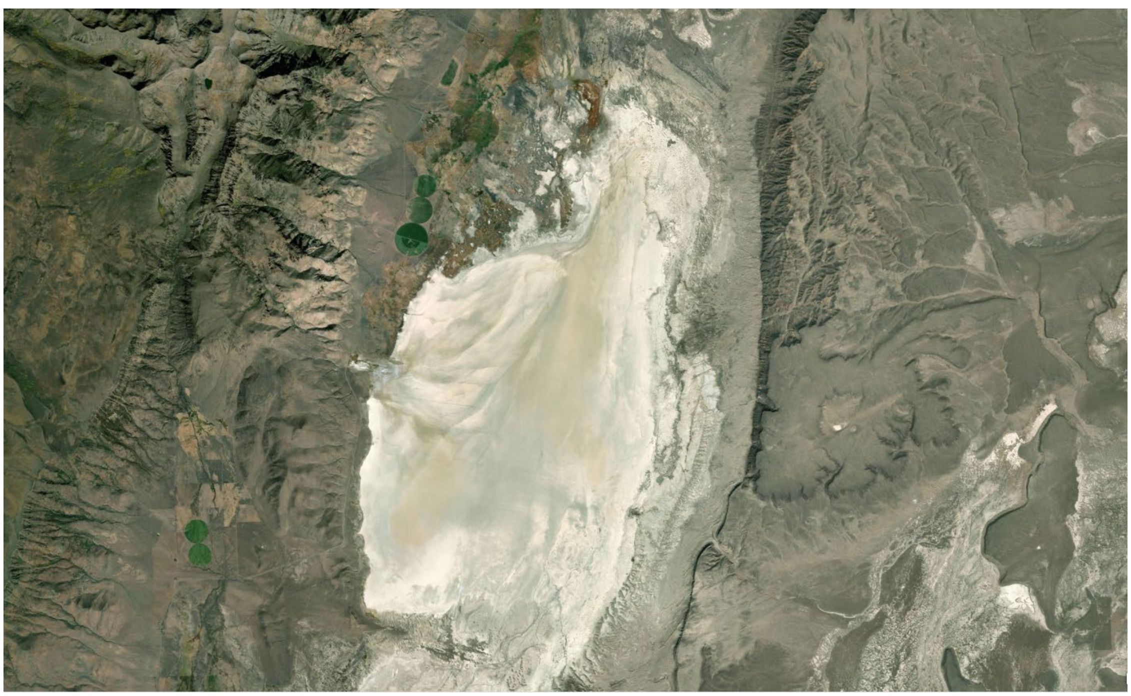
Appendix 20: Ice/Snow

Satellite Imagery vs. Reclassified



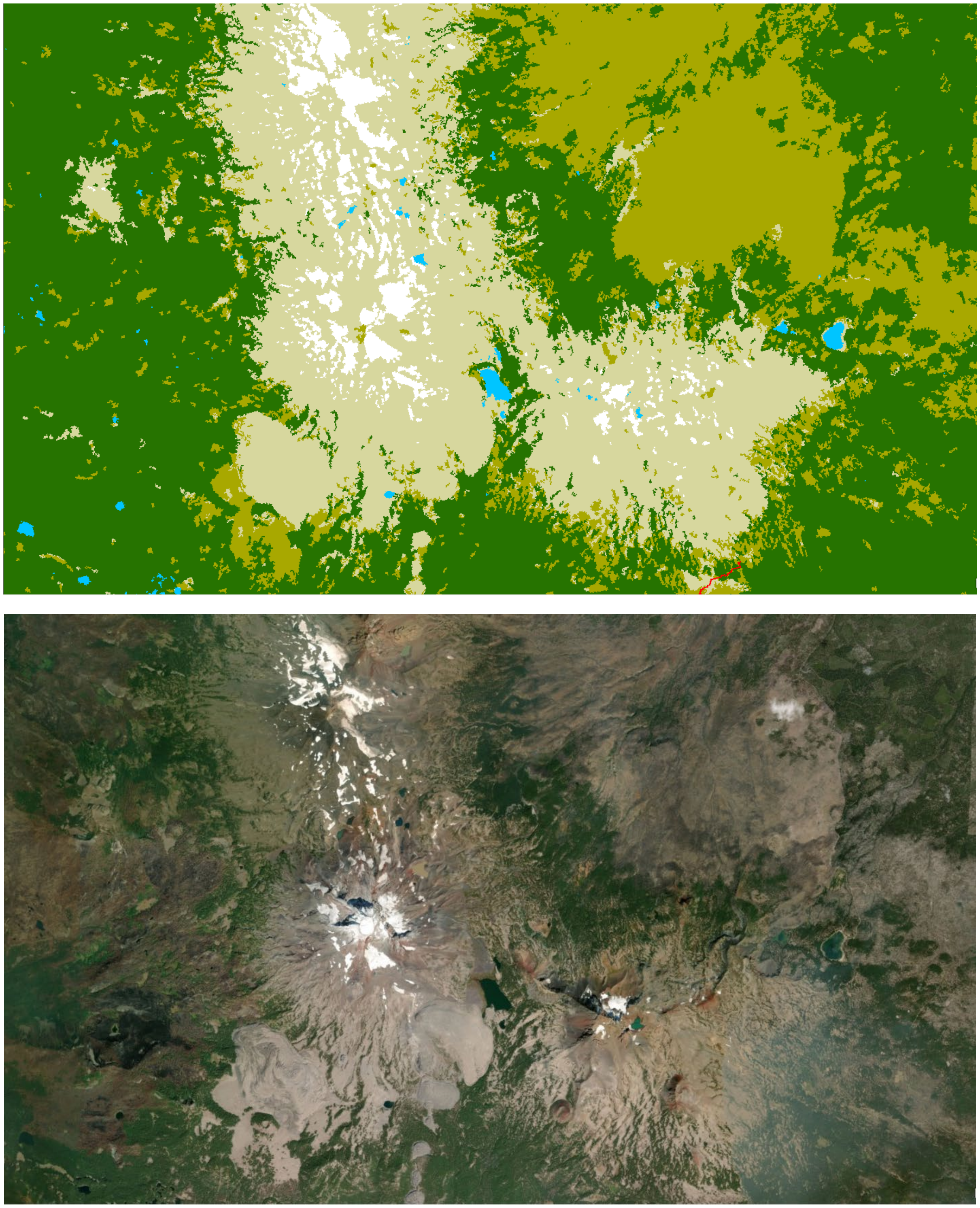
Appendix 21: Urban

Satellite Imagery vs. Reclassified



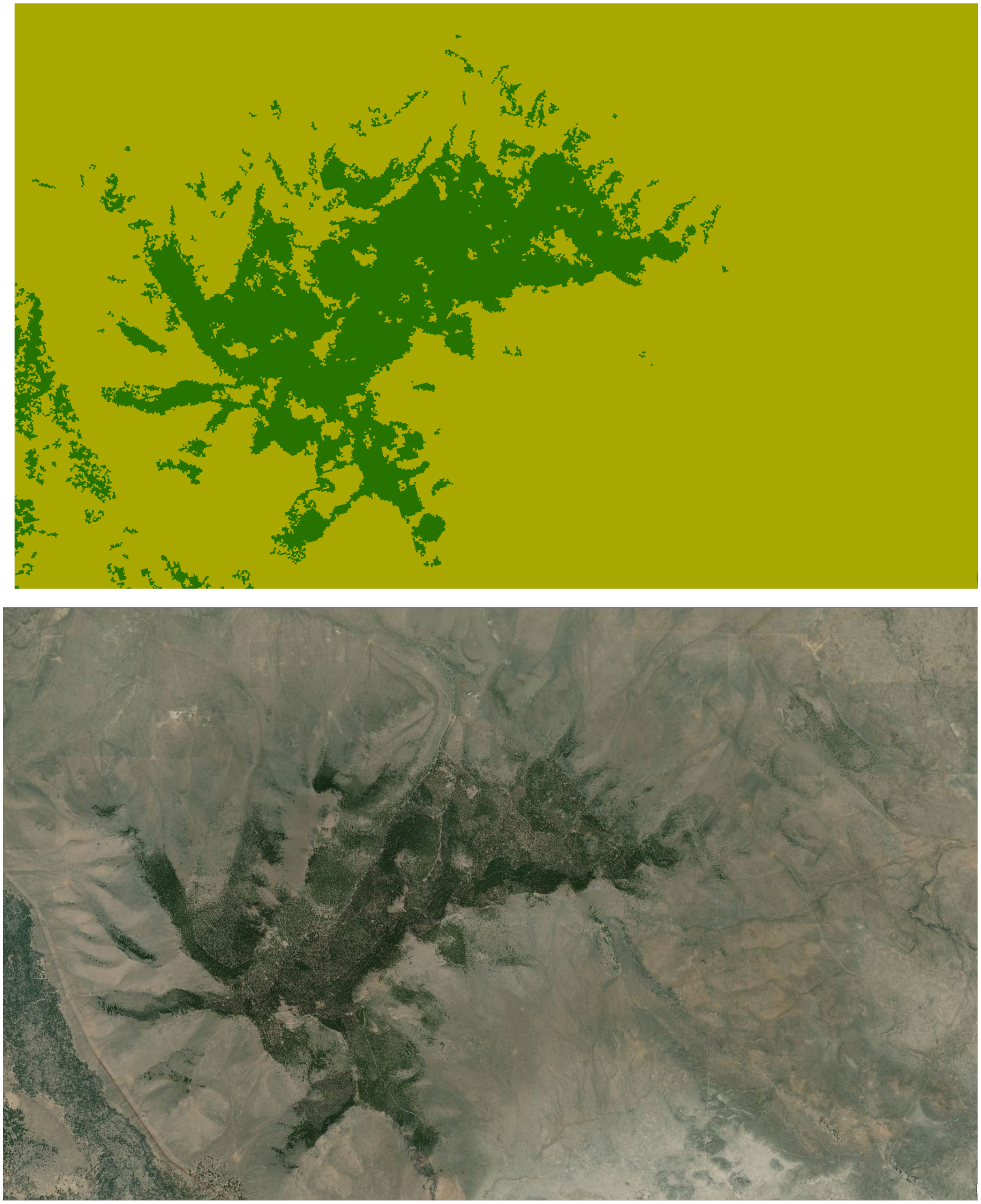
Appendix 22: Barren Land

Satellite Imagery vs. Reclassified



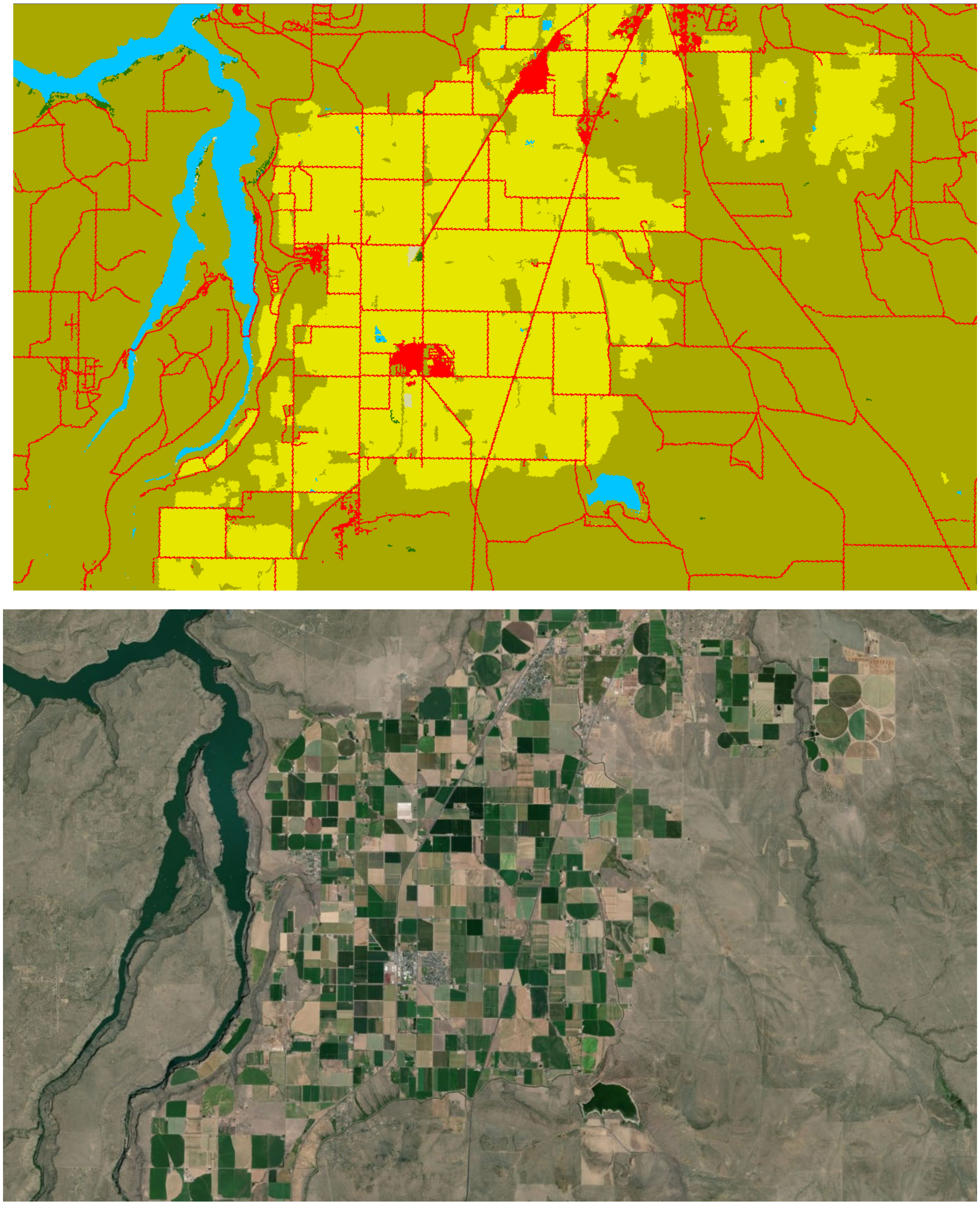
Appendix 23: Tree Cover

Satellite Imagery vs. Reclassified



Appendix 24: Short Vegetation

Satellite Imagery vs. Reclassified



Appendix 25: Crops

Satellite Imagery vs. Reclassified

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