AN ABSTRACT OF THE THESIS OF

Tyler C. Harris for the degree of Master of Science in Geography presented on March 8, 2018.

Title: Understanding Patterns of Timber Harvest and their Drivers: A Quantitative Assessment of Forest Governance in the Western Cascades of Oregon.

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Robert E. Kennedy

Effective forest governance is central to the efficient, sustainable, and equitable use of forest resources, yet challenges in assessing forest governance impede efforts to improve it. Contemporary forest governance involves decisions by multiple stakeholders across multiple sectors of economy and society, from local to global scales – making forest governance assessments inherently complex. Here, we assess forest governance in the context of federal forest management in the U.S. Pacific Northwest (PNW), a region whose history is intertwined with that of a storied and significant federal forestry institution – the USDA Forest Service. Our assessment included (1) a review of literature on the emergence of forest governance and existing methodologies for assessing it, (2) a characterization of forest governance in the PNW by way of a synoptic history of federal forestry in the region, (3) the application of a novel remote sensing-based method to detect patterns of timber harvesting in the Western Cascades of Oregon, a physiographic 'sub-region' of the PNW defined in the Northwest Forest Plan (NWFP). We quantified the volume of timber extracted by two harvest methods ('regeneration harvest' and 'partial harvest') in >7,000 individual harvest events which occurred over a 19-year period (1991-2012). Total annual harvest volumes extracted by each harvest method were aggregated within spatially explicit land use allocations where management objectives are prescribed by the NWFP. For three land use allocation types ('Matrix', 'Late-Successional Reserves', and 'Adaptive Management

Areas') we developed hypothetical expectations for timber harvest volumes. Observed patterns of timber harvest volume were evaluated relative to the expected outcomes. Results indicate that some expectations *have* been met (e.g. timber harvesting methods shifted from regeneration harvests to primarily partial harvests, and total harvest volume declined steeply across all land use allocations), while other expectations *have not* been met (e.g. timber harvest volume was significantly lower than expected, especially in 'Matrix' lands where timber extraction is an intended management priority). Additionally, by objectively analyzing timber harvest volume at the scale of individual harvest events, we demonstrate our method's utility in locating 'outlier' harvests – i.e. those that counter general patterns or are otherwise distinct – which serve as points of reference for further research at local scales.

Understanding Patterns of Timber Harvest and their Drivers:
A Quantitative Assessment of Forest Governance in the Western Cascades of Oregon

by

Tyler C. Harris

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APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Tyler C. Harris, Author

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1.1 The Emergence of Forest Governance

Decisions regarding the utilization and conservation of public forest resources have traditionally been the purview of central governments. However, many scholars in the field of forest policy analysis have identified a shift from top-down decision-making by central governments towards *forest governance*, a concept broadly defined as decentralized decision-making by various non-state actors, either independently or in cooperation with the state (Arts & Visseren-Hamakers, 2012; Agrawal et al., 2008; Gluck et al., 2005). Contemporary modes of forest governance have been characterized as ‘multi-actor’ (involving multiple stakeholders), ‘multi-sector’ (occurring across multiple sectors of economy and society), and ‘multi-level’ (involving interactions between actors across international, national and local scales) (e.g. Lemos & Agrawal, 2006; Buizer et al., 2011; Howlett et al., 2010; Mwangi & Wardell, 2012). This shift towards new modes of forest governance is driven by several factors, including (1) demands by civil society for change in how forest resources are valued and managed, and for new policy mechanisms that expand participation by a broader range of stakeholders in forest-related decision-making (Agrawal, 2008); (2) increasing international concern over complex and persistent, forest-related environmental problems, e.g., deforestation, biodiversity loss, and carbon emissions (Jänicke & Jörgens, 2006); (3) perceived difficulties, limitations and failures of international deliberations to address these problems by forming a binding global forest regime (see the United Nations Conference on Environment and Development) (Cashore et al., 2010). Consequently, many international organizations and governments have strived to develop new policy instruments that expand capacity for responding to an increasing variety of social, economic and environmental demands on forests. Examples include legally and non-legally binding international agreements on specific subjects (e.g. the International Tropical Timber Agreement), marketization (e.g. market-driven certification of forest products, and payment for ecosystem services), and participatory forest management (e.g. community-based forestry). Another category of policy instruments is ‘National

Forest Programs' (Gluck, 1999), which are commonly based on principles such as long-term and iterative planning processes, implementation and monitoring of policy, and ecosystem approaches to management that integrate biological conservation and sustainable forestry (Gluck et al., 2005).

1.2 Assessing Forest Governance

Discourse on the emergence of new forest governance arrangements, and associated institutional forms and policy instruments is paralleled by increasing efforts to develop methodologies for assessing forest governance. Considering that "[forest] governance […] operates at every level of human enterprise, be it the household, village, municipality, nation, region or globe" (UNDP, 2006), the choice of appropriate methods, and the scale and/or level at which to apply them are key considerations in assessing forest governance. Existing methodologies are 'practice-oriented', meaning that they function as practical guides for assessing normative concepts of governance quality, e.g. 'good governance' (Arts, 2014; Rametsteiner, 2009) based on value-laden judgements by the organizations who developed them (Giessen & Buttoud, 2014), rely on suites of primarily qualitative indicators of the. At the national/international level, existing methodologies are often e.g. the Analytical Framework for Forest Governance Reforms (The World Bank, 2009); the Framework for Assessing and Monitoring Forest Governance (FAO et al., 2014); the Governance of Forests Initiative Indicator Framework (WRI et al., 2013). These example frameworks seek to establish comprehensive, baseline assessments using widely accepted indicators of 'good governance', such as transparency, accountability, and public participation. Another common approach is the development of 'Criteria and Indicators of Sustainable Forest Management' (e.g. the Montreal Process), and methodologies for criteria/indicator selection (e.g. Mendoza, 2000; Prabhu et al., 2003; Hall, 2001). Methodologies for assessing forest governance at national/international levels are often inapplicable to local or regional scale assessments because they depend on reliable secondary data (i.e. aggregated statistics) or expert consultations that are rarely available at local levels

(Hyden et al., 2008). While many local-level *governance* assessments exist, there are very few examples of tested methodologies for the forest sector (Secco et al., 2014).

1.3 Prelude to Chapters 2 and 3

The objective of this paper is to assess forest governance at the level of federal forest management in the U.S. Pacific Northwest (PNW), a region which presents a salient case study because its history is intertwined with that of the USDA Forest Service (USFS) – a storied and significant federal forestry institution whose approach to forest management has evolved in ways that reflect much of the current scholarly discourse on forest governance. Our assessment begins with Chapter 2, in which we characterize forest governance in the PNW. In section 2.1, we provide a synoptic history of federal forestry in the region. Emphasis is given to the years preceding the 1994 implementation of the Northwest Forest Plan (NWFP), a series of policies that drastically shifted management priorities on federally administered forests of the PNW. The goal is to summarize the changing public values and associated conflicts regarding forest management which culminated in the NWFP's development, as well as the prerequisite institutional changes made by the USFS in order to comply with the mandates of the NWFP. Section 2.3 consists of an overview of the NWFP's objectives and the strategies used to meet them. In section 2.4, we highlight some of the key findings from the NWFP Science Synthesis, an ongoing effort to synthesize the knowledge gained from over twenty years of NWFP implementation monitoring. Altogether, Chapter 2 provides valuable context for understanding present-day forest governance in the PNW, and details of the NWFP which are critical to the analytical portion of our assessment (Chapter 3). In Chapter 3, we apply a novel method of assessing timber harvest volume at multiple scales. The method allows for timber harvest volume to be calculated at the scale of individual harvest events ('local' scale), and aggregated within administrative boundaries (i.e. Northwest Forest Plan land use allocations and physiographic provinces; 'regional' scale). Observed patterns of timber harvest volume serve as quantitative indicators of forest governance.

2. Characterizing Forest Governance in the Pacific Northwest

2.1 Introduction

In the Pacific Northwest (PNW) region of the United States, a large proportion of forest lands – roughly 60% in Oregon and 44% in Washington – are managed by federal agencies, primarily the USDA Forest Service (USFS) (Figure 2). During the 1990s, these lands (as well as federal forest lands in northern California) were at the center of the most intensive forest policy conflict in United States history – the so-called 'timber wars'. At the core of this conflict were changing value systems, new information, and new perspectives regarding federal forest management, which fueled debate over how to balance timber production with protection of forest ecosystems (Swanson & Franklin, 1992). Ultimately, the USFS would be required to make "the largest shift in management focus since its creation, from providing a sustained yield of timber to conserving biodiversity, with an emphasis on endangered species" (Thomas, 2006). The story leading up to this momentous shift is long and complex. In lieu of a comprehensive narrative, which is beyond the scope of this study, and has been provided by other scholars (e.g., Steen, 2004; Williams, 2005), here we offer a concise version that begins with the establishment of National Forest Reserves and subsequent inception of the USFS (in 1897 and 1905, respectively), and ends in the years preceding implementation of the Northwest Forest Plan in 1994. The goal is to highlight the key events, influential legislative acts, and authoritative decisions that together form the basis of present-day forest governance in the Pacific Northwest.

2.2 A Concise History of Federal Forestry in the Pacific Northwest

Over the course of the 19th century, about 70% of forest lands in the United States were transferred to private ownership (MacCleery, 2008). Following the 'closing of the American Frontier' ca. 1890, the United States became an urbanizing, industrial nation where timber was an essential raw material for development (Kennedy & Quigley, 1998). Concerns over uncontrolled short-term exploitation and eventual "timber famine" led to the establishment of National Forest Reserves on remaining federal lands, including 50% of the forest area in the Pacific Northwest (Williams, 1989; Winkel 2014). Soon after, administration of the Forest Reserves was transferred to Gifford Pinchot's newly launched Bureau of Forestry (later renamed the Forest Service), and management of federal forest lands would be guided by his principle of wise use: for "the greatest good for the greatest number in the long run" over the next several decades (~1905-1945). Federal forest management during this period has been characterized as primarily "custodial" (i.e. focused on watershed protection and wildfire suppression), as most of the country's timber needs were supplied by private landowners (Burnett & Davis, 2002). However, with private timberlands heavily exploited during World War II, the post-War economic boom created enormous demand for timber from National Forests (Fedkiw, 1989). The USFS responded by systematically converting older, natural forest stands into plantations, often through high-yield clearcutting (Clary, 1986) (note the near ten-fold increase between 1945-1965 shown in Figure 1).

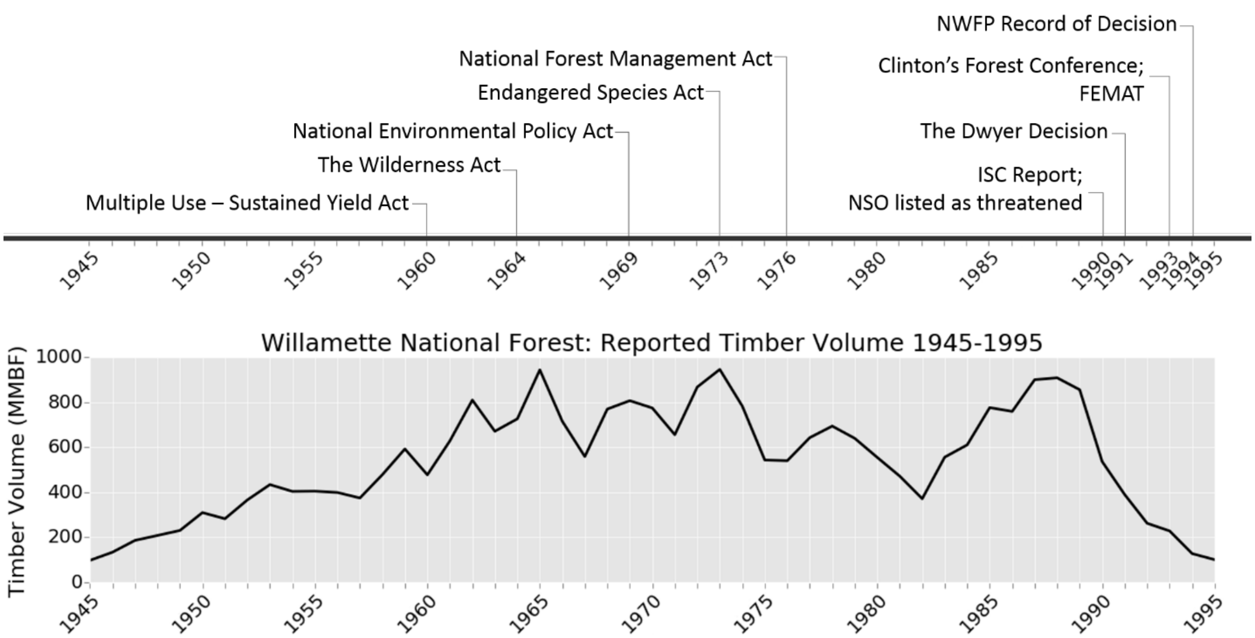


Figure 1. (Top) Timeline of selected events and legislative acts that impacted federal forestry in the Pacific Northwest (1945-1995); (bottom) annual timber volume reported by Willamette National Forest, measured in million board-feet (MMBF).

In parallel to the timber boom, there was a recreation boom as an increasingly mobile and affluent population sought outdoor leisure in the National Forests. Ostensibly, passage of the Multiple Use – Sustained Yield Act (MUSYA) in 1960 codified balanced management of timber and non-timber resources – but from a more strategic perspective, MUSYA "provided the Forest Service with the legal cover it needed to continue its campaign of timber production while publicly embracing multiple use rhetoric" (Burnett & Davis, 2002). While opposition to high-yield, short-rotation forestry began as early as the 1950s, it was not until the "second wave of environmentalism" in the 1960s and 70s that the environmental agenda gained momentum. A series of legislative acts passed during the 1970s placed significant environmental protection obligations on federal agencies; namely, the National Environmental Policy Act (1970), which mandated the disclosure of impacts of all federal management projects, the Endangered Species Act (ESA) of 1973, and the National Forest Management Act (1976), which required the Forest Service to develop land management plans that involved public participation, and enabled clearcutting only when in accordance with these plans. Together, these policies gave environmental organizations leverage to force changes in forest management policy. The 1970s also saw a proliferation of research on late-successional and old-growth forest ecology, and management practices of federal agencies – particularly clearcutting of old-growth forests, became increasingly controversial (Winkel, 2014). By 1990, an intense period of legal battles between environmental NGO's and federal agencies had become known as the "timber wars". The culmination of this turmoil occurred on May 23, 1991 when U.S. District Court Judge William Dwyer ruled in favor of the National Audubon Society and the Sierra Club Legal Defense Fund, who had sued the Forest Service for inadequacies in their management plan for protection of the now threatened northern spotted owl. In 1993, with timber harvesting on National Forests effectively halted, President Clinton convened the Forest Conference in Portland, Oregon where agency personnel, research scientists, and stakeholders gathered to discuss how to move forward. Following the Conference, a group of scientists known as the Forest Ecosystem

Management Assessment Team (FEMAT) was assembled, and given the weighty task of developing new management plan alternatives that would:

1. consider human and economic dimensions of the problem;
2. protect the long-term health of forests, wildlife, and waterways;
3. be scientifically sound, ecologically credible, and legally responsible;
4. produce a predictable and sustainable level of timber sales and non-timber resources that would not degrade the environment;
5. end gridlock and emphasize collaboration among federal agencies.

The creation of FEMAT was an unprecedented approach to forest policy-making in that scientists, rather than managers were tasked with developing options for the President to consider (Moseley and Winkel, 2014). “Alternative 9”, which was considered to be the option that best balanced the objectives to provide timber, restore ecological processes, and maintain biodiversity, was selected and set forth in the 1994 Northwest Forest Plan Record of Decision (ROD) (USFS, 1994a). Although the Forest Service had previously been challenged to adapt their management approaches to accommodate an increasing number and variety of social, economic and environmental pressures, it was not until the Northwest Forest Plan was implemented that the relative autonomy in decision-making the agency had enjoyed for so long was truly undermined (Maier & Abrams, 2018).

2.3 The Northwest Forest Plan

The Northwest Forest Plan (NWFP) is a series of federal policies and guidelines that amended the resource management plans of 19 National Forests and 7 Bureau of Land Management districts within the range of the northern spotted owl (24.5 million acres in total). Its implementation initiated a shift in management priorities on federally administered forests from the provision of a predictable and sustainable volume of timber to protection of late-successional and old-growth forests, and maintaining biodiversity associated with native species and ecosystems (Thomas, 2006). Like all of the alternatives, it designates a system of distributed land use allocations (Figure 3) whose management priorities are described in an attachment to the ROD known as the "Standards and Guidelines" (USFS, 1994b). A distinguishing feature of Alternative 9 was that it included an additional land use allocation type: Adaptive Management Areas, within which the management objective is to develop and test new management approaches to integrate ecologic and economic objectives. Thus, the NWFP was to be implemented using an adaptive management strategy in which forest resources are inventoried and monitored, management outcomes are assessed, and policy is periodically adjusted (FEMAT, 1993). While many components of the adaptive management strategy have yet to be successfully implemented (Moseley & Winkel, 2014), we have learned much from the policy effectiveness monitoring component.

2.4 Key Findings from the Northwest Forest Plan Science Synthesis

The Northwest Forest Plan Science Synthesis (Spies at al., 2016) is an ongoing effort to synthesize more than 20 years of NWFP-related science and policy effectiveness monitoring reports. Here we highlight three key findings which are relevant for this study: (1) only 1.2-1.3% of existing old-growth forest on federal lands at the time of NWFP implementation has been lost to timber harvest, although this level of protection is not mandated (Davis et al., 2015); (2) of the 1.1 billion board-feet expected to be harvested annually during the first decade following NWFP implementation, only 54 percent was ever cut (Charnley et al., 2006); (3) Implementation of the NWFP has varied across the broad and diverse geography to which it applies. This can be attributed to variations in how plan details have been interpreted by different forests, districts, and changing personnel over time. The consequences of this now and into the future are not clear (Spies, et al. 2016).

These findings indicate that timber management under the NWFP has transpired in unexpected ways, and that this could be related to inconsistent implementation of NWFP policy. In order to corroborate this idea, we developed a method of objectively assessing timber management outcomes at scales commensurate with timber harvest decision-making.

3. Assessing Forest Governance in the Western Cascades

3.1 Introduction

Effective forest governance is central to the efficient, sustainable, and equitable use of forest resources, yet challenges in assessing forest governance impede efforts to improve it. Because contemporary forest governance involves decisions by multiple stakeholders across multiple sectors of economy and society, from local to global scales, assessing forest governance is inherently complex. Assuming that “[forest] governance […] operates at every level of human enterprise, be it the household, village, municipality, nation, region or globe” (UNDP, 2006), the choice of appropriate methods, and the scale and/or level at which to apply them are key considerations in assessing forest governance. Here, we quantitatively assess patterns of timber harvesting in the Western Cascades of Oregon, a ‘physiographic province’ defined in the Northwest Forest Plan (NWFP). Observed patterns of timber harvesting are interpreted relative to the outcomes expected if federal forest lands in the Western Cascades had been managed strictly according to the NWFP land use allocation system. In this way, discrepancies between observed patterns of timber harvesting and expected outcomes serve as indicators of forest governance processes that may be contributing to geographic variation in NWFP implementation and outcomes.

3.2 Methods

3.2.1 Overview

Using time-series datasets derived from remote sensing and forest plot data (see Section 3.2.4 for details), we quantified the volume of timber extracted in >7,000 individual harvest events occurring across USFS lands in the Western Cascades of Oregon from 1991-2010 (Figure 3). Our method allows for timber harvest volume to be calculated at the scale of individual harvest events (‘local’ scale), and aggregated within administrative boundaries (i.e. NWFP land use allocations; ‘local’ scale) or any spatially explicit area (e.g. the Western Cascades; ‘regional’ scale). Additionally, timber volume extracted by two harvest methods: regeneration harvest (“clearcut”) and partial harvest (“thinning”) were calculated separately in order to detect shifts in timber management practices (Figure 4a). We evaluate observed patterns of timber harvest volume with regard to expectations developed from NWFP policy documentation, and ascribe differences to governance processes known to be at play in the region.

3.2.2 Expectations for Harvest Volume within NWFP Land Use Allocations

Based on review of NWFP documentation pertinent to the LUA system – the Record of Decision and accompanying Standards and Guidelines (USFS, 1994a; 1994b), we established expectations for harvest volumes if timber management practices were performed strictly according to the priorities prescribed within each land use allocation type. Expectations were developed only for allocations that allow for timber management (see map of land use allocations; Figure 2). It is important to note that another land use allocation type – riparian reserves – were not included in this study due to inconsistencies in defining and delineating the stream network on which riparian reserves are based, and varying site-specific definitions (Moeur et al., 2005).

Matrix

While Matrix lands have important ecological objectives, the primary management objective is to provide timber as a commodity. Matrix lands are intended to allow for stand-replacing logging through regeneration harvest. They also constitute 55% of the total land use allocation area considered in this study. Thus, our expectations for Matrix lands are (1) they will yield the highest proportion of timber volume; (2) most of this volume will come from older, high-volume stands; (3) the dominant harvest method will be regeneration harvest.

Late-Successional Reserves

The objective of LSRs is to protect and enhance conditions of late-successional and old-growth ecosystems. According to the NWFP Standards & Guidelines, this entails timber management through thinning, but only in forest stands up to 80 years old. Thus, our expectations for LSRs are (1) they will yield a low proportion of timber volume compared to Matrix lands; (2) most of this volume will come from younger, relatively low-volume stands; (3) when harvests do occur, the dominant harvest method will be partial harvest.

Adaptive Management Areas

The objective of AMAs was to develop and test management approaches that integrate ecologic and economic goals. Within the Western Cascades there are two: the Central Cascades AMA and the Little River AMA. For the Central Cascades AMA, management objectives emphasize accelerating the development of late-successional forest conditions in young and mature stands. For the Little River AMA, timber management emphasizes integration of intensive timber production with restoration of riparian habitat. Because these AMAs comprise only 7% of the total land use allocation area considered in this study, and because the objectives for each AMA differ, our expectations are (1) a relatively small proportion of volume will be extracted; (2) this volume will be extracted by a mix of both regeneration and partial harvests.

3.2.3 Study Area

The Western Cascades of Oregon is one of 12 “physiographic provinces” defined in the NWFP based on common biophysical characteristics. It encompasses 30,000 km^2 of mountainous terrain that is 96% forested, and 75% federally managed (primarily by the USDA Forest Service; Figure 3). This region contains some of the most productive conifer-dominated forests in the world (Waring & Franklin, 1979), and a high proportion of the remaining old-growth forests within the NWFP area (Davis et al., 2015). National Forests within the Western Cascades include Mt. Hood, Willamette, Umpqua, and the eastern portion of Rogue River-Siskiyou. Historically, Willamette and Umpqua produced high volumes of timber relative to other forests in the National Forest system, and continue to do so today (Rakestraw, 1991). The Western Cascades was also a site of research that contributed to the development of the NWFP during the "timber wars" era (e.g., Forsman, 1980; Forsman et al., 1984; Meslow et al., 1992).

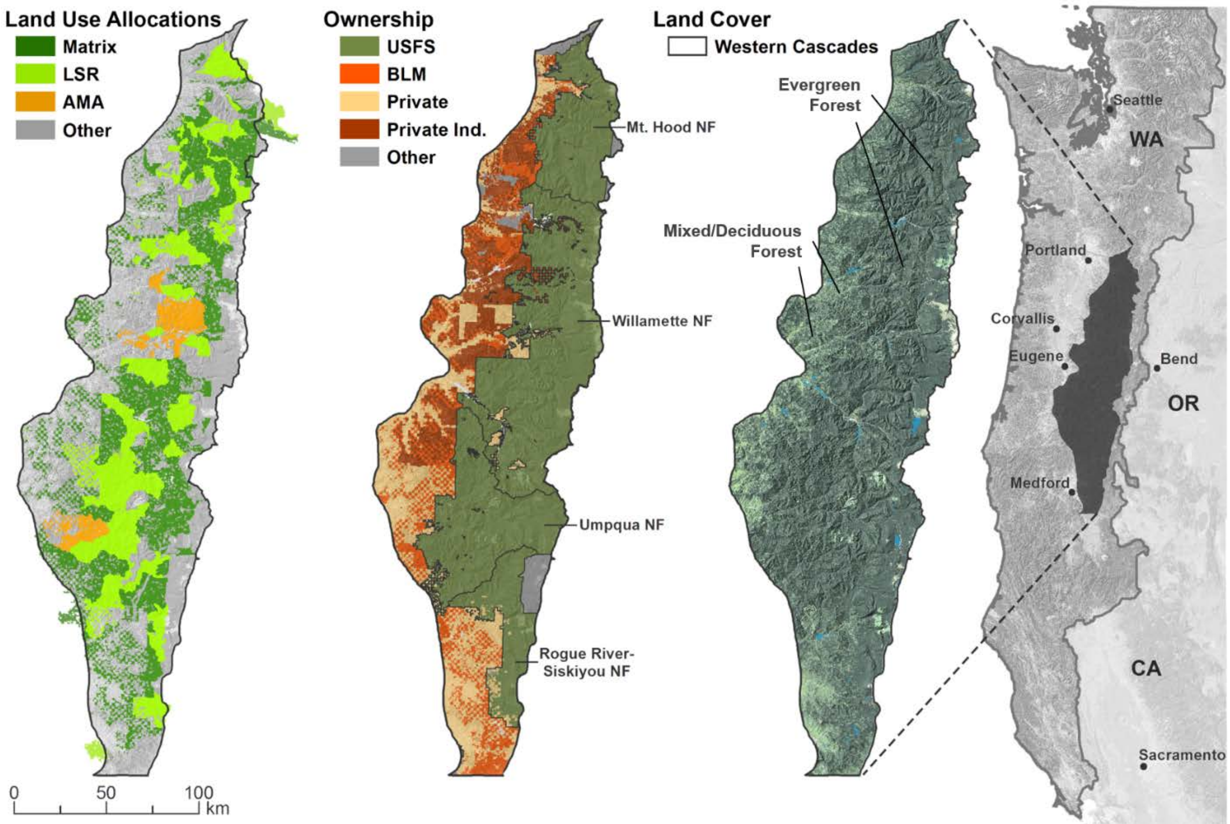


Figure 2. From left to right, maps showing NWFP land use allocations, ownership and land cover within the Western Cascades of Oregon. Note location of the Western Cascades within the larger NWFP area.

3.2.4 Datasets

Our analyses rely primarily on two time-series raster datasets (Figure 3):

1) 30-meter resolution maps of timber harvest events, which are the ultimate data product of LandTrendr (Landsat-based Detection of Trends in Disturbance and Recovery), a land cover change detection algorithm that performs temporal smoothing of pixel-scale spectral variation in Landsat Thematic Mapper time-series images in order to distinguish trends from annual noise (Kennedy et al., 2010; 2015).

2) 30-meter resolution maps of timber volume produced using the gradient nearest neighbor (GNN) imputation methodology, which links forest inventory plot data with a suite of geospatial predictor variables to produce regional estimates of species composition, structure, and other forest characteristics (Ohmann et al., 2012; 2014). We utilized maps of a single GNN variable called “merchantable volume”, which is based on two tree measurements (diameter at breast height, and total tree height) for years 1990-2010.

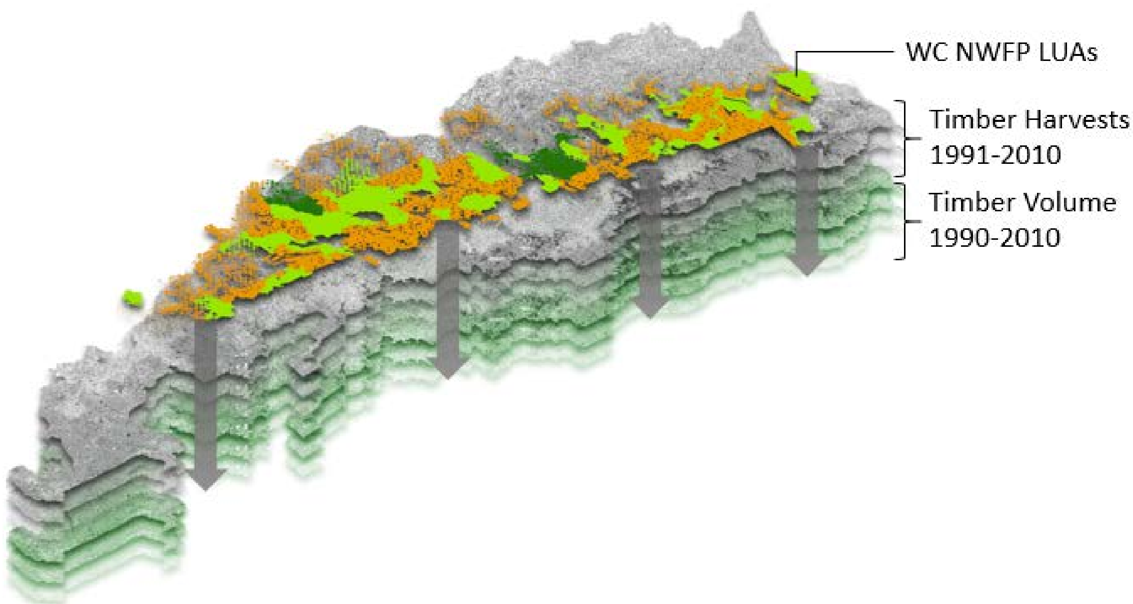


Figure 3. Schematic of harvest volume summary analysis method. Timber harvest volume calculated at the scale of individual harvest events was aggregated by Northwest Forest Plan land use allocations.

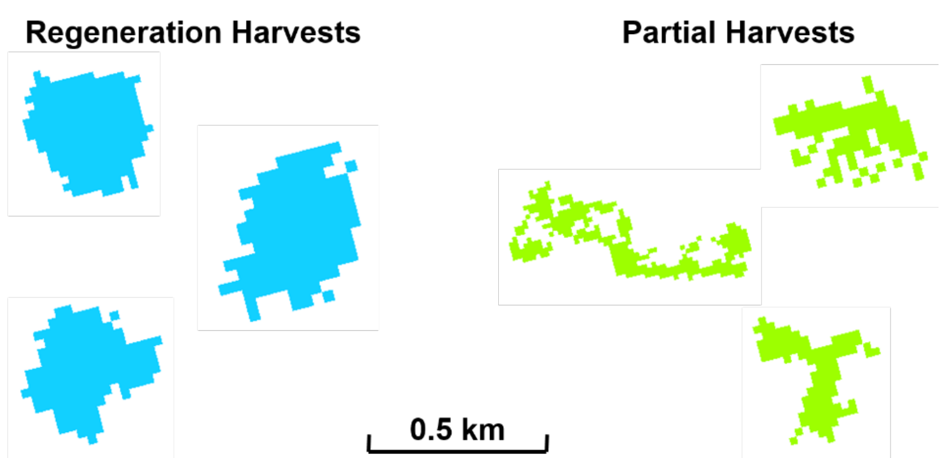
Several other publically available vector datasets were used for delineating the bounds of our study, and for summarizing harvest volumes by ownership, administrative boundaries, and NWFP land use allocations (Figure 3). Additionally, tabular datasets gleaned from annual reports published by the USFS were used to validate our timber harvest volume calculation method (by comparing our observed volume to volume reported by the USFS) and to compare observed volume to expected volume published in NWFP documentation (USFS, 1994a; 1994b).

3.3 Analysis

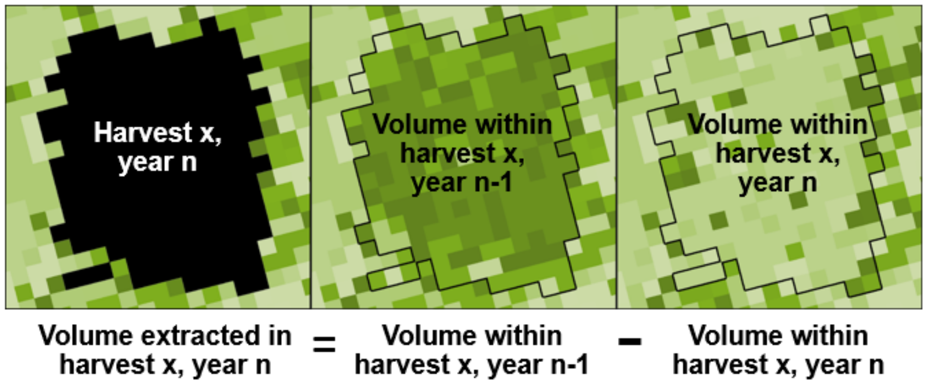
3.3.1 Timber Harvest Volume Calculation and Validation

Our first objective was to validate our method of timber harvest volume calculation so that it could be reliably applied across the Western Cascades. The analytical steps described here are the foundation of the other analyses that follow. From LandTrendr attributed disturbance maps for 1991-2010, we extracted only regeneration harvest and partial harvest events within the Western Cascades (Figure 4a). To calculate the volume extracted in each harvest event, we used simple Map Algebra to subtract the sum of GNN volume pixels within each harvest "patch" in the year after the harvest event from the sum of GNN volume pixels within each harvest "patch" in the year before the harvest event (Figure 4b). Because our method requires timber volume information for the year before harvest events, our calculations of harvested volume are limited to 1991-2010 (Figures 3; 4b). An additional step was to convert the default units of GNN merchantable volume (cubic meters per hectare) to board-feet (the standard unit of timber volume used in forestry) to allow for comparison to harvest volumes reported by the USFS (Figure 4c).

(a)



(b)



(c)

$$\textit{Harvest volume}\ \frac{board\text{-}feet}{pixel} = \frac{harvest\ volume\ \frac{m3}{hectare}\ x\ 900\frac{m2}{pixel}}{10{,}000\frac{m2}{hectare}}\ x\ 423.766\ \frac{m3}{board\text{-}foot}$$

Figure 4. (a) two types of timber harvest distinguished by the LandTrendr algorithm; (b) illustration of harvest volume calculation for a single harvest event; (c) conversion of GNN merchantable volume units from cubic meters per hectare to board-feet per pixel.

The final step in this analysis was to label each harvest event with a code representing the forest, or other administrative unit from which timber volume was extracted, which allowed for total annual volumes to be calculated for any administrative unit. To validate our harvest volume calculation method, total annual volumes were calculated for Willamette National Forest (Figure 6), and compared to annual volumes reported by this forest. Additionally, annual values for estimates of timber volume expected to be harvested (referred to as probable sale quantity in the NWFP documentation) were gleaned from planning documents specific to Willamette National Forest.

3.3.2 Timber Harvest Volume Summaries by NWFP Land Use Allocations

Summarizing harvest volumes by land use allocations relies on the same method described in section 3.1.4. For this analysis, timber volume calculations were separated by harvest type to allow for detection of shifts in timber management practices, or any unexpected patterns of harvest methods (in terms of the LUA type on which they occurred).

3.3.3 Timber Harvest Volume at the Patch-Level

Analyses in sections 3.3.1 and 3.3.2 involve aggregating harvest patch-level timber volumes by administrative boundaries. For this analysis, timber harvest volume remained disaggregated, and we focused on comparing two metrics of individual harvest events: (1) the volume within the bounds of a harvest event preceding the actual harvest ("stand volume"); (2) the volume of timber extracted in each harvest event. Assessing patterns in these two patch-level metrics allowed us to assess patterns of harvest intensity, as well as the characteristics of forest stands targeted for harvest (in terms of age or maturation, for which total volume within a stand serves as a reasonable proxy).

3.3.4 Uncertainty and Accuracy Assessment

The raster time-series datasets on which our harvest volume analyses rely are based on models (LandTrendr and GNN) whose accuracy is affected by the parameters used to constrain them (Kennedy et al., 2018). The LandTrendr algorithm uses 'temporal segmentation' to identify key vertices in annual spectral variation of pixels (whose values represent the Normalized Burn Ratio, a commonly used vegetation index), thereby extracting the dominant signal from the relatively noisy annual change (Kennedy et al., 2010; 2012). Through additional steps, temporally cohesive change 'patches' are labeled with a disturbance agent (Cohen et al., 2010; Kennedy et al., 2012). For the purposes of this study, we extracted only timber harvest events (attributed as either 'regeneration harvest' or 'partial harvest'), which are temporally abrupt, and spectrally obvious (given that they are characterized by relatively high disturbance magnitude, and typically occur in closed-canopy forests). While uncertainties in imputed map predictions arise from a variety of sources (Bell et al., 2015) accuracy assessments by those who developed the GNN method indicate good agreement between predictions and observations in closed-canopy forests of the Pacific Northwest, especially in the western Cascade Mountains (Ohmann & Gregory, 2002). Given that our study was conducted in a region considered to be favorable to the GNN method, and that our analyses are focused on USFS lands where forest inventories that serve as input data for GNN are consistently performed, we have high confidence in the accuracy of our timber volume calculation methods. Figure 5 represents an accuracy assessment for the GNN volume variable used in this study. Because both observed volume (in this case, forest inventory plot data) and predicted volume are both subject to error, we followed (Ohmann et al., 2012) in using the geometric mean functional relationship (GMFR), which measures the symmetrical relationship between two variables.

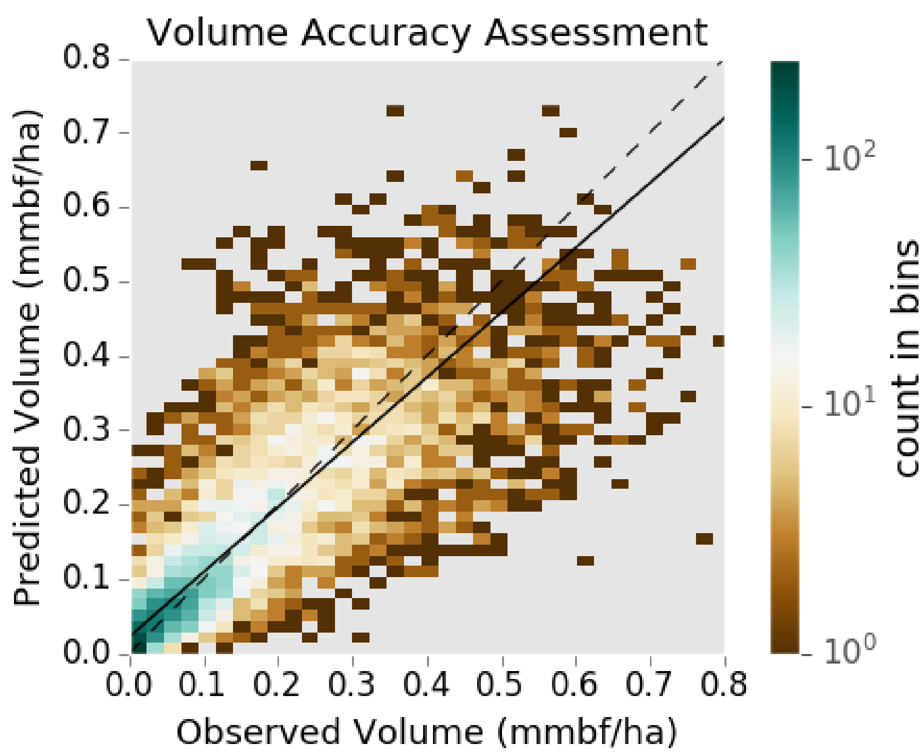


Figure 5. Accuracy assessment for timber volume predicted using the gradient nearest neighbor imputation methodology (GNN). Dashed line represents 1:1, solid line represents the geometric mean functional relationship (GMFR) regression line. RMSE = 0.61.

The analyses performed here are based on harvest volumes calculated at the scale of harvest events that average ~10 hectares in size, and aggregation of timber harvest volumes within NWFP land use allocations which average ~600 hectares in size. At these scales, agreement between observed and predicted volume remains high.

3.4 Results & Discussion

3.4.1 Timber Harvest Volume Calculation Method

Our method of calculating timber harvest volume produced results that track well with reporting by Willamette National Forest for the 1991-2010 observation period (Figure 6a). Following several decades of high timber volume production, a steep decline began in 1988. In the remaining years preceding implementation of the NWFP in 1994, several events contributed to the steep decline in timber volume, including a series of lawsuits brought against federal agencies over inadequate protection of the northern spotted owl and its habitat, the 1990 listing of the northern spotted owl as threatened under the Endangered Species Act, and the ensuing injunction by U.S. District Judge William Dwyer in 1991, which effectively halted timber harvest on federal lands in the region. Following implementation of the NWFP, timber harvest volumes were expected to differ from probable sale quantity because federal agencies needed time to complete required surveys and assessments in order to prepare timber sales consistent with the NWFP standards and guidelines. In 1995, agencies were expected to offer timber sales amounting to 60 percent of PSQ; 80 percent of PSQ in 1996; and volumes equivalent to PSQ thereafter (Grinspoon et al., 2016). On Willamette National Forest, the volume harvested from Matrix lands and Adaptive Management Areas reached a peak of only 52 percent of probable sale quantity over the post-NWFP period (see Figure 6c, year 2005). The spike in 1999 reflects an adjustment made to PSQ in 1998 based on improved estimation methods. The discrepancy between PSQ and the actual volume harvested reflects some of the assumptions on which PSQ estimates were based: (1) during the first decade, about half of the total harvest would come from forests > 200 years old (generally considered old-growth); (3) the main harvest method would be regeneration harvest (USFS, 1994).

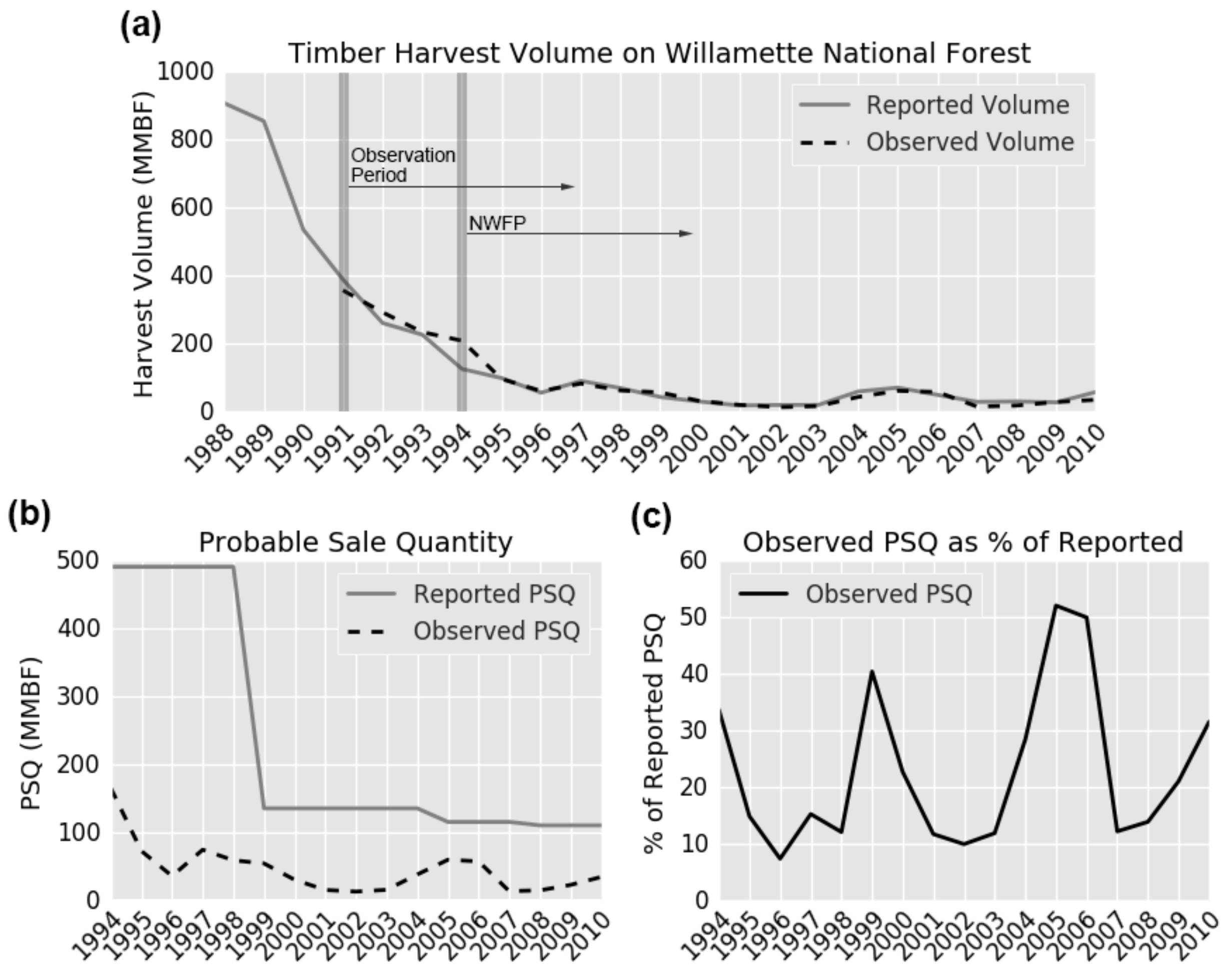


Figure 6. (a) Observed annual timber volume compared to reported volume; note the decline starting at peak harvest volume in 1988 and continuing through NWFP implementation; observed volume includes harvests on all three land use allocation types; (b) comparison of observed and reported probable sale quantities; note that observed PSQ only includes harvest volume on Matrix lands and Adaptive Management Areas, as these are the LUA types that formally contribute to PSQ estimates; (c) observed PSQ as a percentage of reported PSQ.

3.4.2 Timber Harvest Volume Summaries by NWFP Land Use Allocation

Summarizing timber harvest volume by land use allocation, and separating by harvest method allows for evaluating our observations against the expectations established in section 3.1.1. Of the total ~1500 MMBF harvested in the Western Cascades in the post-NWFP period of observation (1995-2010), Matrix lands contributed 81 percent, which meets our expectation that most timber volume would come from this LUA type (Figure 6a). Our expectation regarding harvest method on Matrix lands was partially met in that a majority of timber volume was extracted by regeneration harvest, but only for the first 9-10 years of NWFP implementation (Figures 7b; 8); by 2002 timber management practices began to shift toward partial harvest, and annual harvest volume remained below 90 MMBF through the rest of the observation period (Figure 7c). From 2002-2010, partial harvests on Matrix lands accounted for 68 percent of the ~700 MMBF total, highlighting that timber resources on Matrix lands have not been extracted to the extent allowed by the NWFP, nor by the expected harvest method. Regarding Late-Successional Reserves, our expectations for overall harvest volume were met in that they yielded much less than Matrix lands. However, given that LSRs occupy over 30% of the Western Cascades, the proportion of volume yielded is surprisingly low.

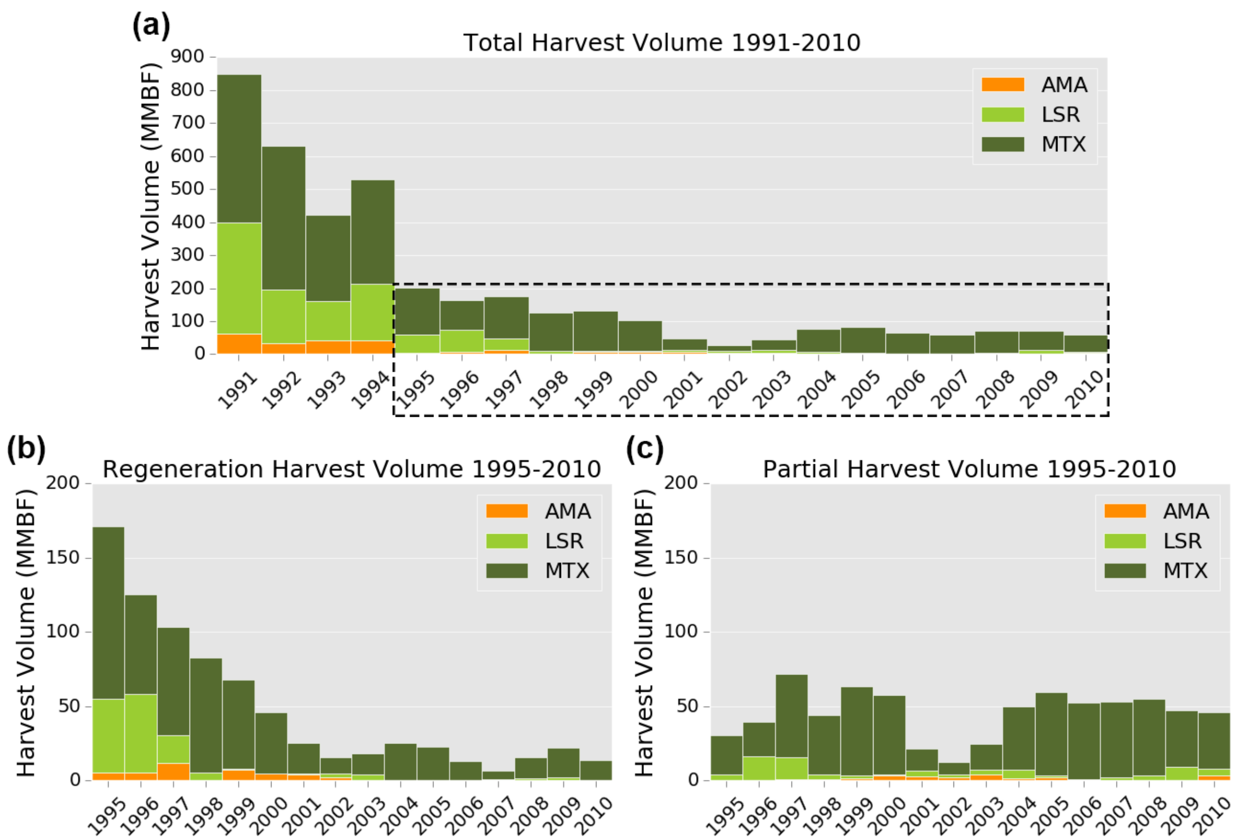


Figure 7. Annual proportions of timber harvest volume in million board-feet (MMBF) for land use allocations where timber management is typically permitted: Adaptive Management Areas (AMA), Late-Successional Reserves (LSR), Matrix lands (MTX). (a) Total harvest volume for the full 1991-2010 period; (b) volume from regeneration harvest only; (c) volume from partial harvest only. Note that (b) and (c) are subsets indicated by the dashed rectangle, which facilitates comparison between regeneration harvest and partial harvest volumes in the post-NWFP period.

Our findings corroborate NWFP monitoring reports which point to appeals and litigation over timber sales that target late-successional and or old-growth forests (Grinspoon et al., 2016) as a primary reason for the scarcity of timber sales on these allocations. Another interesting observation is that there appears to have been a three to four-year lag period following NWFP implementation in which regeneration harvests continued to occur on LSRs (Figures 7b; 8). This could reflect some leniency described in the Record of Decision, which suggests that timber sales offered on LSRs before the ROD would be allowed to proceed, because the acreage of LSRs was increased between the Draft and Final SEIS, and cumulative impacts of these harvests on forest ecosystems was considered to be negligible (USFS, 1994a). Our observations for Adaptive Management Areas show very low timber volume extraction, which was expected given their low proportional area. In terms of harvest method on AMAs, the only clear pattern is that no regeneration harvests occurred after 2002. Interestingly, there seems to have been a “heyday” of timber management activity on AMAs in the first decade following NWFP (Figures 7b; 7c; 8). Somewhat more striking patterns emerge if timber volumes are aggregated into four-year periods (Figure 8). Interestingly, despite their significant difference in total area, volumes extracted from AMAs and LSRs by partial harvests were nearly on par for the 1999-2002, 2003-2006 and 2007-2010 aggregate periods. Over the course of the 1991-2010 study period, we observe a near reversal of timber harvest method (from regeneration harvest to partial harvest).

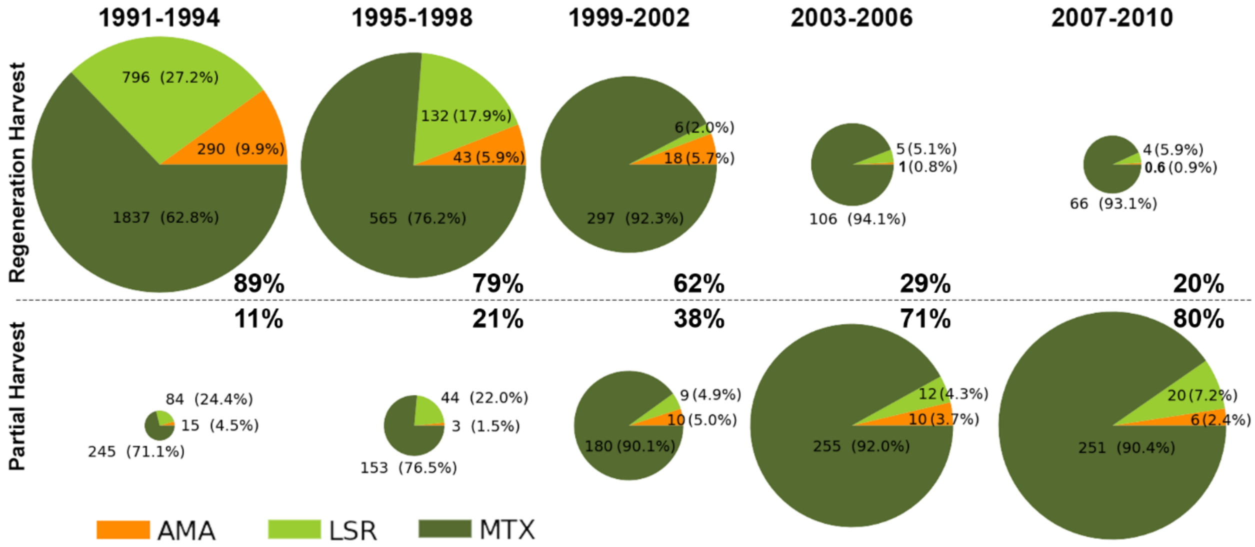


Figure 8. Harvest volumes on USFS lands in the Western Cascades aggregated in four-year periods; separated by harvest type (regeneration harvest (top); partial harvest (bottom)) and NWFP land use allocations (see color key in bottom left corner). Pie charts are scaled according to the proportion of total harvest volume extracted by each harvest type in a given period.

3.4.3 Patch-Level Volume Analysis

In previous analyses, emphasis has been on total volume extraction within land use allocations, and separated by harvest method. Here we consider all harvest events objectively and without regard to harvest method (although harvest method is generally indicated by harvest 'intensity' – the quantity of volume before harvest relative to the quantity extracted. Here we plotted the volume within stands preceding each harvest (x-axis) against volume extracted in each harvest event (y-axis) (Figure 10; see Figure 9 for guidance on how to interpret the position of each harvest even within these plots). We observed a general pattern of more frequent, higher intensity harvests in years preceding the NWFP, and less frequent, lower intensity harvests across all land use allocations following NWFP implementation (Figure 10). We also see the same prominence of Matrix lands previously noted. Years 2000-2003 show a remarkable drop in harvest frequency across all LUAs. Following this lull in timber management activity, Matrix lands continued to be the primary source of timber volume, whereas partial harvests became the primary harvest method, indicated by the frequency of dark green dots that are dispersed further from the dashed 1:1 line, and further along the x-axis. Distance along the x-axis is also indicative of the age of the forest stand targeted for harvest (as age generally correlates with volume), as well as size of the harvest patch.

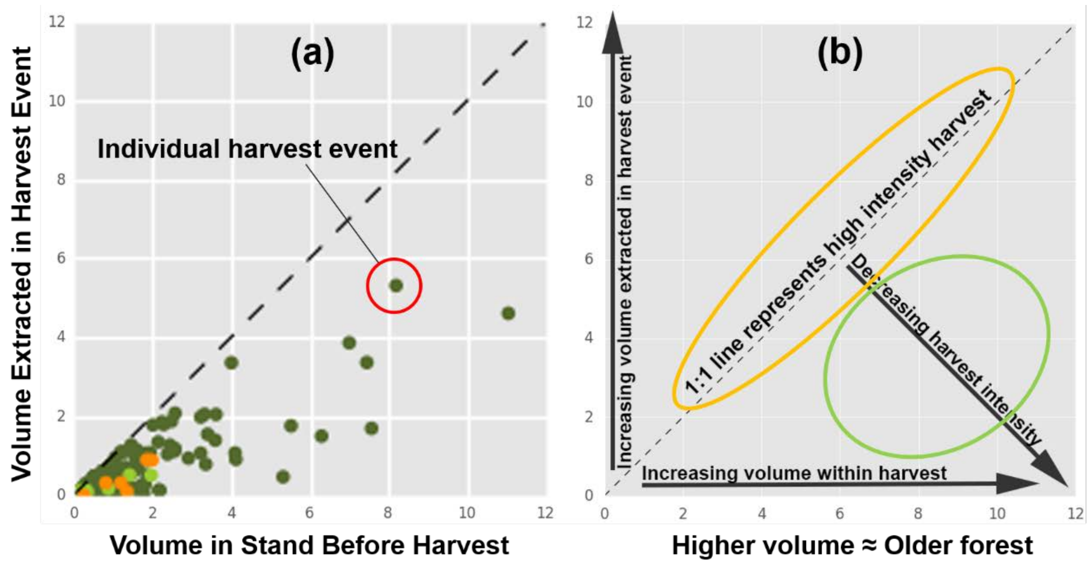


Figure 9. Interpretive aid for Figure 10. (a) Each dot corresponds to an individual harvest event; (b) harvests positioned within the orange oval are relatively intense (likely regeneration harvests); harvests positioned within or near the green oval are less intense (likely partial harvests).

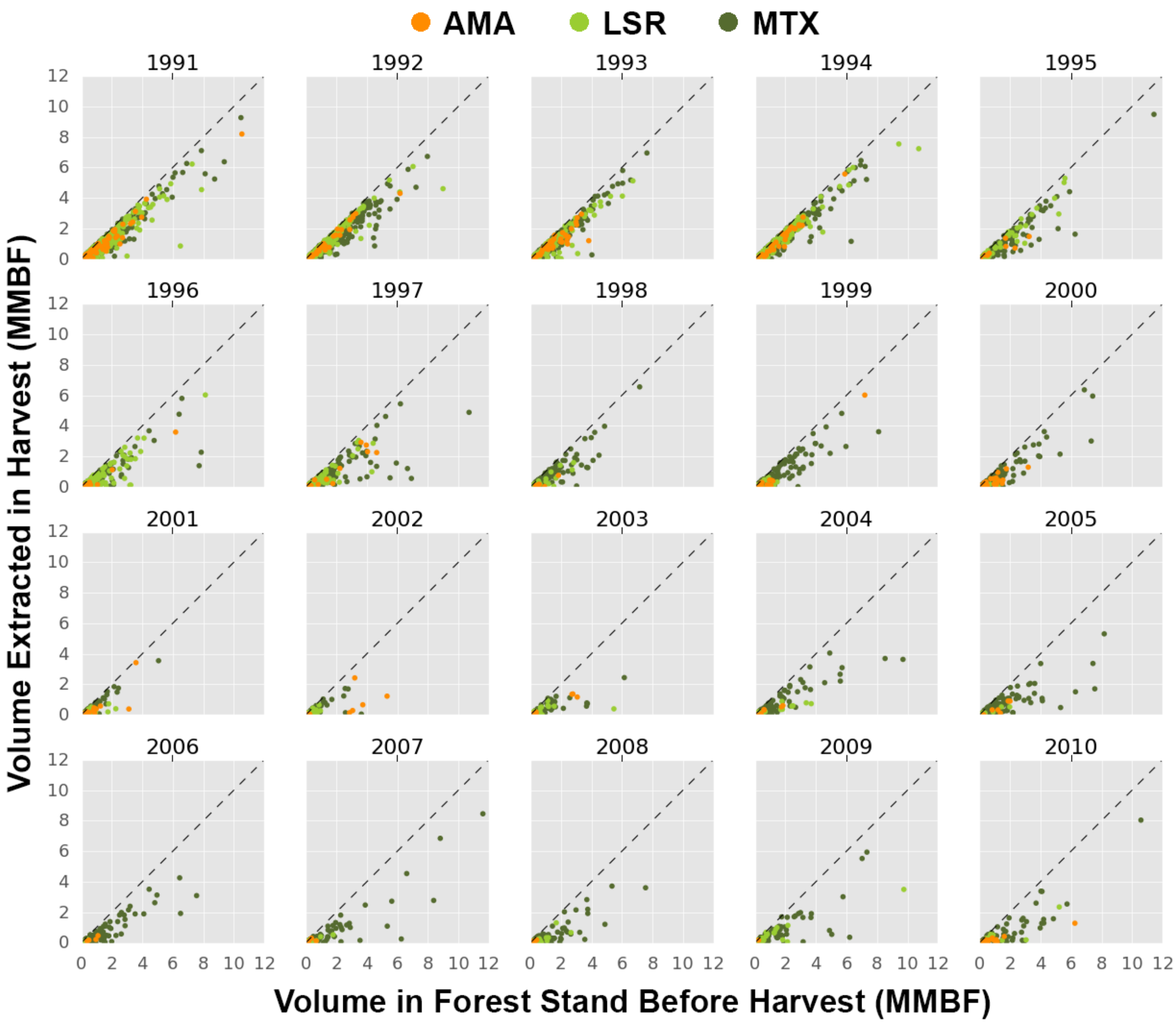


Figure 10. For each individual harvest event: timber volume within forest stand before harvest (x-axis) versus volume extracted in harvest event (y-axis), measured in million board-feet (MMBF).

3.4.4 Locating and Learning from 'Outlier' Harvest Events

An additional merit of the patch-level analysis is that it allows for 'outlier' harvest events to be identified. Then, using ancillary, publically available geospatial information such as land ownership, or timber harvest inventories, we can take a more critical look at particular harvest events, and perhaps understand why they are distinct. Here we highlight a few examples that are relevant to forest governance-related inquiries. Figure 11a shows a cluster of three adaptive management area harvests with similar positions on the scatter plot for 2003. By referencing a USFS timber harvest inventory dataset, we identified these harvests as part of the 'Blue River Face' timber sale, which we learned through further investigation is a controversial project that seeks to mimic the effects of forest fire using small regeneration harvests in older forest. Figure 11b shows a regeneration harvest on Matrix land, which stands out because it is one of few harvests of high intensity in 2009.

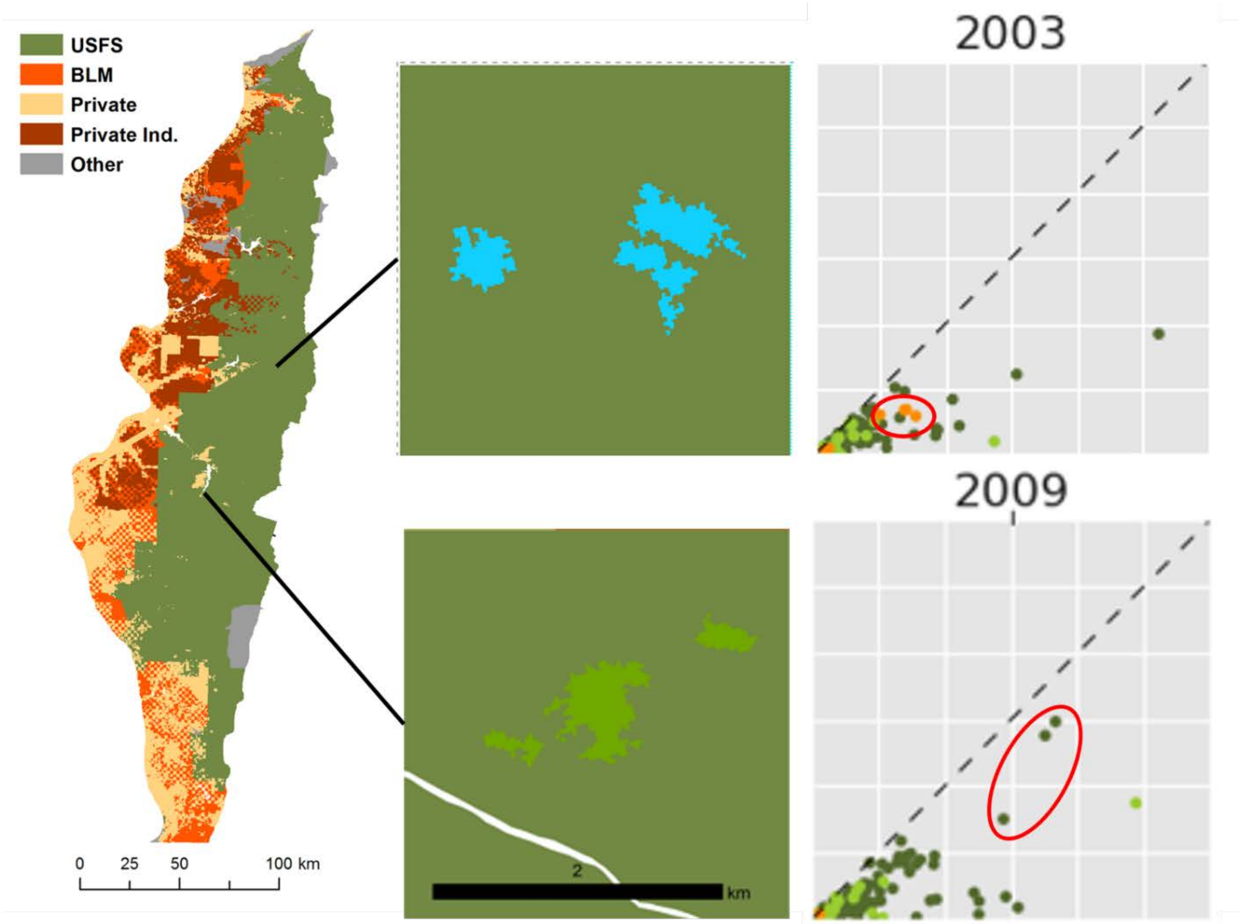


Figure 11. (a) A cluster of regeneration harvests associated with the Blue River Face timber sale, which is part of an Adaptive Management project in Willamette National Forest (b) regeneration harvests associated with a savannah restoration project on Matrix land in the SW portion of Willamette National Forest.

4. Conclusion

We’ve demonstrated that by combing LandTrendr disturbance maps and GNN volume data, we can produce accurate metrics of timber harvest volume at scales commensurate with timber management decision-making. Further, by comparing observed patterns of timber harvest volume to hypothetical expectations, we’ve demonstrated that while implementation of the Northwest Forest Plan has indeed led to shifts in timber management practices, the policy alone cannot explain the spatial and temporal variance of its outcomes. Understanding the connections between our observed patterns and forest governance in the Pacific Northwest will require further research, but by objectively analyzing timber harvest volume at the scale of individual harvest events, our method has great potential to serve as a tool for more focused research by social scientists at local scales.

It is important to acknowledge the shortcomings of our assessment. For one, the temporal range of our study is quite short relative to the long term strategy of the NWFP. Its creators understood that given the far-reaching objectives of the plan, it would take considerable time to realize their desired results. One could argue that priority has been given to the ecosystem so far, but social and economic values remain a primary objective, and it will take much more time and research to understand how this will unfold. Another limitation is that our characterization and assessment of governance focused only on federal forestry. Although federal lands comprise a majority of the Western Cascades, private lands have yielded a much higher volume of timber, highlighting the need for further research focused on private owners (Figure 12) and other aspects of forest governance in the region.

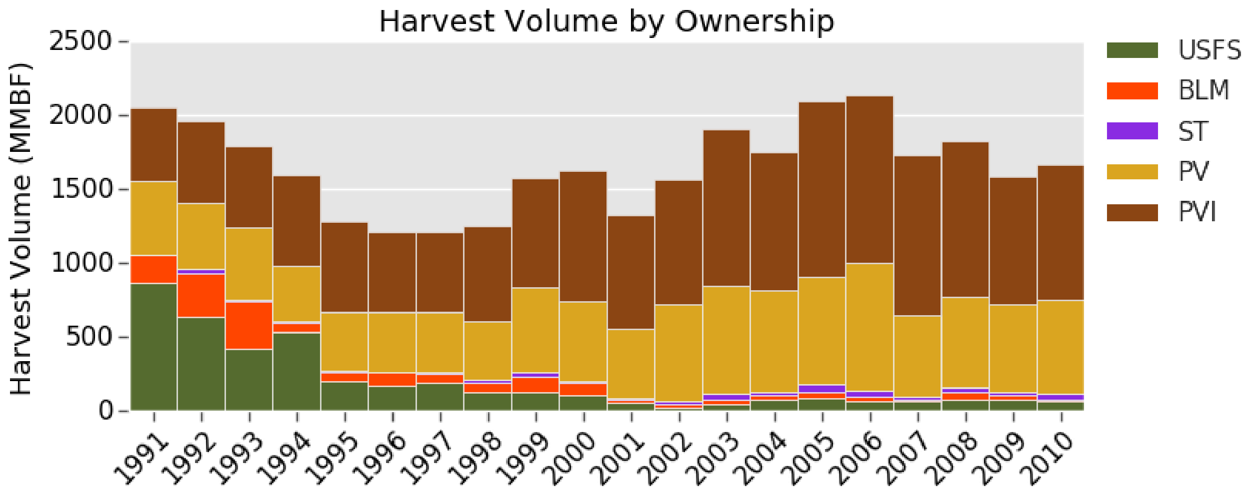


Figure 12. Timber harvest volume by ownership. Note that private lands (PV) and private-industrial lands (PVI) contributed the highest proportion of timber volume during the study period.

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