# Exploring forest structure patterns among ownership and federal NWFP land use allocations in the forested western Cascades of Oregon

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## Abstract

Disturbances resulting from natural forces and human intervention – such as the creation of artificial boundaries, has led to the importance in understanding the best approaches necessary for sustaining critical ecosystem functions and forest structure health. The 1994 Northwest Forest Plan (NWFP) offers an example of federal policies that consider the promotion of sustainable timber harvesting, new forest management approaches, and the protection of late successional, old growth habitats. In this study, I use airborne lidar data to develop a comprehensive high-fidelity census of forest structure patterns across a 530,817-hectare region in the NWFP allocated western Cascades of Oregon. To make sense of forest structural patterns and their arrangement across land-use allocation boundaries and ownership types, I addressed the following questions. **(1)** What forest structures exist across the study area and how do they correspond with commonly recognized forest development stages? **(2)** How are these structures distributed across ownership classes and federal administrative land use allocations? **(3)** 20+ years after the adoption of the NWFP, are the structurally complex forests the plan sought to protect and promote present, and if so, in what amounts and by what ownerships and administrative units? Results: **(1)** Six Structure classes were identified across the Western Cascades of Oregon. **(2)** Forest Structure classes were distributed among clusters of structurally simple and complex forest classes that created assemblages among private vs. public ownership type and Land use Allocations. **(3)** Hight Presence of structurally complex forest Classes were seen among NWFP Land Use Allocations.

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## Acknowledgements

***Amá*** - Me has enseñado lo que significa luchar por lo que nos merecemos y creemos. Este título significa más por la nada que venimos de. Nuestra vida no ha sido fácil, Desde el momento en que llegamos a Estados Unidos. A pesar del miedo de no tener suficiente dinero, o un refugio, todo lo que necesitaba en un mundo tan difícil, -- en un mundo que no esperaba mucho de mí o de nosotros, era a ti. Gracias por creer siempre en mi. Este título es para ti y nuestra familia. Por las oportunidades que no se les dieron, el dolor que han soportado en sus vidas. Estoy agradecido de venir de una familia que sabe lo que significa tener hambre, saber lo que significa no tener nada y exigir lo que se nos debe. Eso significa más que cualquier título que podria obtener. Tengo la suerte y el honor de venir de ti. – Siempre, tu Elenita

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## Introduction:

Global environmental change and human intervention has had a drastic impact on forest ecosystems globally. There is a pressing need in understanding how different socioecological processes impact an ever-changing environment (Ehbrecht et al. 2021, Ali et al. 2020, Gauthier et al. 2015, Seidl et al. 2017). A critical challenge in understanding these processes rests on considering local stakeholders, institutions, and market forces within the creation of land management policy (Kennedy et al. 20012, Vitousek et al. 1997, Lambin et al. 2006, Turner et al. 2007). The Pacific Northwest (PNW) region represents an example how socioecological changes have impacted forest composition and structure. Known as an important area for wood products and timber harvesting, the forests of the PNW play a crucial role in providing valuable ecosystem functions globally (Teztlaff et al. 2013, Caldwell et al. 2016). Specific to the Pacific Northwest region is the federal land management policies established during the creation of the 1994 Northwest Forest Plan (NWFP).

The NWFP was created to guide the management of U.S Northwest Forest ecosystems on federally owned lands. Unlike other land management policies during the 1990s, that were tailored towards economic timber harvesting, NWFP policy centered on creating environmentally sound guidelines that considered the sustainability of forest ecosystem health and economic stability for surrounding forest dependent communities. Since the creation of the NWFP, scientific research has played an important part in managing and monitoring the success of NWFP objectives, specifically in the western Cascades of Oregon. Using field and satellite data (e.g., Landsat multispectral imagery) researchers have produced low- to modest-fidelity maps of forest structure across the area of the NWFP that have assisted in advancing sustainable monitoring practices for the vitality of late successional stands and timber production across the western Cascades (Kennedy et al. 2010).

While there are some studies that have produced high-fidelity maps using ground or aerial lidar in the western Cascades of Oregon (e.g., Griffey et al. 2021, Kennedy et al. 2018) , most research on the classification of forest structure or land management policy has been conducted through lower-fidelity, moderate resolution satellite imagery or modeling (e.g., Spies et al. 1994, Ohmann et al. 2007). There remains a need for spatially explicit data that will accurately monitor land management approaches at a landscape scale. Without these new approaches, forest structural health remains vulnerable to broad ranges of forest structure data that can inhibit sustainable forest management practices and objectives.

Mapping the arrangement of forest structure classes across federal land use allocation and ownership boundaries using high-fidelity airborne lidar data in the western Cascades of Oregon, provides an opportunity to build on previous NWFP research (FEMAT 1993; Bohn 2016). The advancement of robust monitoring approaches can in turn lead to a better understanding of how environmental settings, U.S land management decisions and ownership objectives interact within a subset of the NWFP allocated region (Griffey et al. 2021; Thom et al. 2013; Caldwell et al. 2016).

In this analysis, I use airborne lidar data to create a comprehensive high-fidelity census of forest structure patterns across a 530,817-hectare region in the NWFP allocated western Cascades of Oregon. I focus on characterizing forest structure – the vertical and horizontal arrangement of forest biomass (McElhinney et al. 2001) because of the role forest structure plays in providing valuable ecosystem functions and its importance within NWFP monitoring objectives (Spies et al. 2008). Forest structure affects the accumulation and melting of snowfall, carbon storage and in providing valuable resources for surrounding forest dependent communities (Franklin et al. 2002,Teztlaff et al. 2013, Caldwell et al. 2016). Additionally, changes in forest structure can have effects on other components of forest ecosystems, damaging important food availability or habitat quality for endangered species (Spies et al. 1998). To make sense of forest structural patterns across human made geographic boundaries, I incorporate high-fidelity lidar data to measure fine scale forest structure data, NWFP land-use allocation and ownership data to address the following questions.

1) What forest structures exist across the study area and how do they correspond with commonly recognized forest development stages?
2) How are these structures distributed across ownership classes and federal administrative land use allocations?
3) 20+ years after the adoption of the NWFP, are the structurally complex forests the plan sought to protect and promote present, and if so, in what amounts and by what ownerships and administrative units?

I build upon previous studies related to the intersection of human management decisions, and forest resiliency. Additionally, this study builds on NWFP research- specifically related to enhancing monitoring approaches focused on classifying key social components and drivers of socio-ecological systems. This study as well expands on the work of Griffey et al. (2021) by exploring the arrangement of forest structural patterns through similar methodology and analysis .

## Stand Structure Development in the western Cascades of Oregon

Forest stand structure can be defined as the horizontal and vertical arrangement of live or dead vegetation within forest ecosystems (Spies 1998). Characteristics of forest structure include individual elements such as live trees, snags, logs or the composition, size, age distribution, and height of a species (Franklin 2002, Spies 1998, McElhinny et al. 2005). Forest structure is one of three important attributes used to classify forest ecosystems. In addition, composition (e.g., the assessment of forest components such as age, species, or health) and function (e.g., benefits provided by forests such as water control and air purification) attributes offer insight into the historical development human management practices, topography and natural disturbances have had on forest ecosystems.

Past research on structural developmental stages of complex forests, despite the continuous non-linear nature of forest development have made sense of forest stand development through the classification of distinct processes (Franklin et al 2002, Donato et al. 2012, Oliver and Larson 1990, Spies and Franklin 1996, Carey and Curtis 1996, Bormann and Likens 1979). Franklin et al. 2002 recognized eight developmental stages in stand development within Douglas-fir (Pseudotsuga menziesii) and Western Hemlock (Tsuga heterophylla) forests in the Pacific Northwest: (1) Disturbance and legacy creation, (2) Cohort establishment, (3) Canopy Closure, (4) Biomass accumulation/competitive exclusion, (5) Maturation, (6) Vertical Diversification, (7) Horizontal Diversification, (8) Pioneer cohort loss (Table 1). Natural disturbance agents such as windthrow, or wildfire play an important role in the establishment of stand development, specifically in in Douglas-fire/hemlock forests. The establishment of each successional stage is not only typified by human management practices but of the distinct climate, topography and vegetation in the western Cascades of Oregon that has resulted in a complex mosaic of stands that vary in successional stage in low and mid-elevation stands (Kauffman et al. 2019, Agee and Huff, 1980, Perry 2011, Tepley et al. 2013).

| Typical stand age (Years) | Stand Classification | Description |
|---|---|---|
| 0 -20 | **Disturbance & Legacy Creation \| Cohort Establishment** | Typically begins with a disturbance that enables the conditions for the new establishment of a dominant tree cohort. Disturbances include wildfire, catastrophic windthrow, or clear-cutting management practices. Initiation varies among stands. The intensity, type, size, and frequency of a disturbance results in variable starting points for each stand (Franklin et al. 2002, Zenner et al. 1998, Keeton. 2000). |
| 20-80 | **Canopy Closure \| Biomass accumulation/Competitive exclusion** | A transitional period among cohort establishment and maturation. This stage exemplifies the re-establishment of stand dominance. Reduced light levels, a rise in relative humidity and wind exclusion results in environmental changes in the understory, composition, and function of a forest ecosystem (Franklin et al. 2002) |
| 80 - 150 | **Maturation** | Maximum height and crown spread is established by the pioneer cohort. Other characteristics include the re-establishment of forest understory. |
| 150 - 300 | **Vertical Diversification** | Increased development of old-growth forest attributes. Large number of snags or logs are generated resulting in a larger number of coarse woody debris levels typical of old-growth stands. |
| 300 - 800 | **Horizontal Diversification** | Evolution of multiple stand structural units and gap dynamics from agents such as disease, insects, and wind. Additionally, the reduction of Douglas-fir cohort density. |
| 800 - 1200 | **Pioneer Cohort Loss** | |

**Table 1:** Summary of Franklin et al 2002 Disturbances and structural development of natural forest ecosystems with silvicultural implications using Douglas-fir Forest as an example. Other citations used in summarization of stand structure classifications include: Zenner et al. 1998, Keeton 2002, Donato 2012)

## Forest structure composition, socio-ecological system/history

Current forest composition and dynamics in the western Cascades of Oregon can as well be traced across a socioeconomic historical registry. Before European colonization, more than seventy tribes, comprising four distinct cultural areas, lived throughout Oregon's diverse natural regions. These areas varied in terrain, climate, and environmental resources (Northwest Coast, Plateau, Great Basin, and California) that shaped the relationships of Native traditions, technologies, and culture (Broken Treaties, 2017, Long et al. 2018). Indigenous resource land management practices that account for an important part in forest structure and dynamics includes the creation of small clearings from controlled burning meant to clear undergrowth, enhance plant growth, clear traveling corridors and fireproof indigenous settlements (Kimmerer and Lake 2001). Fire was and remains a vital tool in the creation of habitat areas that ensure a productive, food secure environment for Indigenous communities (Lewis 1985).

Beginning in the early 18th century, Euro-colonial violence, and U.S anti-Indigenous policies resulted in the forced exodus of Indigenous communities from their homelands. U.S land management policies such as the Oregon Donation Land Act (Notarianni 2021), which offered 328-acre parcels to white settlers, resulted in 2.8 million acres of stolen Native land (Whaley, 2010, Spies, 2008; Kimmerer and Lake 2001, Notarianni 2021). The early 19th century brought the proliferation of lumber camps centered on extractive European management techniques in addition to the conversion of forest areas into farmlands across the Pacific Northwest. By the early 20th century, swaths of forest lands were converted into "forest reserves" and placed under federal management (public) for the protection of watershed areas and the continuous supply of timber (Spies et al. 2018). U.S Environmental laws in the 1970s, such as the 1969 National Environmental Policy Act  (NEPA), the 1973 Endangered Species Act (ESA), and the 1976 National Forest Management Act (NFMA) brought in an era of environmental awareness and concern nationally. The growing concern of timber harvesting in old-growth forests ultimately reached a critical point during the 1990 listing of the northern spotted owl on the endangered species list. This led to the subsequent 1991 federal court injunction which prohibited timber harvesting of old-growth forests near northern spotted owl habitats and the 1993 promise by President Clinton to resolve timber disputes (Spies et al. 2018, Franklin and Johnson 2014, Thomas et al. 2006)

The accumulated historical effects of  extractive past land management practices, policies, and the shifting of public perspective favoring environmental awareness led to a postcolonial mosaic of highly fragmented forest structural composition and the eventual passage of the Northwest Forest Plan (NWFP). Created by the Forest Ecosystem Management Assessment Team (FEMAT) in 1994, the NWFP is a series of federal policies and guidelines -- created to (1) promote sustainable timber volume harvesting, (2) protect late-successional, old-growth forests, habitats/waterways, and (3) develop scientifically sound forest management approaches (FEMAT, 1993).

### Northwest Forest Plan Monitoring & Objectives

The key elements of the Northwest Forest plan that evolved from FEMAT only apply to federal lands and include (1) the adoption of a management approach centered on conservation and habitat restoration (2) Designating land use allocation to address management concerns (3) Consultation with federally recognized tribes to mitigate any conflicts among indigenous communities and tribal treaty rights, (4) forest management standards and guidelines, (5) a new monitoring program to track the efficacy of guidelines and (6) The creation of “survey and manage” measures meant to better conserve aquatic ecosystems, and old-growth late successional forests that may be at risk from timber logging practices (Spies et al. 2018).

Land use allocations, specifically those delineated as “reserves” (Riparian, New late-successional, and congressionally reserved areas) --- meant to improve ecological conditions through the implementation of new scientifically credible environmental guidelines, have played an important role in monitoring change in forest conditions and in determining whether NWFP objectives have been met. Since the inception of the NWFP, Scientists have provided robust and reliable literature critical to the success of NWFP forest service management. The unique involvement of the scientific community has been led largely by the necessity to meet standards set by environmental federal laws such as the ESA and NFMA (Thomas et al. 2006).

## Methods

### Study Area

Study area encompasses a 530,817-hectare region in the Grande Ronde Tribal Homelands (specifically Willamette Valley Bands, Molallas, Umpqua & Calapooia, and Rouge River Tribes), also known as the western Cascades of Oregon (Figure 1) (Confederated Tribes of Grande Ronde, 2021). Study area was defined by the availability of lidar acquisition data in forested areas, land use allocation boundary data and ownership type data. This analysis was additionally confined to the following lower-mid elevation ecoregions (1) Western Cascades Lowlands, and (2) Valleys and Montane Highlands (Figure 2).Upper elevation ecoregions such as Cascade Subalpine/Alpine were not considered in this analysis because they represent substantially different forest types in terms of species composition, structure, and function. in the western Cascades (Kauffmann et al. 2019, Agee and Huff 1980, Tepley et al. 2013, Zald et al. 2016). The variable mountainous terrain across the western Cascades results in multi-scale relationships that influence forest composition and structure across topographic gradients (Heyerdahl et al. 2001, Zald et al. 2016). Because of this, the analysis was confined to lower-mid elevational ecoregions.

Forests in lower elevations are dominated by Western Hemlock (*Tsuga heterophylla)* and Douglas-fir *(Pseudotsuga menziesii)*, while Pacific Silver Fir *(Abies amabilis)* and Mountain Hemlock (*Tsuga mertensiana*) are found in mid-elevations across the montane highlands (Franklin and Dyrness 1988). Elevations are less than 975 m in the lowland and valleys ecoregion while in the montane highlands ecoregion, elevation varies from 900 to 1980 m. Mean temperature varies slightly between the two ecoregions. The lowlands and valleys ecoregion consists of 8-10 °C while the montane highlands ecoregion ranges from 4-5°C. Annual precipitation ranges from 2-3 meters within both ecoregions (PRISM Climate Group, 2021). Douglas-fir and Western Hemlock forests in the western Cascades generally have high or mixed severity fires. Historical fire frequencies range from 35-200 years (Agee 1993, Haugo et al. 2019). In this study area, historical wildfires from the 1900s - 2020 are concentrated in the southern extent, with four fire incidents in the northern section of the analysis (total area burned: 7,212 ha). Since the 1900s to 2020, a total of 40 wildfires in BLM land have been recorded within the area of analysis totaling 118,019 hectares of area burned. Recent wildfires include the 2020 Archie Creek fire which burned a total area of 53,209 ha and the 2020 Beachie Creek fires which burned close to 200,000 ha (USFS 2021,BLM 2021). Other dominant chronic disturbance processes in the West side of the Cascades include insects, pathogens, and windthrow (Franklin et al. 2002, Turner et al. 2015).

## Airborne Lidar Data

Lidar data for this study consists of fifteen lidar data acquisitions collected through an array of vendors (Watershed Sciences Inc [now Quantum Spatial], Geoterra Inc, The Atlantic Group LLC, and Weyerhaeuser) from 2008-2016. Data were acquired using Optech Orion H300, Leica ALS60, Leica ALS50, or Leica ALS70 with an aggregate pulse density of 8.1 pulses/m2 and up to 4 returns per pulse recorded (Figure 3). To process acquisition data, USDA's FUSION Analysis and Visualization Software were used (McGaughey 2018). To merge all fifteen acquisitions in the analysis, all units were converted to meters and aligned to one common projection (NAD 1983/Oregon LCC M). To account for peri-urban areas and erroneous data, The Nature Conservancy (TNC) forest data were used to mask non-forest data from the analysis. Lidar acquisitions were lastly clipped to match the study area extent criteria (non-urban areas and within Montane Highlands & Lowlands and Valleys ecoregions). Lidar acquisitions clipped include Metro, Clackamol, Willamette, Lane County, Green Pater, Fall Creek, and Upper Umpqua. Other packages used to prepare the dataset include Raster (Hijmans and van Etten, 2012) and RGDAL (Bivand et al. 2021) in R studio (R Core Team 2021).

## Ownership Identification

Forest ownership data were collected and aggregated into ownership types by the Nature Conservancy (TNC) of Oregon(Figure 4) (Griffey et al. 2021). Oregon county tax lot data were downloaded from the 4th quarter 2017 CoreLogic Parcel Point tax lot database, federal, and corporate tax datasets. Ownership types with less than 11,500 hectares each(< 1% of the total study area) were excluded prior to conducting statistical analyses. Ownership types that had less than 11,500 hectares of land in the study area include Local Government (LG), Non-profit, Tribal, Federal lands, Federal BLM lands, and Federal NPS lands. Because of the low individualized total percent area of private non-industrial ownership types (Private, Private Small, Private Very Small and Private Medium), these ownership types were combined into a single class (Private Non-Industrial ) and represent 7% of the total study area (116,240 hectares).

Public and Private ownerships vary in land management objectives. This study defines public ownerships as areas managed by the Bureau of Land Management (BLM), U.S Forest Service (USFS), Bureau of Land Management O&C (BLMOC), and private ownerships as areas managed by Private Landowners, Timber Investment Management Organizations (TIMO), Real Estate Investment Trusts (REIT); and Families (Griffey et al. 2021). Public ownership types were further defined by government objectives. Federal USFS and Federal BLM O&C lands were grouped by NWFP land objectives while state ownership type was separated into an individualized group representative of mixed government objectives.

Federal USFS (130,985  ha) and Federal BLM O&C ( 524,364 ha) (NWFP Objective Government group) ownership types dominate most of the study area and total 655,350 hectares. Private Non-Industrial (86,378 ha), Private Industrial (366,807 ha), and mixed objective government ownership types (23,771 hectares) total around 476,956 hectares. Objectives in Private ownership can include timber harvest income, estate for children, wildlife habitat protection, or asset management for institutions (TNC, 2019), while public ownership objectives range from timber management to conservation (Spies et al. 2008)(Table 1).

Ownership type data were clipped to study area extent using R studio's Raster and RGDAL packages (Bivand et al. 2021, R Core Team 2021).

| | Ownership Type | Description | Summary of Landowner Objectives |
|---|---|---|---|
| **Ownership Group:**<br>Private Non-Industrial (PVNI)<br>**Rotation Length:**<br>35-70<br>**Study Area Hectares & Percentage:**<br>86,378 ha<br>8% | Private | < 50 acres | Driven by various management approaches, economic and ecological values. |
| | Private Very Small | 50 to 100 acres | |
| | Private Small | 100 to 500 acres | |
| | Private Medium | 500 to 5000 acres | |
| **Ownership Group:**<br>Private Industrial<br>**Rotation Length:**<br>35-60<br>**Study Area Hectares & Percentage:**<br>366,807 ha<br>32% | Timber Investment Management (TIMO) | Procure, manage, and sell timberland assets on behalf of institutions or wealthy individuals. | Maximizing rate of return on timber harvesting, return investment and net present value |
| | Real Estate Investment Trust (REIT) | Manage cash producing real estate and distribute rents to investors. Can be traded on public stock exchanges. | |
| | Integrated | Large forest landowners who also own milling infrastructure. | |
| | Family | Management ranges from long to short harvesting practices. Objectives for family ownership are subjective. | Variable objectives that can include timber harvesting, wildlife habitat protection and land investment |
| **Ownership Group:**<br>Mixed Objective Government | State | Land owned by the state of Oregon | Objectives emphasize stand heterogeneity, in addition to sustainable-yield timber production and management |

|  |  |  |  |
|---|---|---|---|
| **Rotation Length:**<br>80+<br>**Study Area Hectares & Percentage:**<br>23,771<br>2% | Bureau of Land Management | Land managed by the U.S Bureau of Land Management | Objectives and management procedures designated by the Northwest Forest Plan. Conservation of late-successional and old growth forests. Emphasis on habitat and ecosystem stewardship for PNW endangered species. There are some sustainable yield productions on designated land use allocations. |
| **Ownership Group:**<br>NWFP Objective Government<br>**Rotation Length:**<br>80+<br>**Study Area Hectares & Percentage:**<br>655,350<br>58% | U.S Forest Service | Land managed by the U.S Forest Service or the Bureau of Land Management in Oregon and California, BLM O&C consists of lands revested by Oregon and California Railroad | Managed under Northwest Forest Plan procedures and guidelines for the maintenance of late-successional and old growth species, sustainable yield timber production and biological diversity. |
|  | Bureau of Land Management O&C |  |  |
| **Total:** 1,132,307 ha<br>100% |  |  |  |

**Table 4.** Ownership types used in analysis. Management objectives derived from the 2019 Nature Conservancy Ownership data. Rotation length in table defines the average years between timber harvests.

## Federal Land Use Allocations

FEMAT's 1993 Northwest Forest Plan development centers around an ecosystem management plan that emphasizes the conservation of Old Growth, late-successional forests, and the preservation of endangered PNW species. To ensure conservation objectives, FEMAT developed a system of land use allocation (LUA) categories (FEMAT, 1993): (1) Adaptive Management Reserves (AMR), (2) Northern Spotted Owl Reserves (LSR4), (3) Marbled Murrelet Reserves (LSR3), (4) Administratively Withdrawn Areas (AW), (5) Late Successional Reserves (LSR), (6) Congressionally Reserved (CR), (7) Other areas, and (8) Adaptive Management Areas

(AMA) (Table 5),(Figure 5). LUAs are expected to protect against expected future losses from wildfire over the period of 100 years and increase the amount of late-successional/old-growth forest in NWFP reserves (Spies et al. 2018). Each Land-use Allocation varies in management goals for harvesting and thinning operations.

For this analysis, Northern Spotted Owl Reserves (LSR4) were combined with Late Successional Reserve Areas (LSR) due to shared land use objectives and interpretation simplicity. Land use Allocation ‘Other’, dominates the landscape and makes up 565,523 hectares of the study area while Late Successional Reserve areas (LSR4 & LSR) make up 363,063 hectares of the total area. Administratively Withdrawn (AW) (38,291 hectares), Congressionally Reserved (CR) (253,380) and Adaptive Management Areas (AMA) (91,624) total 383,295 hectares. 2013 Land Use Allocation Data were collected through the NWFP Regional Ecosystem Office GIS repository and clipped to study area extent using R studio’s Raster and RGDAL packages (Bivand et al. 2021, R Core Team 2021).

| Northwest Forest Plan Land Use Allocations Objectives | | | |
|---|---|---|---|
| **Land Use Allocation** | **Study Area ha** | **Total % within Study Area** | **Management Description** |
| AMR - Adaptive Management Reserve | 3,700 | 0.28% | Designated as experimental areas to explore alternative management ideas. Objectives include finding new ways to meet the region's social, ecological, and economic needs. AMR Land objectives centered around restoration of LS forests. |
| AW - Administratively Withdrawn | 38,291 | 2.91% | Areas identified in local forest and district plans. Examples include recreation and visual areas, back country. |
| AMA - Adaptive Management Area | 91,624 | 6.96% | Designated as experimental areas to explore alternative management ideas. Objectives include finding new ways to meet the region's social, ecological, and economic needs. AMA Land objectives center around timber harvest with ecological objectives. |

| | | | |
|---|---|---|---|
| CR - Congressionally Reserved | 253,380 | 19.26% | Reserved lands set aside by the U.S Congress. Examples include wilderness areas, wild and scenic rivers, and national parks and monuments |
| LSR - Late Successional Reserve \| Northern Spotted Owl Activity Centers | 363,063 | 27.60% | Reserved for the protection and restoration of LSOG forest ecosystems and PNW endangered species such as Marbled Murrelet reserves (LSR3) and Northern Spotted Owl Reserves (LSR4). LSR4 and LSR3 Combined under LSR LUA. |
| Other - Unmapped Land Allocations and Mix of Riparian Reserves | 565,523 | 42.99% | Category depicts a mix of Matrix, Riparian Reserves, and other unmapped land use allocations. Objectives differ among Matrix and Riparian Reserves. **Matrix management description:** Federal lands outside of reserved allocations where most timber harvest and silvicultural activities occur. **Riparian Reserves management Description:** Protective buffers along streams, lakes and wetlands designed to enhance habitat for riparian-dependent organisms and good water-quality dispersal corridors. |
| **Total** | 1,315,583 | 100.00% | |

**Table 5.** Land Use Allocations based off ESRI polygon class features described in the Northwest Forest Plan (NWFP). Created as an update to 2009 LUA map version. Created by Pacific Northwest Region USDA Forest Service (Umpqua NF, Roseburg, OR) and the UW Fish & Wildlife Pacific Region (Regional Office, Portland OR) (REO USFS, 2021)

### Lidar Data Measurement

Forest structure was measured using four lidar metrics that were calculated through USFS FUSION software (McGaughey 2018) these include: 95th percentile of return height > 2m (P95, a proxy for dominant tree height), 25th percentile of return height > 2m (P25, a proxy for height to live crown), rumple (a measure of canopy complexity), and canopy cover (percent of points above 2m/ all points). Lidar metrics were selected based on previous research that has shown P95, P25, Rumple and Canopy Cover to be strongly correlated with height, cover, vertical distribution, and canopy roughness (Kane et al. 2010, Kane et al. 2018). Selected lidar metrics in this analysis were used to identify forest structure stages or classes from stand initiation to structurally complex forests. Metrics were calculated at a 30 x 30m resolution and chosen to characterize canopy cover, vertical distribution, height, and canopy roughness. Lidar acquisition vendor-supplied ground models were used to normalize return heights to height above ground.

## Statistical Analysis

### Objective 1: Classifying what forest structures exist across the western Cascades of Oregon

To classify forest structure patterns across this study area, P95, P25, Rumple and Cover lidar metrics were chosen through a combination of Kolmogorov-Smirnov (K-S) tests, and niche overlap tests to determine differences in lidar metric distributions among land ownerships and land use allocations (Griffey et al. 2021; Kane et al.2010; Kane et al 2013.)  PCA eigen decomposition was used to simplify lidar metric data and to calculate the position of all points within eigenvector space. Hierarchical classification was then performed on the PCA values of 30,000 random sampled points using Ward's Minimum variance clustering method (Ward.D2) in R studio's  hclust function (R Core Team, 2021) to minimize the total within-cluster variance of the point samples. The resulting dendrogram from the hierarchical clustering analysis was then cut into 6 classes using visual assessment of the scree plot (McCune and Grace, 2002). Descriptive structure class names were designated to each class using the unique distribution of lidar metric value outputs.  Lastly, structure classes were assigned using a random forest model across the study area (Breiman 2001, Cutler et al. 2007), the PCA axes as the explanatory variables and the derived structure classes as the response (Griffey et. al 2021) (Figure 6).

*Forest Structure Interpretation Assistance -*

To assist in the interpretation of forest structure classes,  NAIP imagery (The National Agriculture Imagery Program), -- acquired during the agricultural growing seasons in the U.S. and stand age estimate data from the LEMMA GNN project (Landscape Ecology Modeling, Mapping and Analysis Gradient Nearest Neighbor project) -- derived from 2012 Landsat Thematic Mapper and field plot data (Griffey et al. 2021) were used.

NAIP imagery data aggregated via Google Earth Engine (GEE) were used primarily to visualize and provide a snapshot of how the landscape of each lidar acquisition appeared during the time of collection. The year of lidar data collection for each acquisition varies from 2008-2016, because of differences among forest structure and composition annually -- caused by human or natural disturbances, the development of a visualization tool was important in illustrating how the landscape appeared during the year of collection. Having an aerial snapshot of each lidar acquisition helped in aligning forest structure classes with previously established forest stand development stages (Franklin et al. 2002).

All fourteen lidar acquisitions were imported to GEE and composited to NAIP imagery most aligned to the acquisition date of collection (Google Earth Engine, 2020). Considering the differences in years NAIP imagery were collected, (three-year data collection cycle since 2009) (USDA,2021), there are some temporal lags among forest structure acquisitions and NAIP imagery used for interpretive classification. Important inconsistencies to note include the use of 2011 NAIP imagery for Deschutes 2010 data collection, 2014 NAIP imagery for Lane County and Abiqua acquisitions collected in 2013, and lastly, 2016 NAIP imagery used for Umpqua and Abiqua 2015 acquisitions.

GNN stand age estimate data were used to interpret structure classification outputs and ascribe estimated years within each structure class. Comparative results were then juxtaposed against age ranges typically found among structural development post-natural regeneration (Franklin et al. 2002) Despite differences in data fidelity between lidar metrics and GNN stand age estimates, GNN data have been used in previous airborne lidar studies for comparative analysis and structure classification validation (Griffey et al. 2021; Zald et al. 2014; Ohmann and Gregory. 2002; Kennedy et al. 2018; Kane et al. 2019; Bell et al. 2018) (Figure 6).

### Objective 2: Examining the Distribution of forest structure classes across Ownership and Land Use Allocation Boundaries

To examine forest structural patterns across Ownership and Land Use Allocation boundaries, principal component analysis and stacked bar charts illustrating the percent area of each structure class among  (1) Land-Use Allocation, and (2) Ownership type were used. Principal component analysis was used to reduce the dimensionality of data and explore relationships among structure class variables and explanatory samples. Packages used within this analysis include ggfortify and ggplot2 (Horikoshi et al. 2016, Wickham 2016, R Core Team, 2021) (Figure 10 and 11).

### Objective 3: Exploring the amount of structurally complex forests present among land use allocations and Ownership Types

To explore the amount of structurally complex forest classes distributed across NWFP land use allocations, stacked bar chart illustrating the hectare amount of each Land Use allocation among the classified forest structure classes were created. Similarly, a stacked bar chart showing the hectare amount of each ownership type among identified forest structure classes were created. Packages used within this analysis include ggplot2 (Wickham 2016, R Core Team) (Figure 12 and 13).

## Results:

### *Six structure classes were identified across the western Cascades of Oregon*

Six types of forest structure classes were identified from hierarchical cluster analysis classification (Figure 7 A & B) and based on principal component analysis ordination values

(Figure 8 B). Analysis was limited to six structure classes to align with Griffey et al. (2021) structure classification and overall interpretation simplicity. Classes were sorted based on increasing median P95 height. Additionally, median, and interquartile ranges for lidar metrics representative of dominant tree height (P95), and canopy complexity (rumple), increased in a positive progression within structural classification boxplots (Figure 8 A). PCA results showed a dominant distinction among stand heights (most correlated with PC1). Canopy cover and stand complexity (Rumple) explained less variation and were not correlated with one another. Additionally, results showed a weak correlation among dominant tree height (p95) and stand complexity (rumple). PC1 drove 69.4% of the variation (Figure 8).

Following forest structure classification methodology by Griffey et al. (2021), statistically distinct structure classes were aligned with the forest development stages for PNW forests, identified by Franklin et al. (2002) (Table 6 ) and GNN stand age estimates. Structure classes were considered representative of the following forest successional stages: (1) Initiation, (2) Canopy Closure, (3) Harvestable/Maturation, (4) Vertical Diversification, (5) Complex, (6) Highly Complex. Structure class 1 was interpreted as stand initiation based on it’s short (median 5 m) p 95 heights and GNN median estimated stand age of 70 years. Similarly, structure class 3 was interpreted as Harvestable/maturation based on median p95 heights of 25 m and GNN median estimated stand age of 95 years. Lastly, structure class 6 was interpreted as highly complex given the tall (median 55 m) p95 heights and GNN median estimated stand age of 225 years.

### ***Overall higher percent cover of structurally complex classes in Mixed & NWFP Objective Government Ownership Types***

Total structure class percent area within each ownership type illustrates an overall higher proportion of Complex and Highly Complex structure classes (5-6) among public land groups (Mixed Objective government & NWFP Objective Government), compared to Private ownership groups (Figure 10). Private Industrial Ownership types (e.g., Family, TIMO, REIT, and Integrated) displayed the highest percent cover of Initiation, Canopy Closure and Maturation (Harvestable) Classes (1-3). The Private non-industrial ownership group, which consists of Private Very Small, Private Small, Private, and Medium ownership types displayed the highest percentage of Vertical Diversification (4) within their group (Figure 10 B) and around 25-30% of Complex and Structurally Complex Classes.

Principal component analysis (PCA) results – illustrating the relative percentage of structure classes by ownership type, showed a divide among two distinct ownership groups – Public and Private Ownership Groups. Results show an association among Public Ownership Types (e.g., Federal BLM O&C, Federal USFS and State lands) and Complex Structure classes (5). Similar associations can be seen among early, non-structurally complex classes (1-3) and private ownership groups (PVNI and Private Industrial) (Figure 10).The strongest differentiation among classes was by the relative amount of area in less complex stands (classes 1 – 3, stand initiation through harvestable/maturation) vs the more complex classes (classes 5 – 6, vertical diversification through highly complex). Additionally, 8.5% of the variation was explained by relative amounts of structure classes within structure class groups.

### ***Structurally Complex Forest Classes most present among Adaptive Management Reserves***

Land use allocation (LUA) structure class percent area analysis illustrates the highest percentage of Complex and Highly Complex classes (5-6) among Adaptive Management Reserves (Figure 11 B). 75% of Adaptive Management Reserve percent cover consisted of

Complex and Highly Complex Classes (5-6). Second in highest proportion of structural complexity were Administratively Withdrawn and Congressionally Reserved allocations, which consisted of similar percentages of Complex and Highly Complex classes (5-6). Both made up around 40% cover within each Land Use Allocation. Adaptive Management Areas and Late Successional Reserves had similar percentages of structurally Complex classes (5-6) and only differed slightly from Administratively Withdrawn and Congressionally Reserved Allocations. Land Use Allocation Other, had the smallest percent cover of structurally complex classes (5-6) (Figure 11 B).

Principal Component Analysis results for Land Use Allocations showed a strong divide among forest structure classes 1-4 (e.g., Stand Initiation through Vertical Diversification) vs classes 5 -6 (e.g., Complex and Highly Complex) (94.1 % of the ordination variation). Additionally, 4.7% of the variation was explained by the amount of structure classes between these two groupings. Adaptive management reserves – experimental areas meant to explore alternative management ideas and centered around restoration of late successional forests (Table 5), were clustered among highly complex forest structure (6), while administratively withdrawn – areas defined as local forest and district plans such as back country areas, and congressionally reserved allocations – wilderness areas, national parks and monuments reserved by U.S congress, clustered around vertical diversification (4). Late Successional Reserves – areas designated for the restoration of late successional and old growth forest ecosystems, Adaptive Management Areas – experimental areas meant to explore management ideas centered around ecologically sustainable timber harvesting and other – unmapped land allocations such as matrix and riparian reserves, were clustered around Canopy Closure (2) and Maturation (Harvestable) (3) structural classes (Figure 11 A) (Table 5).

**Discussion:**

Understanding the impact human disturbance plays on forest structure can help promote forest resiliency, animal habitat suitability and resources necessary to the economic stability of forest-dependent communities. There exist minimal studies that use high-fidelity aerial lidar imagery to create a landscape census of forest structural patterns distributed among anthropogenic boundaries. I build upon previous studies that have successfully derived stand structure classification through lidar measurement metrics (Kane et al. 2018, Kane et al. 2010, Zhao et al. 2011), and have used high-fidelity aerial lidar imagery to make sense of forest structure classes across ownership in the Oregon coastal range (Griffey et al. 2003) (Table 3). By creating a census of forest structural patterns among Ownership and NWFP Land Use Allocation Boundaries, this study helps address key research gaps (e.g., restoration monitoring, climate change and the success of land use allocation guidelines) discussed in the 2018 NWFP Scientific Synthesis by Spies et al. (2008). Results produced the following insights: **(1)** Six Structure classes were identified across the Western Cascades of Oregon. **(2)** Forest Structure classes were distributed among clusters of structurally simple and complex forest classes that created assemblages among private vs. public ownership type and Land use Allocations. **(3)** High Presence of structurally complex forest Classes were seen among NWFP Land Use Allocations.

### ***The identified six structure classes formed two dominant clusters of forest structures varying in structural complexity***

Six structure classes were identified across the Western Cascades of Oregon and structurally distributed among two distinct structure class groupings. Simple forests classes were made up of Initiation/Cohort Establishment (1), Canopy Closure (2), and Maturation (Harvestable) (3) classes . While Complex forest classes consisted of Vertical Diversification (4), Complex (5) and Highly Complex(6) classes. Principal Component analysis of forest structure across Ownership Types and NWFP Land Use allocations (Figures 10 A -11A ) assisted in interpreting the clustering among Simple vs Complex forest structure class groups.

Principal Component analysis results of the relative percentage of structure classes by ownership type (Figure 10 A) showed a strong group association among structure classes (1-3) (e.g., Simple forest structure class group) and structure classes (5-6) (e.g., Complex forest structure class group). PCA Ownership results additionally illustrated a divide among Public, Private Industrial, and Private Non-Industrial (PVNI) ownership types. Public Ownership Types (e.g., Federal BLM OC and Federal USFS) were strongly associated with Complex and Highly Complex classes while Private Industrial Ownership types (e.g., REIT, Integrated, Family, TIMO) were associated most with Initiation-Maturation (Harvestable) structure classes (1-3). Additionally, PVNI (Private Non-Industrial Ownership type) strongly associated with structure class (4) (Figure 10 A).

Principal Component analysis of NWFP Land Use Allocations (Figure 11 B) showed a similar association among Simple (1-3) Forest classes and Complex Forest classes (5-6). Additionally, PCA results showed that Vertical Diversification (4) was statistically associated with Simple forest classes (1-3). Adaptive Management reserves – designated as experimental areas meant to explore alternative management ideas that center around the restoration of Late-Successional forests were the only Land Use Allocation statistically associated with Highly Complex forest structure (6). Administratively Withdrawn, Adaptive Management Areas, Congressionally Reserved, Late Successional Reserves and Other were clustered among forest structure classes (1-4) (Figure 11 A).

GNN stand age data of estimated forest ages were consistent with forest structure classification identified within this analysis – specifically among Maturation and Vertical Diversification classes. GNN estimated age among Harvestable/Maturation (3) had an estimated mean age of 95 years while Vertical Diversification (4) had an estimated mean age of 156. Estimated stand ages align with typical stand age years summarized by Franklin et al. 2002. Complex and Highly Complex classes fell within the Horizontal Diversification development stage. Mean estimated stand age for Complex (5) class was 182 while for Structurally Complex (6) the estimated stand age was 225 (Figure 9) (Table 1). Given the typical stand age years for forest development stages classified as old growth (Franklin et al. 2002) (e.g., 100 – 1200), Vertical Diversification was considered part of the complex forest class group.

### Presence of Structurally Complex forest Classes among NWFP Land Use Allocations

A critical component of the Northwest Forest Plan includes the creation of land allocations with individualized management standards and guidelines. The original Land Use Allocations were developed from Option 9 of the Forestry Ecosystem Management Assessment Team (FEMAT 1993) which came to be the Northwest Forest Plan in 1994. LUA boundaries have gone through several modifications. The most recent update was in 2013 and consist of the following land use allocations: Adaptive Management Reserve, Administratively Withdrawn, Adaptive Management Area, Congressionally Reserved, Late Successional Reserve, Northern Spotted Owl Activity Centers and Other. A primary objective for LUAs has been the protection and promotion of structurally complex forests in the NWFP region. Results from structure class distributions among Land Use Allocations illustrate two findings: (1) There exists an overall high percentage of complex structure classes across all Land Use Allocations and (2) Adaptive Management Reserve display the highest percentage of Complex and Highly Complex Classes.

Administratively Withdrawn, Adaptive Management area, Congressionally Reserved, Late Successional Reserve and Other had the highest percentage of Vertical Diversification (4) among all structure classes (Figure 11 B), this can additionally be seen among PCA Land Use Allocation results, which illustrate a relatively stronger association among structurally simple forest classes rather than structurally complex (Figure 11 A). Complex and Highly Complex structure classes made up around 75% of percent cover in the Adaptive Management Reserves. Differences among Land Use allocations could be based on land management objectives. Aside from Adaptive Management Reserve Allocations and Adaptive Management Areas, most allocations are designated as reserved – areas without any set land management objectives . Management objectives within these LUAS additionally remain unclear. With 40% of the study area consisting of Other, there exists a large amount of undesignated land use allocations.

Land Use allocations had an overall higher hectare area of structurally complex classes (4-6) compared to structurally simple classes. Complex classes 4-6 in land use allocations totaled 436,808 hectares while Simplex classes (1-3) in land use allocations equaled 170,776 hectares (Figure 13). The distribution of structurally complex classes across ownership type in this study area illustrated a slightly higher percentage of structurally simple complex classes that totaled to 519,212. Structurally complex classes (4-6) for combined ownership types equaled 479,110 hectares.

Public ownership types such as Public Mixed Objective or Public NWFP Objective Ownership types had a higher area of complex structure classes compared to private ownership types (Private Non-Industrial and Private Industrial). Complex classes in Public Ownership Types totaled 476,125 ha while Private Ownership Types totaled 2985 ha (Figure 12). An important consideration to take note of is that while public ownerships had a higher percentage of structurally complex forest classes, this is representative of the overall higher area of public ownership types in this analysis.

## Expanding on forest structure classification literature and NWFP Monitoring Research

Enhancing monitoring approaches that consider complex ecosystem processes at a landscape scale remains a key NWFP management need (Spies et al. 2018, Griffey et al. 2021). Various scholars have utilized a breadth of active and passive remote sensing techniques to characterize forest structure patterns (Bell et al. 2015), carbon sequestration (Kennedy et al. 2010), land use change (Cohen et al. 2002), and to examine the effectiveness of NWFP policies in the Western Cascades (Davis et al. 2013, DellaSalla et al. 2015) (Table 1 and 2). Passive remote sensing techniques have been used to produce consistent forest structure spectral profiles in the Blue Mountains of Eastern Oregon (Pflugmacher et al 2012) and to compare radiometric procedures for the monitoring of stand replacing disturbances (Schroeder et al. 2005). Active remote sensing techniques- specifically high-fidelity aerial lidar imagery offers an alternative to characterizing forest structure patterns at a finer scale that can be instrumental to NWFP land management monitoring and habitat restoration. Work by Hagar et al. (2020) which used Lidar metrics to improve habitat modelling for arboreal species, found that Lidar metrics critically assisted the model's ability to differentiate among structurally complex suitable habitat areas in Southwestern Oregon. Similarly, work by Tweedy et al. (2019) which used Lidar and ground based surveys to evaluate marten resting habitat areas in Lassen National Forest, California illustrates the importance of incorporating high-fidelity lidar data to address future monitoring needs across the NWFP region.

## Future Research

Directions for future research could build off methodology designed by Griffey et al. 2021 and utilize percent area of each structure class, area-weighted mean patch size, and juxtaposition index (IJI; structural heterogeneity) calculated in the landscapemetrics R package (Hesselbarth et al. 2019) to quantify how ownership or land use allocations affect landscape patterns. Additionally, future work could focus on how best to utilize lidar derived stand structural data to deal with uncertainty, and vulnerability to heterogenous ecosystems and human communities within the NWFP region. By developing approaches centered on publicly accessible lidar derived stand structural data, collaboration among communities and land managers can be strengthened. Additionally, data could assist in the contribution of vulnerability mapping by offering a more robust fine scale analysis of structurally complex forests to neighboring forest dependent communities.

## Conclusion

Increasing wildfire activity, climate change uncertainty and the evolving public perception of forest ecosystem objectives validates the need for adaption strategies and monitoring protocols that are consistent and operative at a landscape scale (Spies et al. 2018). Characterizing forest structural patterns across Land Use Allocation and Ownership using high-fidelity airborne lidar presents an opportunity to build upon previous NWFP monitoring work.

This analysis found that the highest percentage of structurally complex forest classes were among public land ownerships, and complex forest structure classes existed across each Land Use Allocation. This work builds on previous research in Western Oregon, and Griffey et al.'s (2021) research that examined how human management practices impact and modify forest structural patterns using airborne lidar data in the Coastal Range of Oregon.

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Appendices:

| **Passive Remote Sensing Techniques** | | | | |
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| Defined as data collected by remote sensing systems that measure energy naturally available. Passive remote sensing systems utilize hyperspectral and multispectral sensors to collect band combination data. Examples of remote sensing systems include Spectrometer, Radiometer etc.(EOS 2021) | | | | |
| **Reference** | **Location** | **Objectives** | **Data** | **Conclusions** |
| Bell et al. 2015 | Western Cascade Mountains | **(1)** Characterize the imputation uncertainty in predictions for six forest attributes **(2)** Assess how imputation uncertainty varies across regional ecological gradients. | 2012 Landsat imagery \| LandTrendr | Although maps of uncertainties in imputed map predictions are becoming more common, there remains little direction on how to use these uncertainties to understand limitations on imputed maps |
| Gosnell et al. 2020 | Western Cascades of Oregon | Analysis of discrepancies between national forest policy as stated and implemented. Linked time-series satellite data with forest inventory to track patterns of timber harvests. | Temporal segmentation of the Landsat satellite image archive using the LandTrendr algorithms. Spatial resolution 30 by 30 m. \| Forest Inventory and Analysis (FIA) plot data \| LUA NWFP data | Remote sensing-based approaches provide novel insights into trends of change over time in forest landscape patterns. Results and mixed methods approach explain why NWFP has not been implemented as planned as evidenced by actual harvest patterns in LUAs. |
| Jiang et al. 2004 | Portions of Washington and Oregon. | Providing data that will fill the gap for late seral conifer forests. Primarily through vegetation classification using remote sensing. Correctly classified images will represent areas of vegetation with similar spectral characteristics. | Landsat 7 Enhanced TM plus (ETM+) 2000 \| USGS DEM Model Data \| Oregon Digital Ortho Qua (DOQ) images by USGS | Results show that Individual or single-scene classification potentially offers a better accuracy for mapping vegetation cover types than a mosaic of multiple scenes. Results show that subdividing a scene into sub-scenes provides greater vegetation classification accuracy. |
| Mccomb et al. 2007 | Oregon Coast Range | How do Forest policies affect various measures of biodiversity over a multi-ownership region? How to evaluate the trends in habitat availability for three focal species under current | Spatial simulation modelling used for future habitat availability modeling \| Oregon Ownership Data \| satellite imagery vegetation data. | Land ownership influenced the spatial arrangement of habitat for focal species. Thinning management techniques on federal lands did not impact focal species. |

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| | | forest policies in the Oregon Coastal range. | | |
| Ohmann and Gregory 2002 | Oregon Coastal Province | Characterize quantitatively and spatially the current patterns of forest vegetation in Oregon. **(1)** quantifying spectral, environmental factors associated with regional gradients **(2)** GIS-based model to integrate field plot, remote sensing, and environmental data **(3)** vegetation map productions. | Vegetation field plot collected from regional forest inventories (CVS, FIA, OGS) \| Landsat 5 TM Imagery \| PRISM Data for precipitation, temperature, and elevation | Species composition and structure were most associated with Landsat TM variables. Predictions by GNN/study closely matched systemic grids of inventory plots. |
| Schroeder et al. 2005 | Western Oregon (Summer Months) | Objective is to compare the effectiveness of absolute and relative radiometric correction procedures with the goal of producing consistent temporal reflectance of forests recovering from stand replacing disturbances. | 1984-2004 Landsat -5 TM and 3 Landsat-7 ETM+ images | The most effective method for atmospheric correction of a time series image is "absolute-normalization". Method normalized all images in a time-series to an atmospherically corrected reference image. |
| Senf et al. 2017 | Central European Forests (5 sites) | **(1)** Map forest disturbances across five protected forests and their surroundings using 32 years of Landsat observations. **(2)** Characterize and compare forest disturbances among protected and managed forests to understand the effect of management on spectral, temporal, and spatial characteristics of forest disturbances in human/natural systems. | 1985-2016 Landsat TM, ETM+, and OLI data from USGS and ESA archives | Landsat is suitable for mapping forest disturbances on varying agents in the coupled human and natural systems. There were some challenges in disturbance mapping. Forests close to the tree line were synchronized across different levels of human influence. |
| Zald and Dunn 2018 | Douglas Complex, Southwestern Oregon, USA | **(1)** What is the importance of difference variables driving fire severity **(2)** Is intensive plantation forestry associated with higher fire severity? | Landsat 8 Operational Land Imager \| Elevation and topographic variables from National elevation Dataset 30 m digital elevation model \| Fire weather condition rasters | Daily fire and weather were an important predictor of fire severity following stand age, ownership, and topography. Young forests (plantation forestry) are significant drivers of wildfire severity. |

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| Haugo et al. 2015 | Eastern Washington and Eastern Oregon in addition to southwestern Oregon | New approach for evaluating where, how much, and what types of restoration are needed to move present data landscape scale forest structure toward a natural range of variability. Approach builds on conceptual LANDFIRE framework. | Mapping biophysical settings using 30 m pixel integrated landscape assessment projects (PVT) Data set \| LANDFIRE Data | Forest structural restoration needs across eastern Washington and eastern/southwestern Oregon were dominated by the need for thinning/low severity fire transitions within low/mixed severity fire regimes. Study identified 1.7 million ha in need of disturbance to restore forest structure. |
| Cohen et al. 2002 | Western Oregon | Analysis of stand replacement disturbance over 4.6 million forested hectares within three major provinces in W Oregon. (Between 1972 and 1995). Objectives **(1)** characterize the rate and distribution of stand replacement disturbance **(2)** contrast the relative importance of wildfire and clear-cut harvest as forest disturbance agenda **(3)** compare patch size distributions of forest cutting units. | 1972-95 Landsat MSS & TM Imagery | In dense canopied forests, stand replacement disturbance can be monitored with Landsat data. \| Rates of harvest varied by ownership \| The degree to which forest management can be effectively monitored with remote sensing remains open ended. Paper called for the combination of Landsat data and inventory data or lidar etc. |
| Davis et al. 2013 | Northwest Forest Plan Boundary Extent | Analysis of whether NWFP is providing for conservation and management of northern spotted owl (NSO) habitat as anticipated) Report centers around the spatial arrangement of NSO habitats across NWFP area. | LandTrendr \| GNN Data | From monitoring analysis: Results showed a net decreased of nesting/roosting habitat on NWFP federal lands. This occurred despite gross losses from wildfire. This analysis used LandTrendr (Landsat TM) for monitoring areas and forest vegetation change. - developed following methods in Kennedy et al 2010,2012). (REVISIT THIS) |
| Kennedy et al. 2012 | Northwest Forest Plan Boundary Extent | **(1)** Does the aggregate disturbance vary across ownership, states, and ecoregions? **(2)** Did the disturbance rate on federal lands change during counter injunctions. **(3)** Did the disturbance rate on non-federal lands change in | 1984 to 2008 Landsat TM & ETM+ data | Free-data access policy of Landsat archive improves our ability to map landscape processes in forests. NWFP appears to have affected forest disturbance rated intended by the policy. Rates of disturbance on federal lands were lower under the NWFP than before. |

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| | | response to the change on federal lands? | | |
| Spies et al. 2007 | Western Cascades - Coast Range Physiographic Province of Oregon | **(1)** Develop and evaluate concepts and tools to understand the patterns of regional ecosystems and how they are affected by forest policies. **(2)** Learn how to inform managers, policy makers and other scientists about some of the potential ecological socioeconomic consequences of current alternative forest policies across ownerships. | Landsat imagery \| Forest inventory plots \| Vegetation conditions estimated from GNN \| Lamps simulator \| CLAMS approach | Two major shortcomings on biodiversity policies in this multi-ownership region **(1)** except for the federal lands, biodiversity policy goals are not stated explicitly enough to be used alone as benchmarks for measuring progress. **(2)** No policy addresses the entire province |

**Table 2.** Literature review of passive remote sensing techniques used to analyze forest structure class or composition. Literature cited primarily focused in NWFP region, specifically the western Cascades of Oregon

| **Active Remote Sensing Techniques** | | | | |
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| Active remote sensing techniques provide their own energy source. Sensors emit a signal to the targeted object and collects the emitted radiation from the target. Examples of active remote sensing data includes Lidar or radar. | | | | |
| **Reference** | **Location** | **Objectives** | **Data** | **Conclusions** |
| Ahmed et al. 2015 | Vancouver Island, British Columbia | Analysis of random forest potential to estimate lidar measured canopy structure using time series of Landsat imagery. | 2004 lidar data acquired in 2004 by Terra Remote Sensing \| Landsat Imagery between 1972 and 2004 | Study shows the value of using disturbance and successional history to inform estimates of canopy structure and obtain the improved estimated of forest canopy cover. |
| Boucher et al. 2020 | New England Region | Monitoring insect disturbances with ALS and GEDI data in the Eastern US. | GEDI data \| Airborne Lidar Data \| Forest GEO plot data | Results show how linking the change in simulated GEDI waveforms with the deteriorating condition of hemlock stands in a temperate New England Forest. Study demonstrates how a time |

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| | | | | series of lidar waveforms can capture structural change and classify disturbance. |
| Coops et al. 2007 | Vancouver Island, BC | Study shows the capacity/capability of small footprint, discrete returns made to measure foliage height and canopy structure attributes. | 2004 Lidar data acquired by Terra Remote Sensing | Study illustrates that small footprint and discreate lidar return observations can provide quantitative information on stand and tree height. |
| Dalponte et a. 2019 | Alps | **(1)** Map fine-scale variation in aboveground carbon density (ACD) and its change over time and **(2)** link these changes to species composition, FS attributes and local topography. | 2007 forest plot data \| 2007 Lidar data acquired from Optech sensor | Results shows that majority of the landscape in 2007 and 2011 increased in ACD. Additionally, study illustrated the potential for repeat lidar when it comes to characterizing structure and composition of carbon dynamics. |
| Falkowski et al. 2009 | structurally diverse, mixed-species forest in Northern Idaho | Classification of forest successional stages using Lidar height metrics. Objectives: **(1)** Determine the most important lidar metrics for forest structure classification. **(2)** select the most parsimonious classification model while retaining the highest degree of classification accuracy as possible. | 2003 Forest inventory plots \| Landsat-derived lead area index layer \| | Successional stage classifications presented an overall accuracy of 90%. Results show that lidar data alone can accurately characterize structure classes. Like other lidar studies though, more work is needed to assess the understory characteristics and other attributed critical to wildlife habitat assessment. |
| Griffey et al. 2020 | Oregon Coast Range | **(1)** What distinct classes of forest structure exist across out study area? **(2)** Does the distribution and pattern of forest structure vary across the area? **(3)** What implications do the fine and sub-regional scale patterns have for ownership types? | 2008 Quantum lidar data \| Ownership vector data | Six different forest classes were found in areas and could be separated among public vs. private. Analysis provides an example of the importance lidar placed in contextualizing the structural variability within Oregon. |
| Hagar et al. 2020 | Southwest Oregon, Forested lands of Coos Bay District | Exploration of Lidar metrics available in FUSION and identify those that best quantify important structural attributes | NSO occurrence data collected from public land management | Lidar metrics can be used to track development of mature second-growth forests and characterize |

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| | Bureau of Land Management (BLM) and the Elliott State Forest. | associated with nest site occupancy by the Northern Spotted Owl. | agency surveys \| Airborne lidar was collected through the Oregon Lidar Consortium | suitable habitat for spotted owls and other old-growth associated species. |
| Kane et al 2010 | Cedar River Municipal Watershed, WA | Test whether lidar measured canopy structure were consistent with structures predicted by stand development models in WA region. | 2003-2005 Field Data Sample Plots \| Spectrum Mapping LLC Lidar Data | Canopy complexity is not linearly related to forest age or elevation. Lidar data can be used to stratify structural conditions across a range of forest ages. |
| Kennedy et al. 2018 | Western Cascades of Oregon and California | Creation of a forest biomass monitoring system. Article examines methodological uncertainties of biomass model to understand spatial and temporal patterns of forest biomass dynamics. | LandTrendr \| Field Plot data using GNN \| Airborne lidar data | Creation of an empirical approach to monitor live forest carbon at broad scales suing a mixed methods approach. |
| Means et al. 1999 | Western Cascades of Oregon - H.J Andrews Experimental Forest | Measuring structure of PNW forests using SLICER (Scanning lidar sensor).The airborne pulsed laser developed by NASA were also cross referenced with 26 plot data ground measurements for accuracy/relationship comparison. | SLICER (airborne lidar) data \| ground plot data \| Forest Inventory Data | Strong correlation among large-footprint airborne scanning lidar and ground-based forest plot data, showing promise for stand structure charact-erization and management |
| Moran et al. 2018 | Northern Rocky Mountains | Development of framework meant to identify predominant forest canopy structures across diverse landscapes without the need for field training data. Study uses high-density small footprint lidar data spanning 6 ecoregions to develop/test methods. | Quantum spatial 2014 Lidar data \| 2014 Forest ground plot data | Each selected feature showed significant correlation to at least one field metric. Study adds to the abundance of lidar data sets capable of deriving actionable information for structural classification. |
| Wiggins et al. 2019 | The Sierra de San Pedro Martir National Park & Baja California, Mexico | Study assessed bias in the processed LiDAR data by comparing datasets of field-measured and LiDAR detected trees of various height classes. Overall objective: **(1)**Quantify overstory forest structural and spatial variation across a Mediterranean-Climate reference landscape and **(2)** determine | E W Wells Group, LLC collected discrete point-return lidar data in 2015 \| 2014 ground plot data | Results bolster growing body of literature supporting the reliability of ITD-based stand-level structure and spatial pattern estimate when minimum height cut-offs are applied. Applying cut-offs resulted in fine-scale heterogeneity and accurate assessment of |

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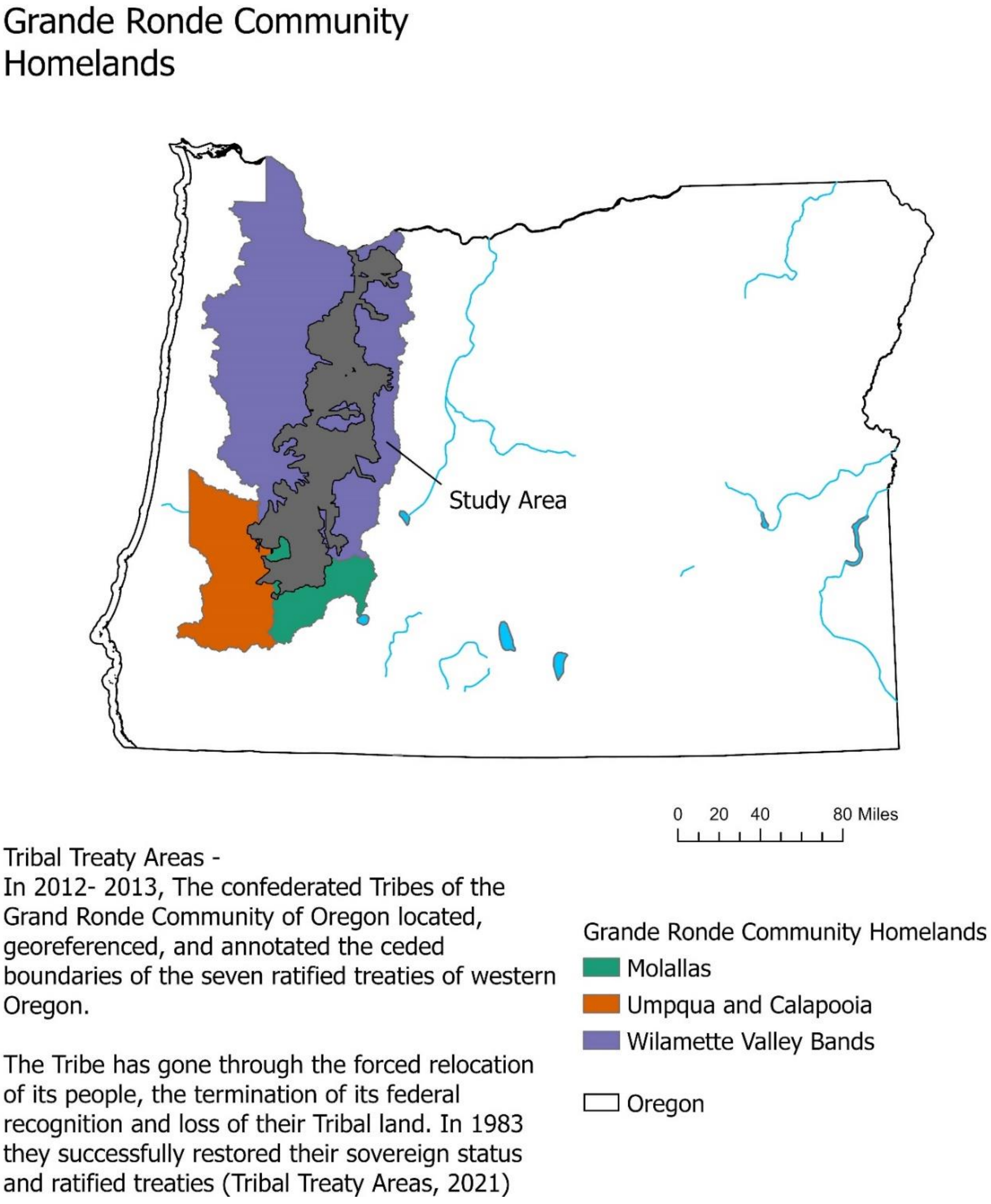
| | | whether these attributes vary across different landforms. | | tree clumps and sizes (structures highly linked to forest resiliency). |
| Zald et al. 2014 | Central Oregon Cascades, USA - Deschutes National Forest | Can lidar and LTS disturbance metrics improve the accuracy of regional NN imputation maps of forest vegetation composition and structure? | 2004 and 2009 forest plot inventories \| Watershed Sciences, Inc 2009 and 2010 Lidar Data \| PRISM Data | Integrating lidar and LTS disturbance metrics into NN imputation can greatly improve mapping of forest composition and structure over large landscapes. |
| Zimble et al. 2003 | Idaho | **(1)** Determine if tree height variances can be used to separate two vertical structure classes (single-story vs. multistory). **(2)** Establish whether any differences exist between field and lidar derived tree height variances **(3)** Develop a methodology for mapping the distribution of vertical structure at landscape scales. | 2000 Field inventory data \| 1998 Lidar data acquired by Earth Data Technologies | Field-derived tree height variances could be used to distinguish between single-story and multistory classes of vertical structure within forests of the study area. |
| Bell et al. 2018 | Coos Bay, Colville, Deschutes | Determine whether high-resolution lidar-based and moderate-resolution Landsat Forest biomass maps showed similar predictions at stand- to landscape -levels and whether differences were contingent on biophysical setting. | Lidar and LTS-based mean AGB (Above Ground Biomass) maps for each study region collected from 2008 to 2010 | Lidar and Landsat based map deviations indicate that satellite-based approaches may represent general gradients in forest biomass. Factors affecting the measurement and prediction of forest biomass, such as species composition need to be considered. |
| Pflugmacher et al. 2012 | Blue Mountains of Eastern Oregon | Are Landsat disturbance history data a good predictor of current forest structure? Analysis explores empirical relationships between field-measurements of current forest structure. | 2008 Forest Inventory Plot data \| 2008 Lidar data \| Landsat Data 1972-2010 | Metrics extracted for annual trends in forest disturbance and recovery showed areas in which Landsat and Lidar data performed similarly. |

**Table 3.** Literature review of active remote sensing techniques used to analyze forest structure class or composition. Literature cited primarily focused in NWFP region, specifically the western Cascades of Oregon



Tribal Treaty Areas -
In 2012- 2013, The confederated Tribes of the Grand Ronde Community of Oregon located, georeferenced, and annotated the ceded boundaries of the seven ratified treaties of western Oregon.

The Tribe has gone through the forced relocation of its people, the termination of its federal recognition and loss of their Tribal land. In 1983 they successfully restored their sovereign status and ratified treaties (Tribal Treaty Areas, 2021)

Figure 1. Map of study area extent overlaid with Tribes of the Grande Ronde Community of Oregon. (Tribal Treaty Areas, 2021)

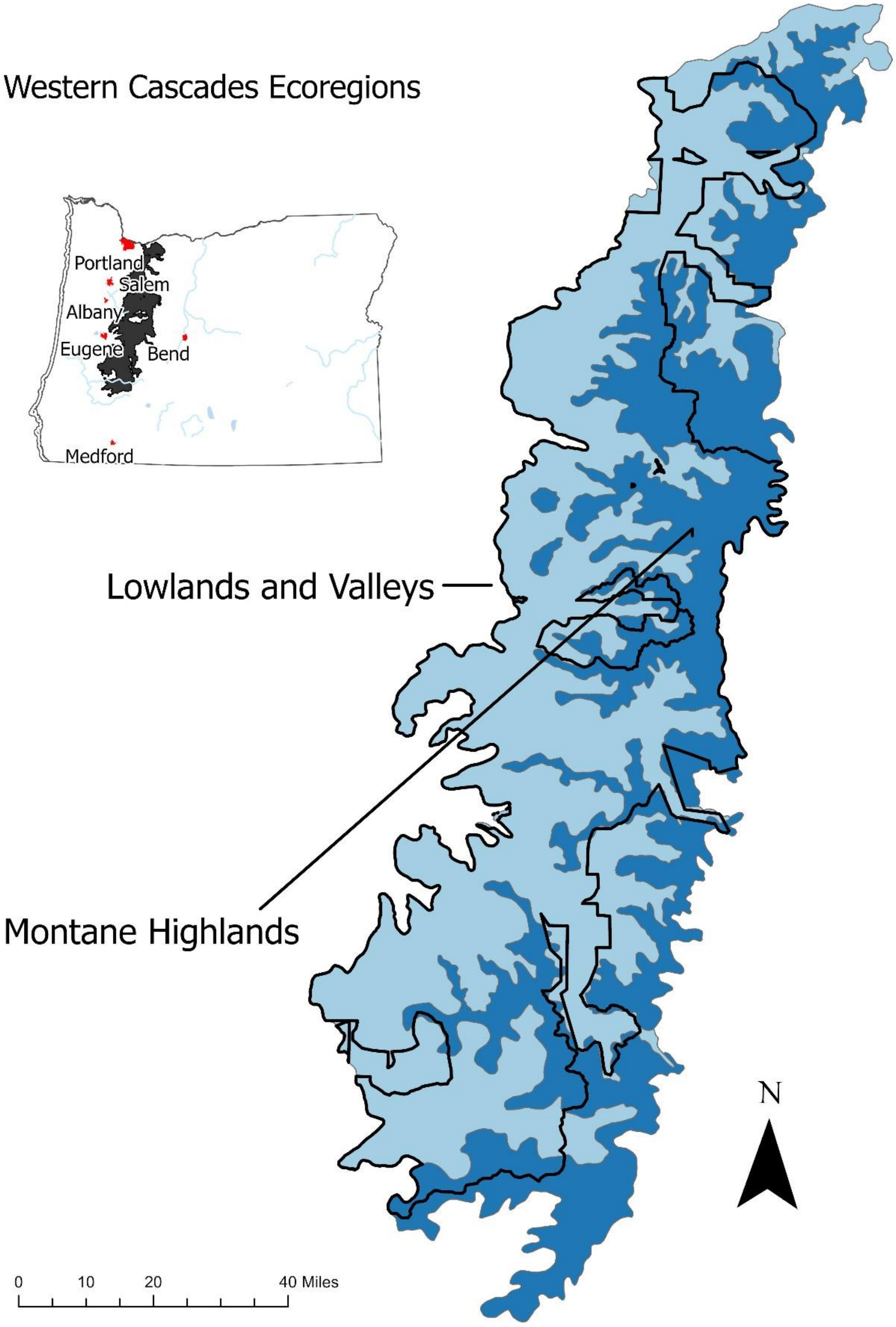


Figure 2. Map of study area ecoregions included within the analysis (EPA 2021).

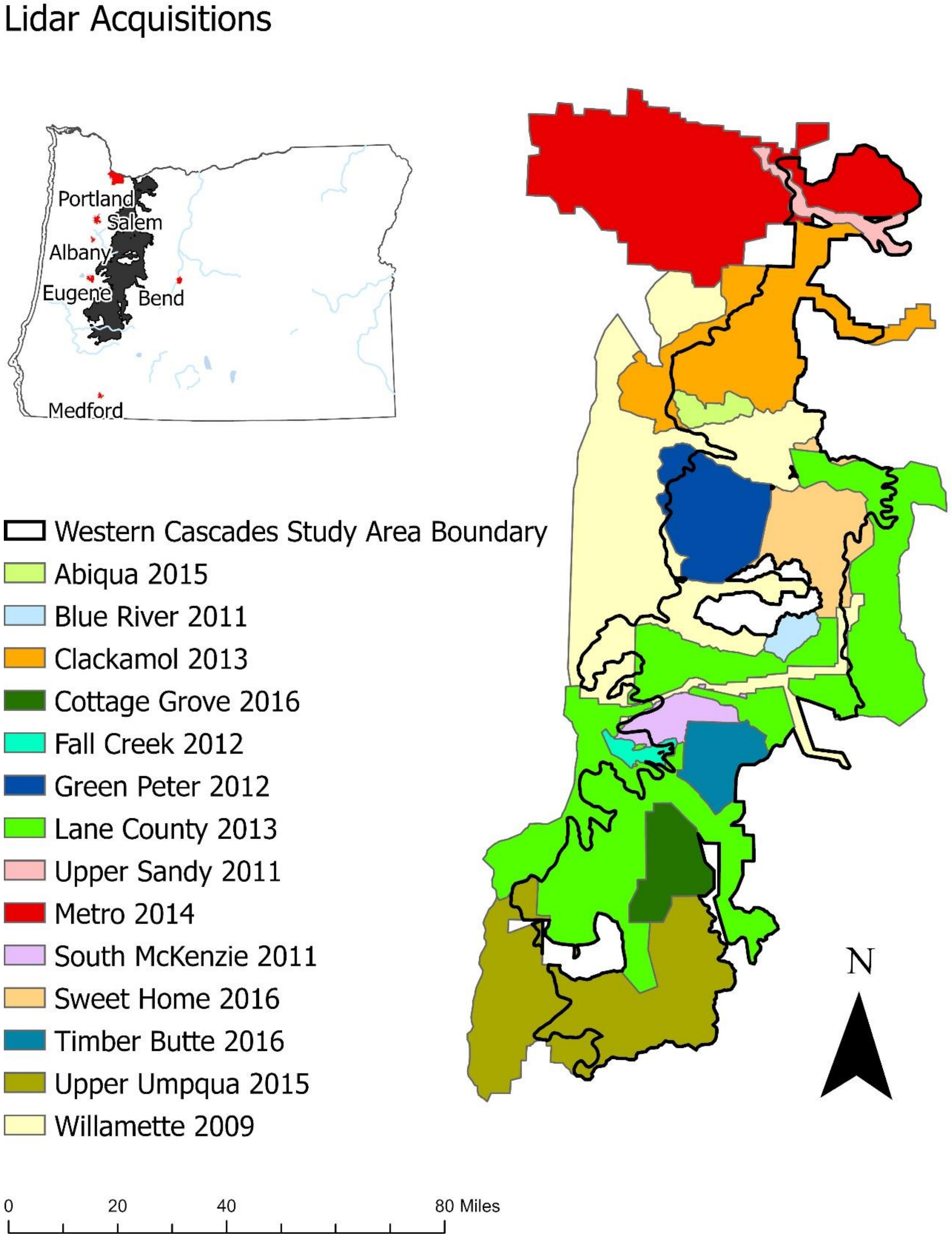


Figure 3. All acquisitions combined in study area. Lidar data acquisitions collected by Quantum Spatial Inc. (Formerly Watershed Sciences Inc.) Weyerhaeuser, and the Atlantic Group LLC. Sensors used for data collection include – Leica ALS 50,60,70,80 or Optech Orion. Months varied for each acquisition.

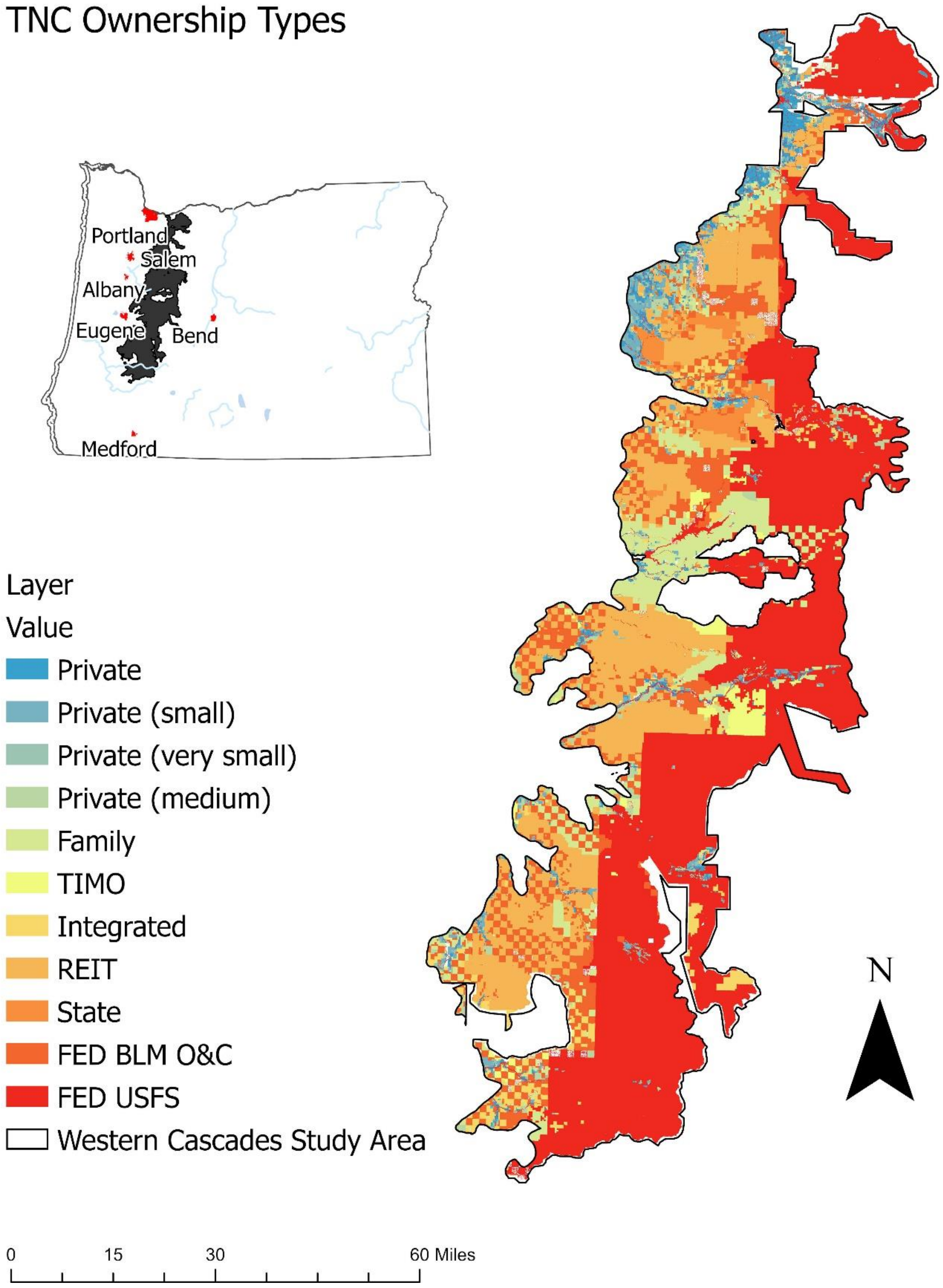


Figure 4. Map of ownership groups in western Cascades of Oregon study area. (TNC 2020)

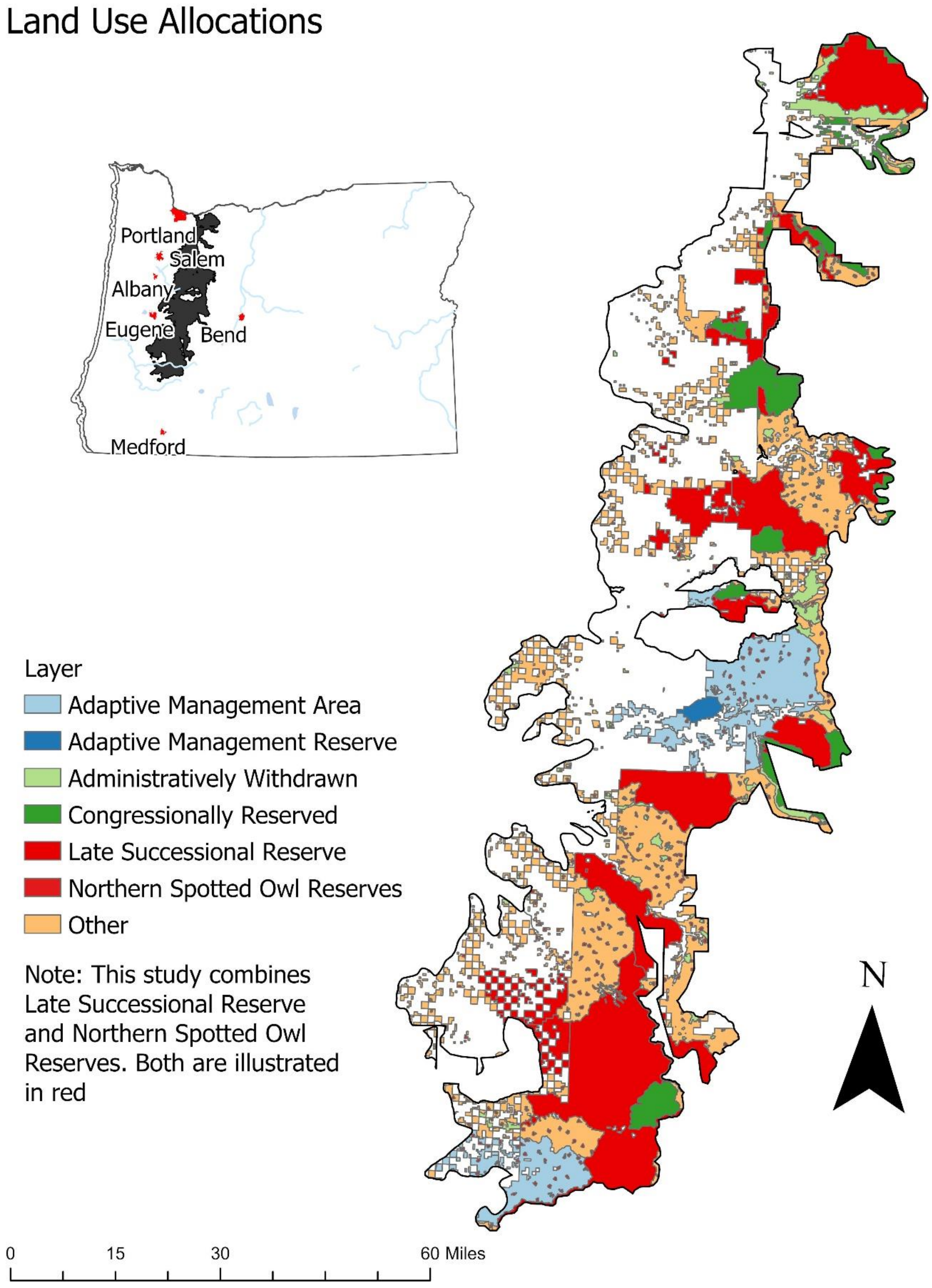


Figure 5. Map of 1994 Northwest Forest Plan land use allocations. Data were collected by the Late-Successional Work Group. Data are an update to the 2009 LUA map. (NWFP 2021)

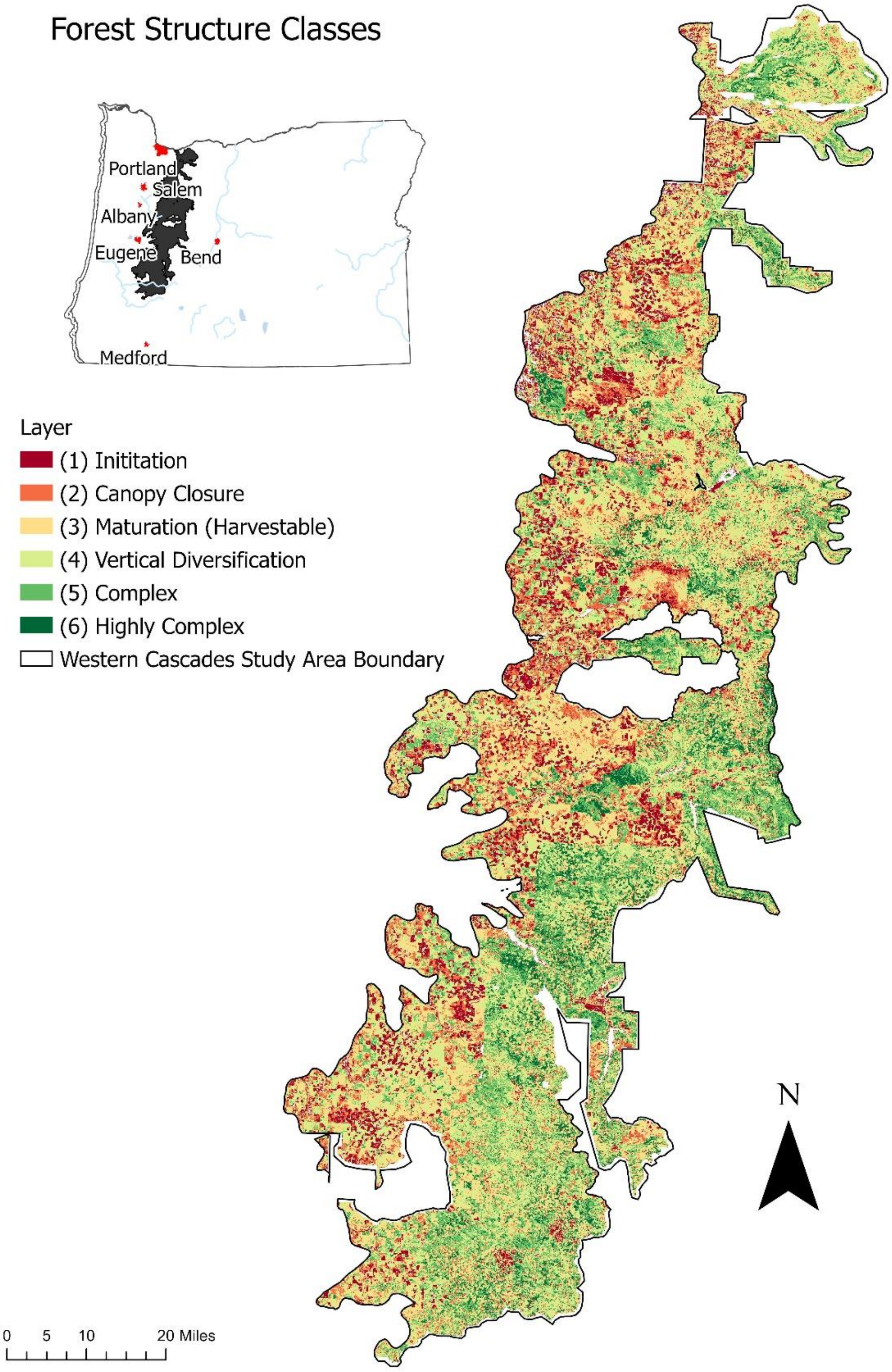


Figure 6. Map of forest structure classes created by hierarchical classification analysis of lidar metrics calculated in FUSION.

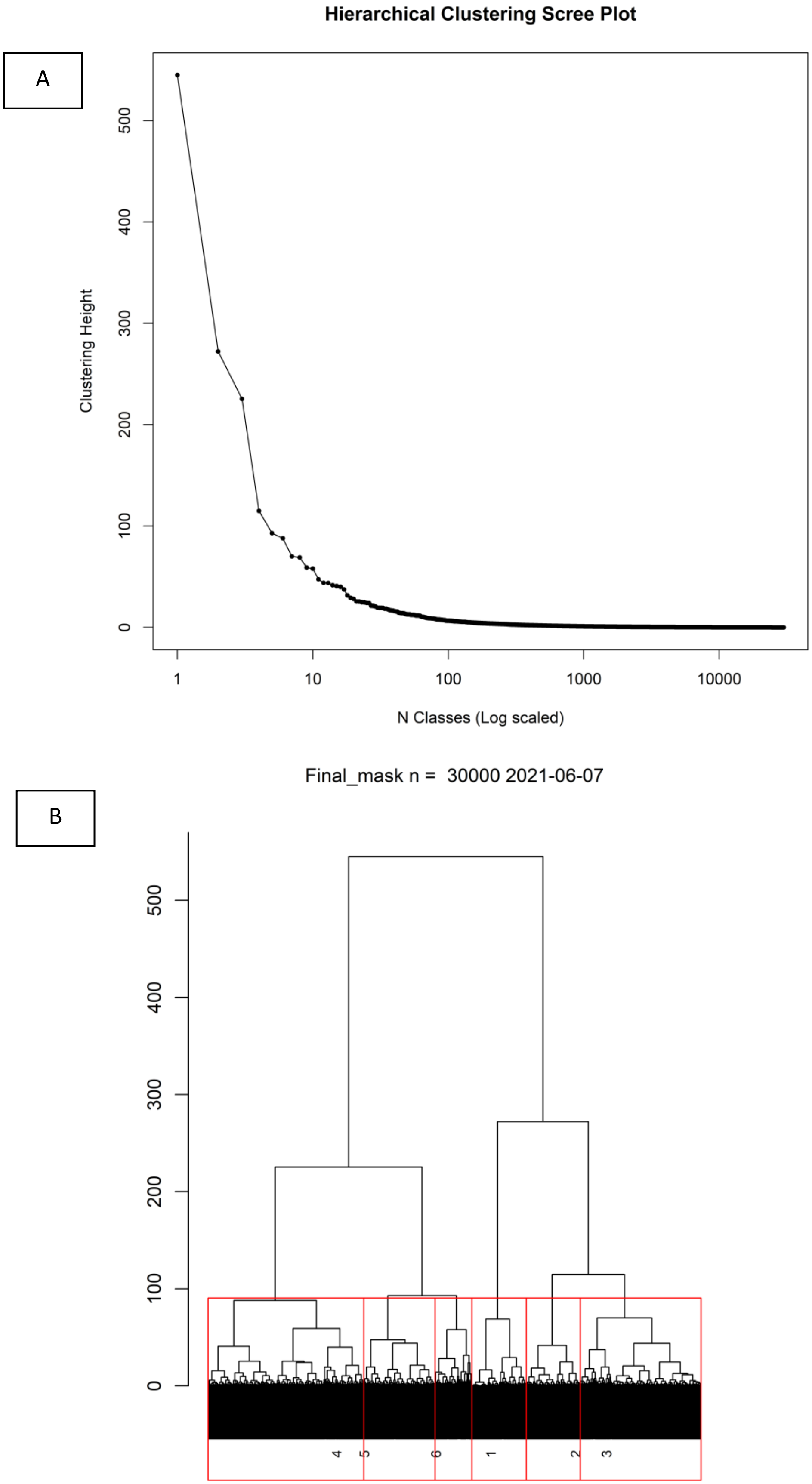


Figure 7. (A) Scree plot created from Principal Component Analysis of lidar metrics. (B) Dendrogram of forest structure classes performed from hierarchical clustering.

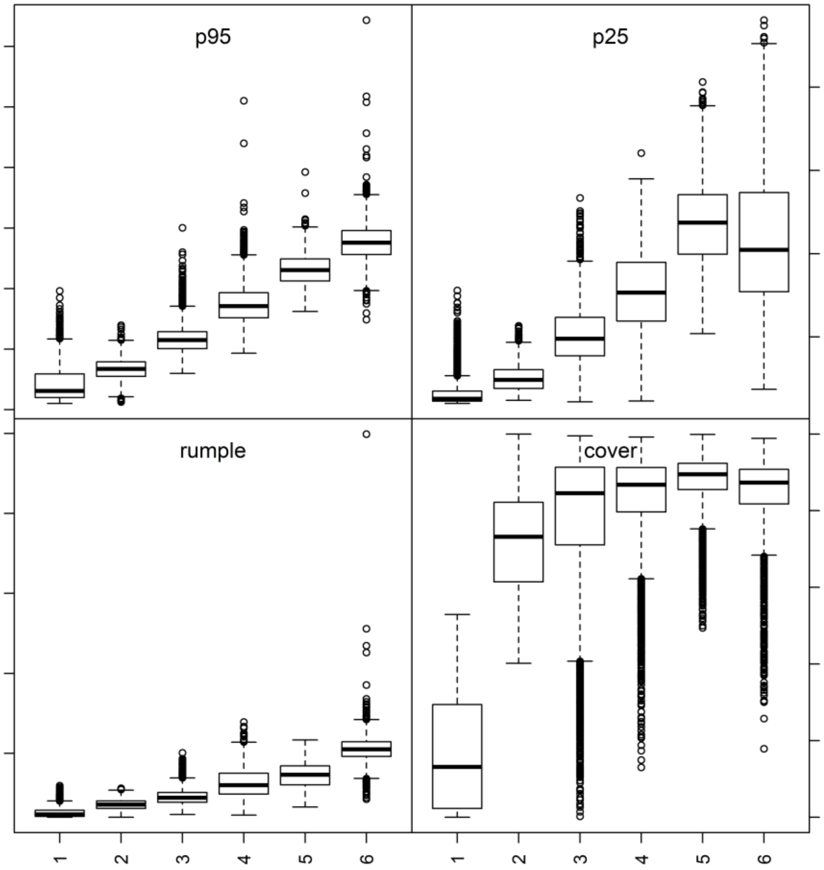
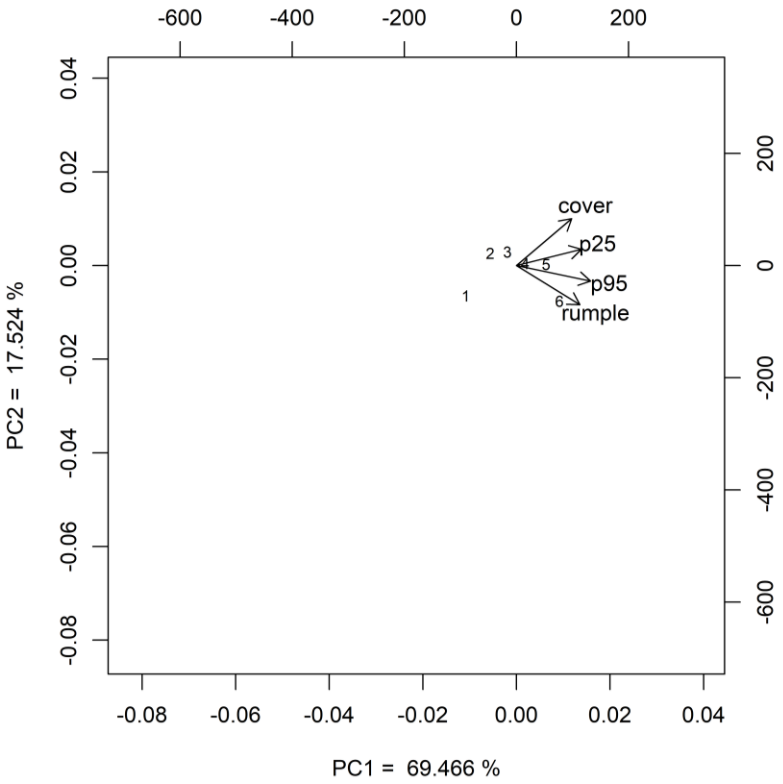


Figure 8. (A) Distribution of lidar metrics within each forest structure class identified through forest classification analysis. (B) Ordination of Principal Component Analysis for lidar metrics – p95, p92, cover, rumple.



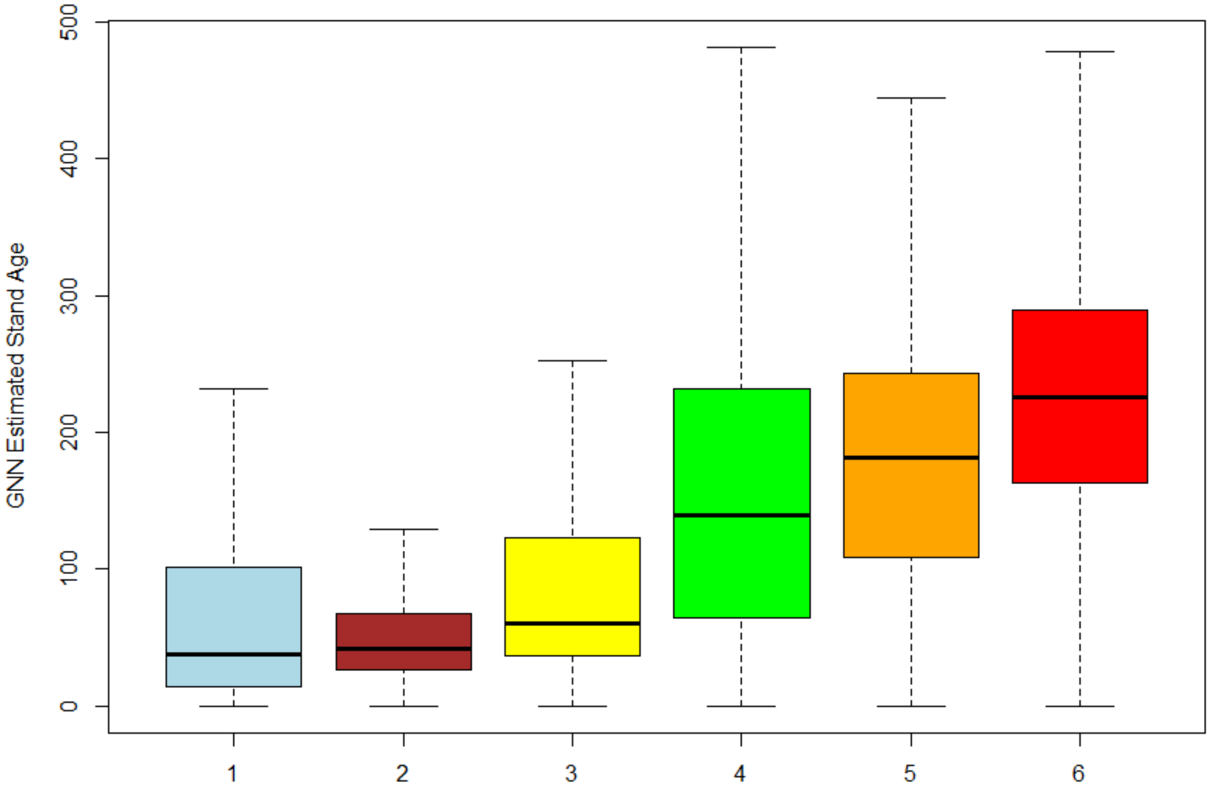


Figure 9. Boxplots of GNN stand age estimates across identified forest structure classes. (1) – Initiation/Cohort Establishment | (2) – Canopy Closure | (3) – Harvestable/Maturation | (4) – Vertical Diversification | (5) – Complex | (6) Highly Complex

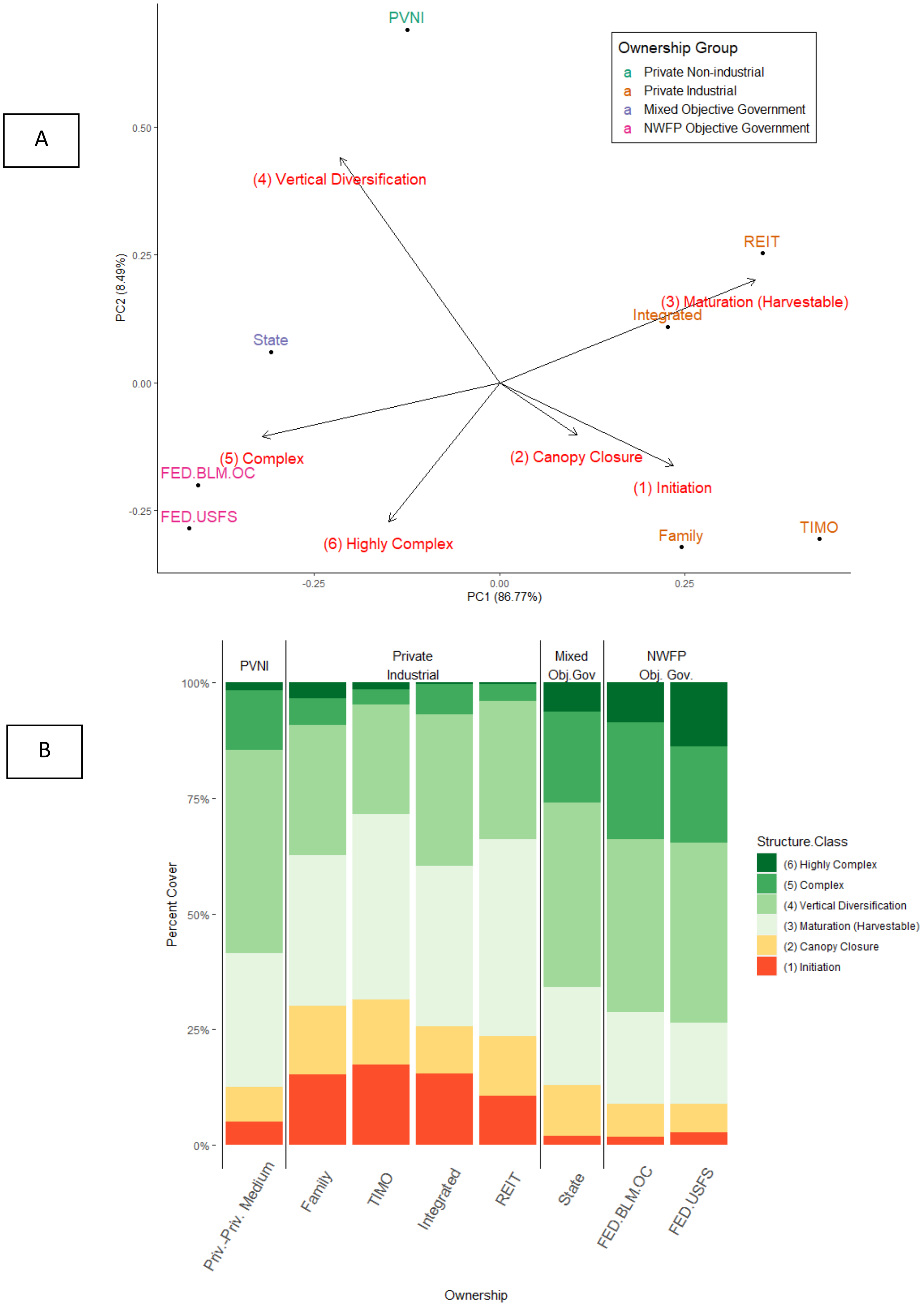


Figure 10. (A) Principal Component Analysis ordination of forest structure classes with Ownership type overlaid on ordination to illustrate relationships. (B) Percentage area in each structure class per Ownership Type and Group. TIMO – Timber Investment Management Organization | REIT – Real Estate Investment Trust. For more information on Ownership type, refer to Table 4 – TNC Ownership Type Descriptions.

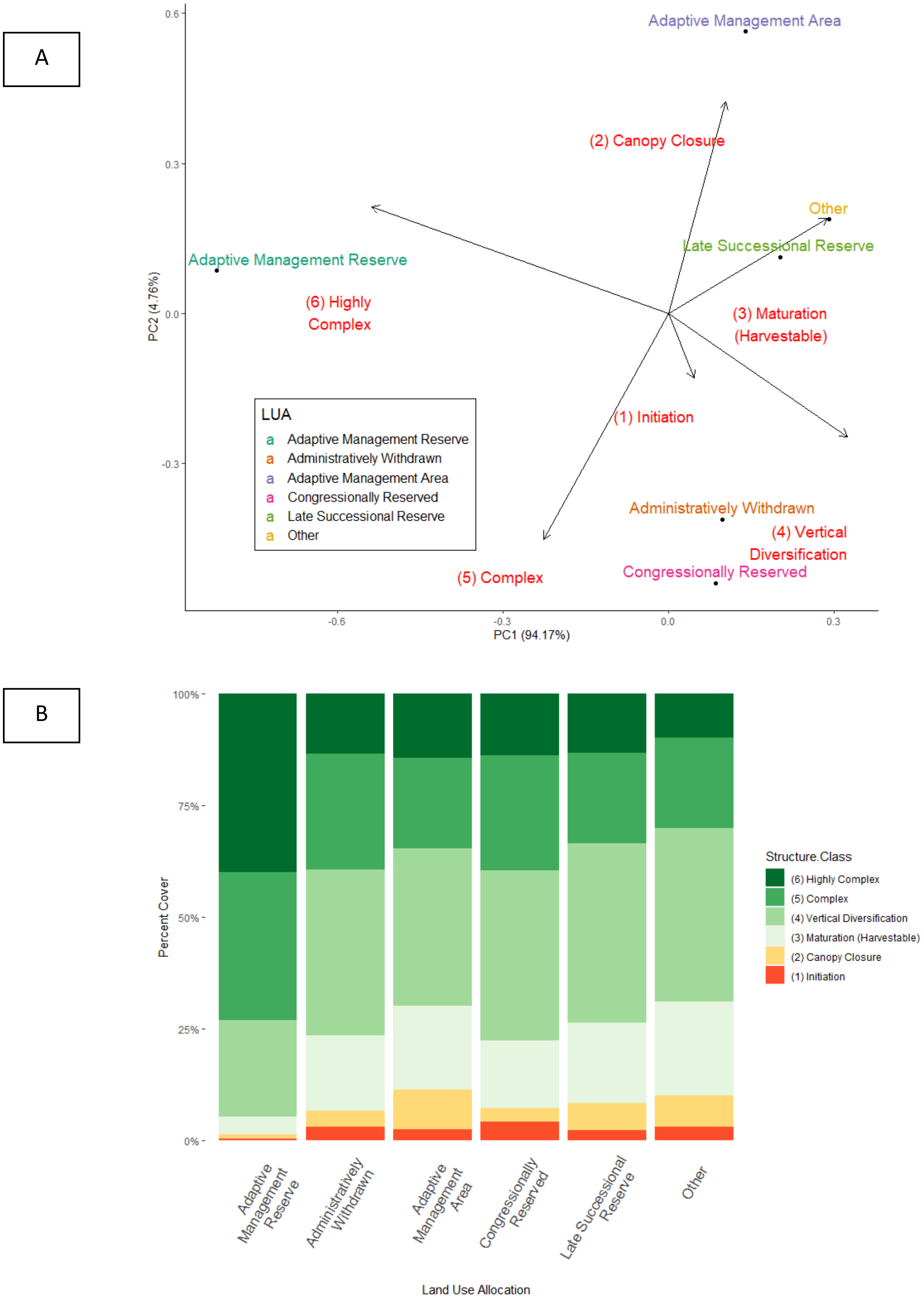


Figure 11. (A) Principal Component Analysis of forest structure classes with Land Use Allocations overlaid on ordination to illustrate relationships. (B) Percentage area in each structure class per Land Use Allocation. For more information on Land Use Allocations refer to Table 5 – NWFP Land Use Allocation Descriptions

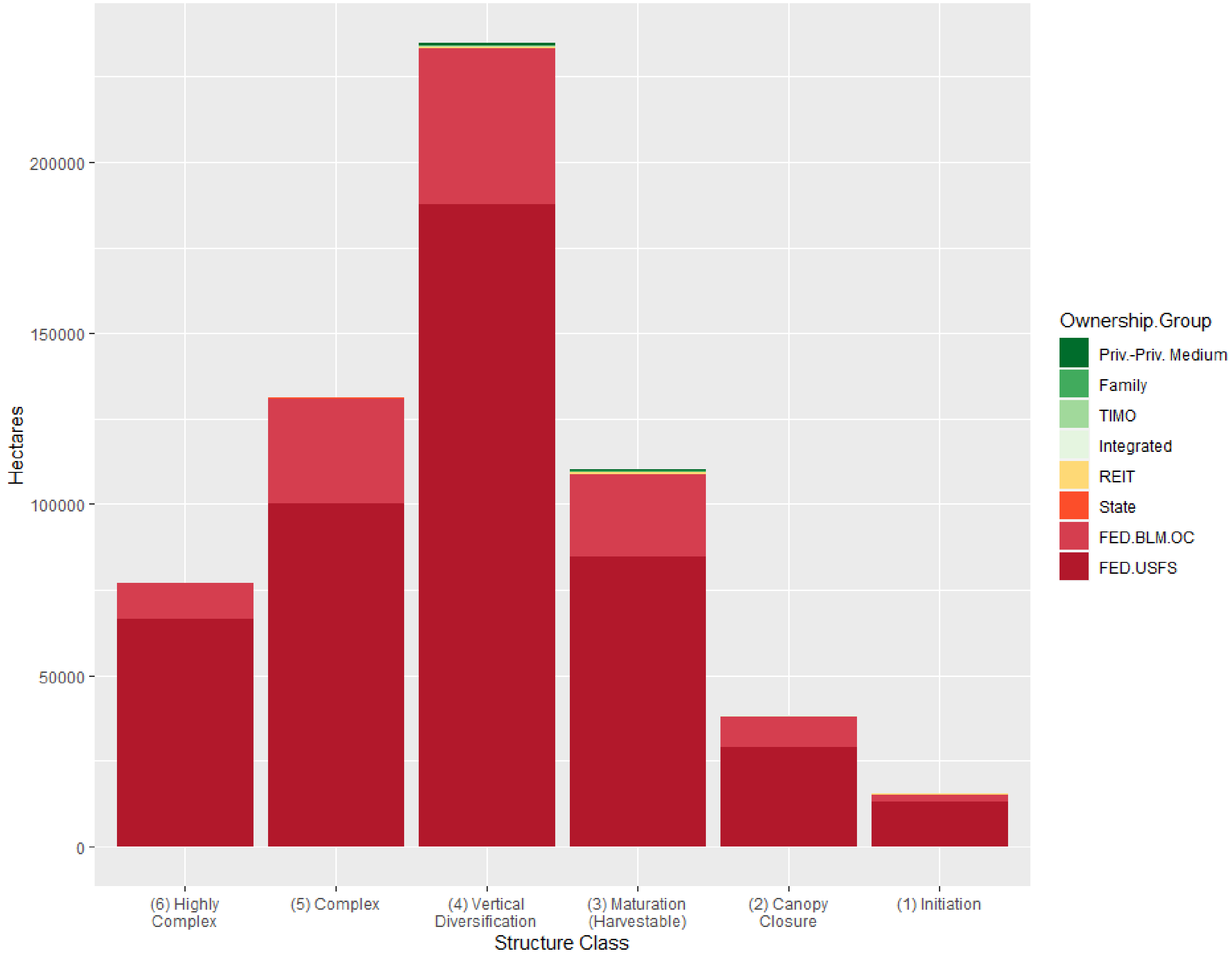


Figure 12. Stacked bar chart illustrating the amount of each ownership type among structure classes.

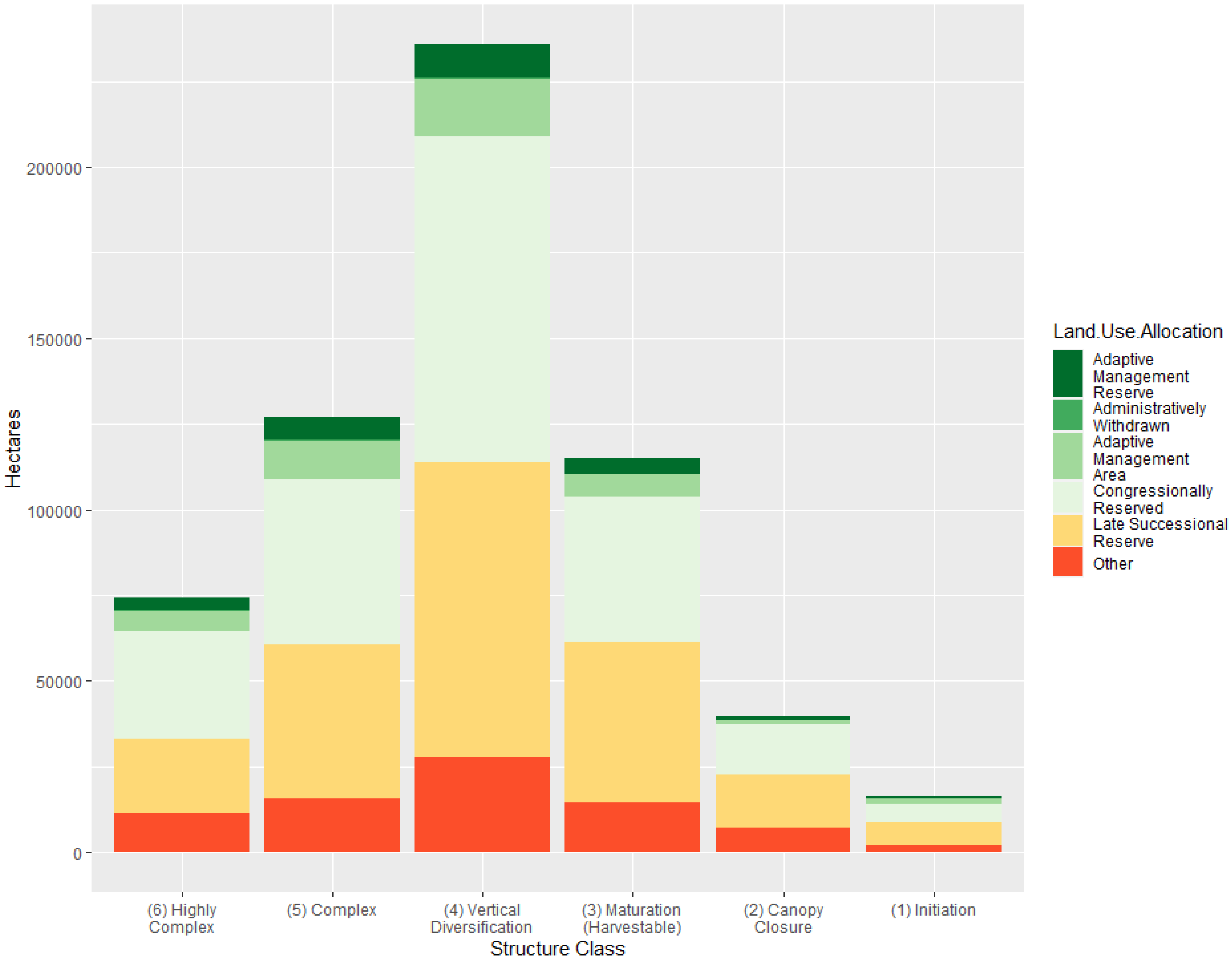


Figure 13. Stacked bar chart illustrating the amount of each land use allocation among structure classes.