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Prepared By:

Aaron Dushku, Sandra Brown, Silvia Petrova, Jonathan Winsten, Nick Martin, Timothy Pearson, and John Kadyszewski

Winrock International
Ecosystem Services Unit
1621 N. Kent St, Suite 1200
Arlington, VA 22209

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Prepared For:
Public Interest Energy Research (PIER) Program
California Energy Commission

Guido Franco
Project Manager

Beth Chambers
Contract Manager

Kelly Birkinshaw
Program Area Lead
Energy-Related Environmental Research

Laurie ten Hope
Office Manager
Energy Systems Research

Martha Krebs
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

B. B. Blevins
Executive Director

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1 Sohngen, B., J. Cathcart, and T. Ifie. 2005. *Baselines, Carbon Supply Curves, and Pilot Actions for Terrestrial Carbon Sequestration in Oregon.* Report to Winrock International.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
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- Renewable Energy Technologies
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In 2003, the California Energy Commission's Public Interest Energy Research (PIER) Program established the **California Climate Change Center** to document climate change research relevant to the states. This Center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

Carbon Sequestration Through Changes in Land Use in Washington: Costs and Opportunities is a final report for the West Coast Regional Carbon Sequestration Project (contract 500-02-004, work authorization number MR-021), conducted in part by Winrock International. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

This report estimates the carbon sequestration potential of various land use activities in Washington state: afforestation of rangelands; afforestation of croplands; changes in forest management, including extending timber harvest rotations and widening riparian buffers; and hazardous fuel reduction to reduce emissions from wildfire in fire-prone forest ecosystems. For each activity, methods and results are presented for estimating the total quantity of carbon that could be sequestered, followed by an economic analysis summarizing the total costs of converting lands or changing management to sequester carbon. Carbon supply curves and maps illustrate the total area of land that would be converted or put under different management, and the total quantity of carbon thus sequestered, at different prices for carbon credits. The report concludes with a summary of next steps and further refinements for the second phase of study by the West Coast Regional Carbon Sequestration Partnership.

Keywords: Carbon sequestration, afforestation, reforestation, forest management, hazardous fuel reduction, CSCH, cut-skid-chip-haul, WESTCARB

Executive Summary

Introduction

In the search for effective ways to sequester the carbon dioxide gases that contribute to global climate change, several studies have estimated the potential of various regions of the United States for terrestrial carbon storage—that is, carbon fixation in plant matter. These studies were based on biological and technical criteria coupled with coarse-scale consideration of the economic costs associated with changing land management practices. Recent work by Winrock International for California—and for all states in the U.S. Department of Energy's Southeast Regional Carbon Sequestration Partnership—has focused on (1) adding more detailed analysis of opportunities on both agricultural and forest lands; (2) biological rates of carbon sequestration, considering variations in site conditions across the landscape; and (3) more detailed analysis of all costs. By considering the varying carbon sequestration potential of different land classes and other economic factors, more realistic estimates of carbon storage potential and associated costs can be obtained. Realistic, finer-scale assessments—estimating the quantity of carbon credits that might be available at different price points for different classes of land use activities—are vital to helping policy makers and the private sector prepare for an uncertain regulatory future.

Purpose

This study is part of a larger project conducted by the West Coast Regional Carbon Sequestration Partnership (WESTCARB): "Baselines, Carbon Supply Curves, and Pilot Actions for Terrestrial Carbon Sequestration." The broad purpose of the WESTCARB effort is to (1) quantify terrestrial carbon sequestration opportunities across the West Coast Partnership region (Arizona, California, Oregon, and Washington) and (2) estimate the carbon credits that might be available at different price points. Focusing on the state of Washington, the present study estimates the potential carbon supply from afforestation of rangelands and croplands and from changes in forest management.

Project Objectives

Using methods developed by Winrock International in previous research, this study developed carbon supply curves for potential land-use and forest management activities in Washington. Specific objectives were to:

- Estimate carbon supply for different types of potential terrestrial project activities, including afforestation of cropland, afforestation of rangeland, and changes in forest management.
- Assess the potential for hazardous fuel removal from forests with high fuel loads as a carbon sequestration activity. By preventing catastrophic, high-intensity fires, hazardous fuel removal could potentially reduce carbon emissions.

The analysis classified the state of Washington into three main types of land: forest, rangeland, and agricultural land. Forests (about 20.2 million acres or 8.17 million hectares) include conifers, hardwoods, and mixed classes; rangelands (about 11.7 million acres or 4.7 million hectares) include a variety of non-woody and woody ecosystems; and agricultural lands (about 9.6 million acres or 3.9 million hectares) include a wide range of non-woody crops such as wheat and hay and woody crops such as vineyards and orchards. Given the economic value of various crops, the analysis considered only those agricultural lands growing wheat and hay.

For rangelands and croplands (growing wheat and hay), the potential carbon sequestration yield was estimated for afforestation using native species. Historical evidence suggests that, in many areas, large tracts of forest may have once stood on present-day grazing and agricultural lands. The general approach was to identify existing rangelands and croplands where biophysical conditions could favor forests, estimate the rates of carbon accumulation for the forest types projected to grow in specific locations (pine, hemlock/spruce, mixed, and so forth), and assign values to each contributing cost factor. Carbon supply was estimated for 20 years, 40 years, and 80 years of forest growth to reflect the impact of activity duration on the likely carbon supply and to inform both near-term and longer-term planning horizons.

Carbon sequestration options for forestlands focused on three alternative activities for 20-year and/or permanent contract periods: (1) allowing timber to age past economic maturity (lengthening rotation time); (2) increasing the riparian buffer zone by an additional 200 feet (61 meters); and (3) reducing the hazardous fuel load to decrease the incidence of catastrophic forest fires (which would emit large quantities of greenhouse gases), and subsequently burning the removed fuels in biomass power plants.

Cost estimates for the first two options—allowing timber to age and enhancing riparian zone management—were based on specific counties for public and private landowners and then extrapolated to all counties throughout the state. For the fuel reduction alternative, the analysis used a "Suitability for Potential Fuel Reduction" (SPFR) score on forest landscapes with the potential for significant carbon loss from moderate- to high-intensity wildfires. The SPFR scores were created in a geographic information system using slope, distance to biomass plants, and distance from roads as equally weighted factors in the decision-making process.

Project Outcomes

This report presents land use activity costs and potential carbon sequestered in terms of metric tons (t = tonnes) of carbon dioxide (CO_2) and carbon (C).

Afforestation of Rangelands and Croplands
Table ES-1 summarizes the amount of carbon and the area available for afforestation of rangelands and croplands at three commonly used price points:

- ≤ \$2.40/t CO_2 (\$8.81/t C)
- ≤ \$10.00/t CO_2 (\$36.67/t C)
- ≤ \$20.00/t CO_2 (\$73.33/t C)

At a price of \$2.40/t CO_2, no carbon could be sequestered by afforesting rangelands or croplands at 20 and 40 years, but the amount reaches about 1,399 million metric tons (MMT) of CO_2 at 80 years. If prices per tonne of CO_2 rose to \$20, it would be possible to convert more productive rangelands and croplands with higher opportunity costs, sequestering almost 289 MMT CO_2 carbon in only 20 years; the total amount rises sharply to more than 1,233 MMT CO_2 at 40 years and approximately 3,176 MMT CO_2 at 80 years. Converting this total amount at 40 years to an approximate annual rate results in about 31 MMT CO_2/yr.

Table ES-1. Carbon supply (million metric tons CO_2) and area (million acres) available at selected price points ($/tonne CO_2) for afforestation of existing rangelands and croplands over 20-year, 40-year, and 80-year durations

$ per Tonne	Quantity of Carbon (MMT CO_2)			Area Available (million acres)*		
	20 years	40 years	80 years	20 years	40 years	80 years
Rangeland Afforestation						
≤$2.40	0.0	0.0	1,399	0.0	0.0	3.1
≤$10.00	0.0	877.9	2,153	0.0	4.3	6.2
≤$20.00	279.4	1,178	2,450	4.2	8.8	8.9
Cropland Afforestation						
≤$2.40	0.0	0.0	14.4	0.0	0.0	0.0
≤$10.00	0.0	0.0	140.5	0.0	0.3	0.3
≤$20.00	9.8	54.9	725.9	0.1	1.4	5.5

* To convert to million hectares, multiply by 0.4047.

Changes in Forest Management

Although Washington has substantial forest area, the cost of carbon sequestration from changing forest management practices is relatively high and the quantity of carbon that could be sequestered is relatively small. All of the carbon available at prices of less that $10/t CO_2 for extending rotations by five years is located on non-federal public lands; only when prices reach $10–$20/t CO_2 do private lands generate potential carbon credits. If all of the private and non-federal public land nearing the economically optimal rotation period (1.46 million acres or 0.59 million hectares) were contracted to increase rotation ages by up to 15 years, 61.6 MMT CO_2 could be sequestered for average costs of $37/t CO_2.

Extending Timber Harvest Rotations

For extending rotations by five years, all of the carbon available at less than $10/t CO_2 is located on non-federal public lands; only when prices reach $10–$20/t CO_2 do private lands generate potential carbon credits. If all the private and non-federal public land nearing the economically optimal rotation period (1.46 million acres or 0.59 million hectares) were contracted to increase rotation ages by up to 15 years, 61.6 MMT CO_2 could be sequestered for average costs of $37/t CO_2.

Wider Riparian Buffer

The potential area of mature forests where the riparian buffer zone could be increased by an additional 200 feet (61 meters) was estimated at 34,900 acres (14,125 hectares). The additional carbon that could be stored on these lands if the forests were conserved is 2.2 MMT CO_2 at an average cost of $33.3/t CO_2.

Hazardous Fuel Reduction
The area of Washington forests with historically low-severity and mixed-severity (HLS-HMS) fire regimes is estimated to be 3.3 million acres (1.3 million hectares). A commonly used method of hazardous fuel reduction (HFR) is "Cut-Skid-Chip-Haul" (CSCH), a treatment in which hazardous fuel is harvested in the woods, bunched and skidded to a landing, chipped into a chip van, and hauled to a biomass energy facility for electricity and/or heat generation. Washington has approximately 1.2 million acres (0.49 hectares) of forestlands with HLS-HMS fire regimes to which this treatment could be applied.

Two removal scenarios were analyzed: HFR removal of 4 bone dry tons (BDT) per acre on these lands would yield 5 million BDT of biomass fuel for use in energy facilities, while removal of 8 BDT per acre would yield 10 million BDT of biomass fuel. Total costs and potential revenue from these removals were estimated.

During moderate to intense fires, 10 to 70 percent of the biomass stock burns and is emitted as CO_2. Considering the differences in CO_2 emissions between high-, medium- and low-intensity fires, preliminary analysis suggests that HFR treatments which reduce fire intensity would avoid sufficient emissions to be able to cover—at commonly used prices for carbon of $2.40/t CO_2 and $10/t CO_2—the subsidies needed to pay for CSCH treatment. This result supports the argument for qualifying hazardous fuel reduction as a carbon offset project.

Conclusions

The key conclusions from this work are:

- The largest terrestrial sequestration opportunity, both in terms of absolute quantity and costs, is afforestation of rangelands.
- Lengthening the timber harvest rotation age beyond the economical rotation has limited potential both in terms of quantity and costs.
- Forest conservation, such as extending riparian buffers, is limited in scope and tends to be expensive.
- Of the forest management activities analyzed, fire appears to be the most important issue to address, and hazardous fuel removal has the potential to avoid substantial carbon dioxide emissions.

Recommendations

Further characterization work is needed to refine these analyses and to evaluate additional carbon sequestration opportunities for the state and region. It is recommended that further work focus on two areas: afforestation using native or fast-growing species such as hybrid poplar for timber production or biomass energy; and refinements to the analysis of hazardous fuel reduction in wildfire-prone forests.

Afforestation for Harvest
The present study considered only forest restoration with native species. The economics and carbon supply would differ for afforestation projects that plant trees for timber and non-timber

products using both native and fast-growing species. Further study is needed to determine how the associated changes in carbon sequestration rates for different species and changes in project economics would affect the total carbon supply across the region.

Hazardous Fuel Reduction

Recommended next steps include (1) analysis of other fuel removal treatments (besides CSCH) and how the constraints on each treatment affect the amount of forestland that could be treated, and (2) development of baselines for various wildfire-prone forest types. Such baselines should include field data and models to quantify the likelihood of fires occurring (for example, fire return interval) as well as the effects of different intensities of fire on greenhouse gas emissions (how much of the forest's carbon stock in different pools is emitted under different fire intensities and stand structures). More detailed economic analysis is also needed to determine if fuel removal produces sufficient emissions reductions to pay for currently uneconomic treatments.

1.0 Introduction

Many past studies estimate the terrestrial carbon storage potential in regions of the United States based on biological and technical criteria coupled with coarse-scale consideration of the economic costs associated with changing land management practices. Recent work by Winrock International—for California and for all the states under the U.S. Department of Energy's Southeast Regional Carbon Sequestration Partnership—has focused on adding more detailed analysis of opportunities on both agricultural and forestlands; estimating biological rates of carbon sequestration, taking into consideration variations in site conditions across the landscape; and incorporating more detailed analysis of all costs. Consideration of the varying carbon sequestration potential of different land classes and other economic factors will yield more realistic estimates of carbon storage potential. Realistic assessments of the potential for carbon sequestration from changes in land use can help policy makers and the private sector prepare for an uncertain regulatory future by providing estimates of the quantity of carbon credits that might be available at different price points for different classes of activities.

The main goal of this study is to generate estimates of potential carbon supply—including total amount of carbon in metric tons (t), \$/t CO_2 (dollars per tonne of carbon dioxide), and location—for changes in the use and management of three classes of land in Washington: rangelands, croplands, and forestlands.

The remainder of this report is divided into the following chapters: Chapter 2, carbon sequestration potential through afforestation of rangelands and croplands, Chapter 3 on potential changes in forest management to sequester additional carbon, and Chapter 4 on hazardous fuel load reduction in wildfire-prone areas to reduce emissions and/or sequester carbon.

2.0 Afforestation of Rangelands and Croplands

2.1. Background

Over 100 years ago, when Washington had not yet attracted thousands of people into the region to exploit its forest resources, historical evidence suggests that in many places, tracts of forest may have once stood where human populations, agriculture, and grazing lands now do. This project hypothesizes that a significant proportion of today's woodland, shrub, and grassland vegetation types on Washington's rangelands and much of its agricultural lands were once either closed forests or similar woodlands but with significantly higher biomass than they currently contain.

There are approximately 16.0 million acres of agricultural land in Washington (Karl et al. 1999). The top-grossing non-orchard, agricultural commodities in Washington are greenhouse and nursery products, cranberries, hops, and potatoes. Lower-value crops include hay (the state's sixth largest agricultural sector) and wheat (Washington is the nation's fifth largest wheat producer). Hay was produced on over 810,000 acres of Washington agriculture land in 2003 and wheat on approximately 2.3 million acres (USDA-NASS 2004).

Washington's cattle and calves industry is the state's fifth largest agricultural sector. Dairy production is the second (USDA-NASS 2004). Washington is the 29th leading beef cow–producing state in the U.S., and the state has a total of over 1.1 million head of cattle. Washington ranks within the nation's top ten states for milk production (USDA-NASS 2004).

Presently in Washington, on lands that were once forestland, wheat and hay farms occupy the majority of the croplands, and ranching takes place on the rangelands (Figures 2-1 and 2-2).

Figure 2-1. Washington croplands
Photo credits: WA State Tourism, John Marshall

Figure 2-2. Washington rangelands
Photo credits: www.mckuster-ranch.com, WA State Tourism

2.2. Approach

Unless otherwise noted, the methods applied in this section are identical to those of a previous Winrock study by Brown et al. in 2004 *(Carbon Supply from Changes in Management of Forest, Range, and Agricultural Lands of California)*. In addition to rangelands in Washington, potential opportunities also occur on croplands. Methods used for analyzing costs on croplands are practically the same as those used in a previous Winrock International study for the Southeast Regional Carbon Sequestration Partnership (Brown and Kadyszewski 2005a).

The analysis took the following steps to assess the quantity and cost of potential carbon sequestration:

- Identify the area and current use and cover of lands that have the potential to be managed for carbon sequestration—referred to as "candidate lands," including rangelands and selected croplands.
- Estimate the area and geographic location of candidate lands that could be afforested and the rates of carbon sequestration on them.
- Estimate the total cost of afforesting candidate lands, including opportunity cost, conversion cost, maintenance costs, and measurement and monitoring costs.

- Combine the estimated quantities of carbon per unit area with the corresponding area and cost to produce estimates of the total quantity of carbon that can be sequestered for a given range of costs, in $/tonne CO_2.
- Determine the geographic distribution of available carbon at various prices.

The analysis was performed in a geographic information system (GIS) to superposition the diversity of existing land cover, rates of carbon sequestration, and costs. As a result, not only are more realistic estimates of the potential supply of carbon produced, but the use of GIS shows where the least to most expensive carbon credits will most likely be found.

For agricultural lands, high-value crop producing areas are unlikely to be converted for carbon sequestration activities due to high opportunity costs. The value of hay production per acre is significantly more than the value of open rangeland, often by 10 times or more. However, in certain places hay production may provide good opportunities for affordable carbon sequestration activities because the overall value per acre is still generally low. Also, with average yields of 59.4 bushels of wheat per acre, wheat-producing land has a production value of generally less than $250 per year (USDA-NASS 2004), making wheat land another attractive candidate for carbon projects.

This study used a wide variety of spatial and non-spatial data sets. The spatial data include:

- National Elevation Dataset 30-m DEM grids, developed by USGS (2004a).
- National Land Cover Dataset, developed by USGS (2004b).
- NRCS STATSGO soil survey maps and databases and resultant analyses by non-NRCS researchers (Schwarz and Alexander 1995; Miller and White 1998).
- DAYMET Mean Annual Temperature map (Thornton et al. 1997).
- DAYMET Mean Annual Precipitation map (Thornton et al. 1997).
- Northwest Regional Gap Analysis land cover data set (Karl et al. 1999).

Non-spatial data include, for example, forest growth models, regression equations for converting U.S. Forest Service Forest Inventory and Analysis (FIA) data to biomass carbon, published literature, experience from other Winrock activities, and state and county reports of agricultural statistics. Details on all of these data and their applications are given in the appropriate sections below.

The carbon supply for afforestation options is estimated for three time durations—20 years, 40 years, and 80 years—to reflect the impact of activity duration on supply and to provide an assessment for the near-term and longer-term planning horizons. Several key assumptions of the analysis are shown in Figure 2-3 with the corresponding steps of the analysis.

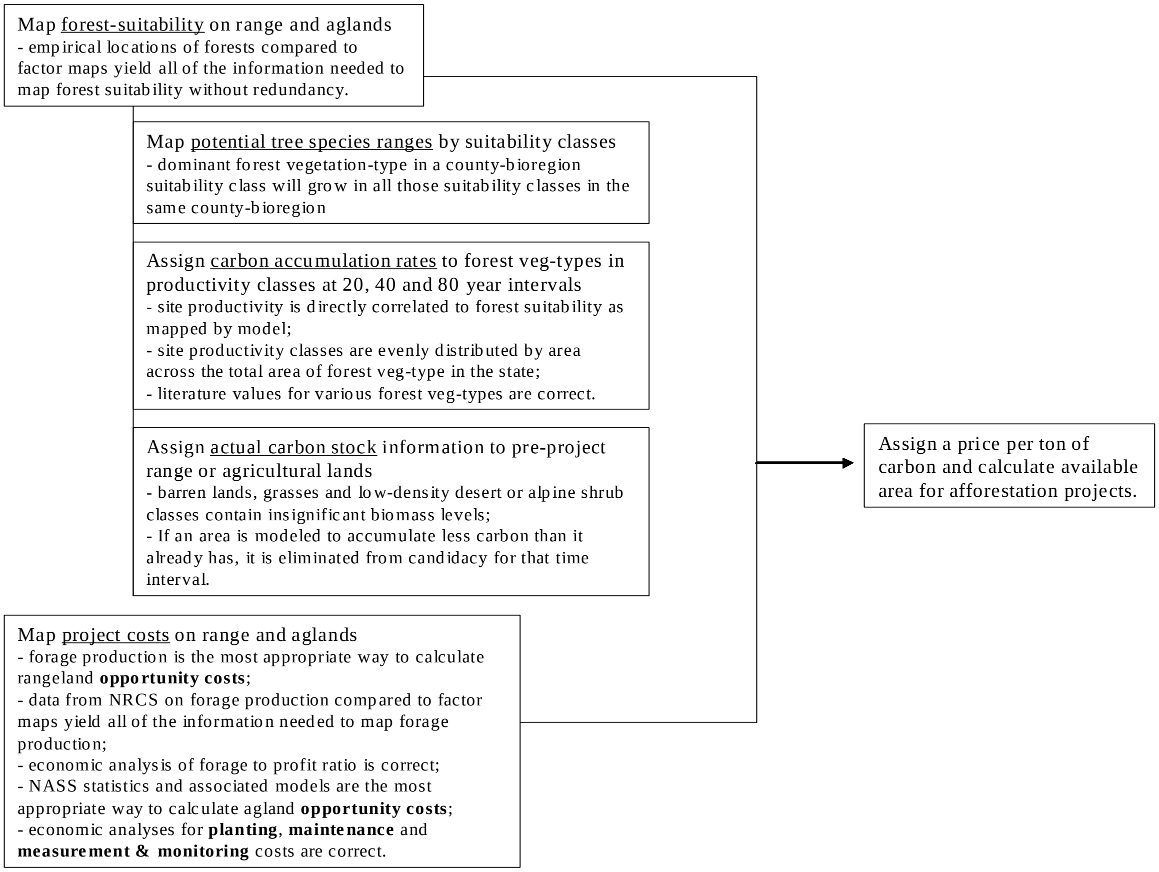


Figure 2-3. Flowchart of carbon supply curve analysis with key assumptions listed below each step

2.2.1. Scale of Analysis

This study aims to estimate the amount of carbon that can be sequestered on the selected areas through afforestation. The level of resolution used in this analysis is the same as that used by NLCD (30-meter pixels) and by the Washington GAP Analysis in its land cover map product. GIS software used in the analyses was ESRI's ArcGIS 9.0 suite and ArcView 3.3, with Idrisi Kilimanjaro and ERDAS Imagine also used intermittently.

2.2.2. Washington Land Cover Characterization

The 30-meter resolution, NW Regional Gap Analysis land cover map (Karl et al. 1999) was used as the basis for vegetation mapping because it allowed for greater resolution between forest and rangeland classes than the USGS NLCD and because it offered a uniform vegetation classification system for comparison with a similar analysis for the state of Oregon. Although the Washington portion of the map was produced in the late 1990s, the majority of the data used to create it came from Landsat satellite imagery gathered in the early 1990s. Much inquiry and investigation was made into the incorporation of other, more-recent data sets into this analysis, although all assembled data sets were eventually rejected due to incomplete coverage or incompatible land cover classification systems. Several well-known Landsat satellite imagery-based examples follow with the justification for not using them:

- The Interagency Vegetation Mapping Project (IVMP) was an initiative that mapped the forest types and attributes of the coastal areas of the Pacific Northwest from 1998 to 2002. The project mapped only forest land cover types and no agricultural or rangelands and did not cover the entire state. **http://www.or.blm.gov/gis/projects/ivmp_data.asp**.
- The National Landcover dataset (NLCD) from the USGS mapped land cover in 1992. Although it did include three agricultural land cover classes that the GAP Analysis did not have, all other classes were too coarse for making species-specific discriminations. **http://landcover.usgs.gov/nlcd/show_data.asp?code=WA&state=Washington**.
- The Northwest Habitat Institute's vegetation maps used slightly more recent Landsat imagery than the GAP Analysis or NLCD to map vegetation communities in Washington, but the classes were more mixed in their species types with a larger variety of biomass levels within each one as compared to the GAP Analysis. **http://www.nwhi.org/NHI/default.asp?pageurl=books/booklist.asp**.
- Various other data sets at the National Forest or county level.

For individual land cover types or specific regions of the state, some of these other data sets may have provided a better idea of the actual characteristics of the land today. Nevertheless, the regional GAP Analysis map compiled by Karl et al. (1999) from the original Washington GAP Analysis (Cassidy et al. 1999) is the most up-to-date and detailed land cover data available *for the entire state* of Washington that exists at this time.

The vegetation classes present in the land cover data set were combined into four discrete classes: agriculture, rangelands, forests and "other.". The "other" class included urban and residential development and water bodies. The full classification rules are shown in Table 2-1. Forests cover the largest area of Washington at 47% of the total area, followed by rangelands at 27%, and agriculture at 22%, with "other" occupying the remaining 4% (Table 2-1).

The three broad classes are shown in the map in Figure 2-4. The area of rangelands (12 million acres) in Washington is less than that for forests (20 million ac). Any inconsistency in these numbers with other published data may be due to the inclusion of the generally low-biomass "Western Juniper" areas in the rangelands class instead of forests. Agriculture lands cover about 9.5 million ac or about half the area of forests and three quarters that of rangelands (Table 2-1).

Candidacy for afforestation on agricultural lands was not based on the GAP Analysis's "agriculture" class. Lands targeted by this study were wheat and hay fields, but given the lack of any resolution within the GAP Analysis's "agriculture" vegetation class, another data source was tapped. The USGS NLCD data set (USGS 2004b) disaggregates agriculture into "small grains," "row crops," "pasture/hay," and "fallow." The two data sets were combined to create a new layer of agricultural land cover candidates wherein anything that was mapped by NLCD as "pasture/hay," "small grains," or "fallow," plus any lands mapped as agriculture by the GAP Analysis and not by NLCD, were made candidates for afforestation (Figure 2-5). The decision to put into candidacy the "fallow" and unmapped agricultural lands is based upon the fact that most agricultural lands in the state are pastures, hay, or wheat (USDA-NASS 2004).

Table 2-1. Land cover classification, areas, and class generalization in Karl et al. (1999) GAP Analysis

GAP Analysis Vegetation Class	Broad Land Use Category	Hectares	Acres	% of Total
Mixed Mesic Coniferous Forest	FOREST	3,107,941	7,676,614	17.70%
Mesic Douglas Fir	FOREST	1,308,695	3,232,477	7.46%
Ponderosa Pine	FOREST	1,103,451	2,725,524	6.29%
Mesic Mixed Forest	FOREST	703,169	1,736,828	4.01%
Mixed Subalpine Coniferous Forest	FOREST	620,319	1,532,188	3.53%
Deciduous Forested Riparian	FOREST	335,469	828,609	1.91%
Xeric Douglas Fir	FOREST	293,264	724,363	1.67%
Mixed Xeric Coniferous Forest	FOREST	237,510	586,649	1.35%
Mixed Coastal Forest	FOREST	169,016	417,470	0.96%
Xeric Mixed Forest	FOREST	111,853	276,276	0.64%
Mesic Deciduous Forest	FOREST	68,746	169,803	0.39%
Mixed Riparian	FOREST	66,484	164,215	0.38%
Xeric Deciduous Forest	FOREST	31,775	78,485	0.18%
Subalpine Fir	FOREST	20,904	51,632	0.12%
Coniferous Forested Riparian	FOREST	4,497	11,108	0.03%
Other	FOREST	11	28	0.00%
Subtotal		**8,183,105**	**20,212,269**	**46.6%**
Agriculture	**Agriculture**	**3,867,456**	**9,552,616**	**22.03%**
Urban/Developed	OTHER	433,556	1,070,884	2.47%
Water	OTHER	259,804	641,716	1.48%
Ice/Snow	OTHER	55,769	137,750	0.32%
Estuarine Emergents	OTHER	5,639	13,927	0.03%
Exposed Rock	OTHER	3,708	9,159	0.02%
Tidal Flats	OTHER	1,043	2,576	0.01%
Subtotal		**4,626,975**	**11,428,628**	**26.4%**
Xeric Grasslands	RANGELAND	1,872,706	4,625,585	10.67%
Upland Shrublands	RANGELAND	1,208,207	2,984,271	6.88%
Big Sagebrush	RANGELAND	868,378	2,144,894	4.95%
Subalpine Meadow	RANGELAND	707,320	1,747,081	4.03%
Shrub Dominated Riparian	RANGELAND	37,455	92,515	0.21%
Alpine Meadow	RANGELAND	22,266	54,997	0.13%
Graminoid/Forb Riparian	RANGELAND	17,499	43,223	0.10%
Salt-Desert Shrub	RANGELAND	8,938	22,078	0.05%
Other Sagebrush	RANGELAND	1,336	3,299	0.01%
Subtotal		**4,744,106**	**11,717,941**	**27.0%**

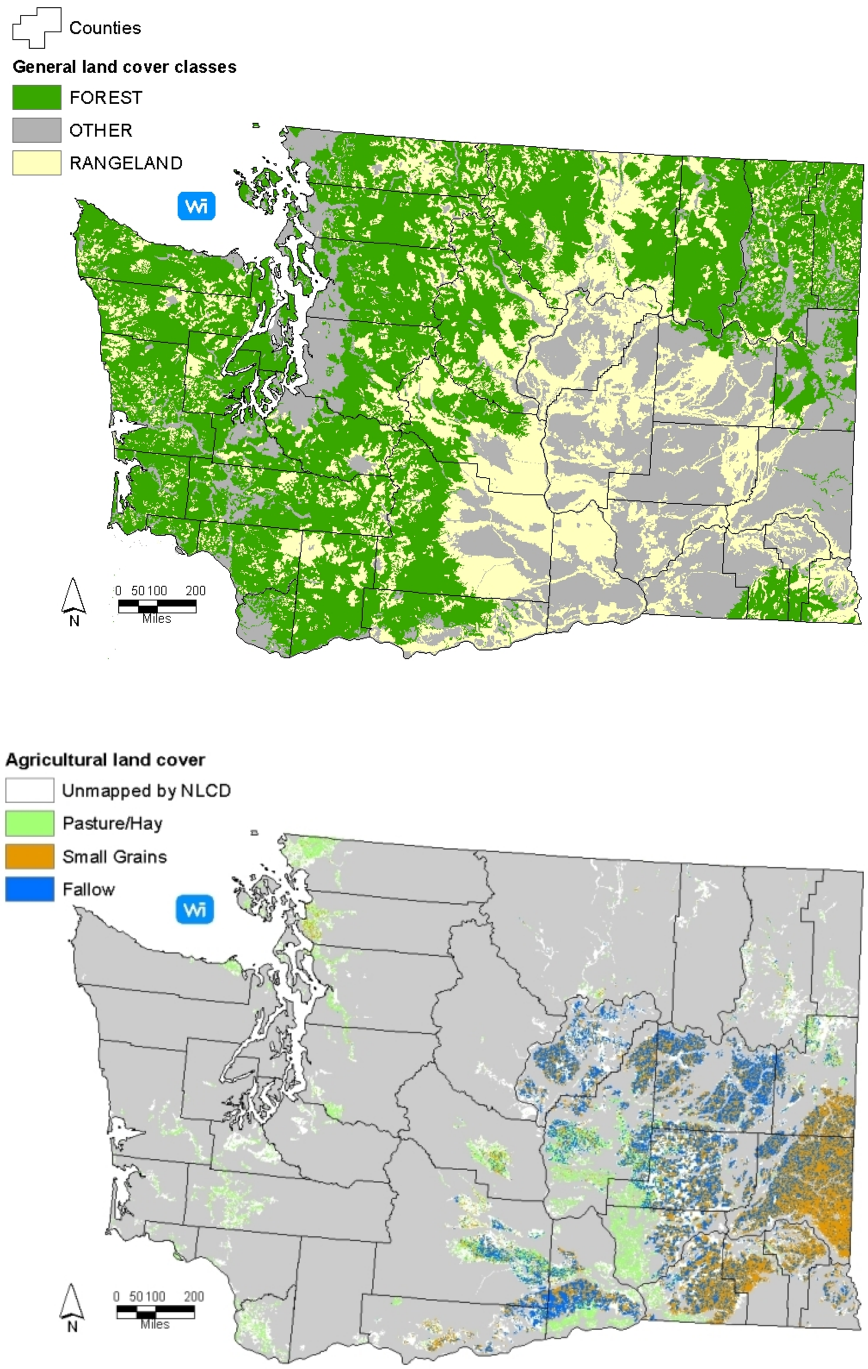


Figure 2-4. Broad land cover classes from NW Regional GAP Analysis (top) and cropland cover classes from the NLCD map (bottom)

2.2.3. Mapping Suitability for Afforestation with Native Species

To map the suitability for a non-forested landscape to grow trees, certain variables in the State Soil Geographic (STATSGO) databases—"sitind" (site index, unitless), "woodprod" (wood production in cubic feet per acre per year)—have been successfully used in the eastern states of the U.S. (e.g., Brown and Kadyszewski 2005a). In more arid landscapes, where forests are not the dominant vegetation type, there are complications with using these databases because they lack data in areas of sparser forest cover or areas that have not been under forest cover in recent memory. In Washington, as in California (Brown et al. 2004), data in the Washington STATSGO soils data sets for the "woodprod" (Mean Annual Increment) variable were incomplete across the state (Figure 2-5).

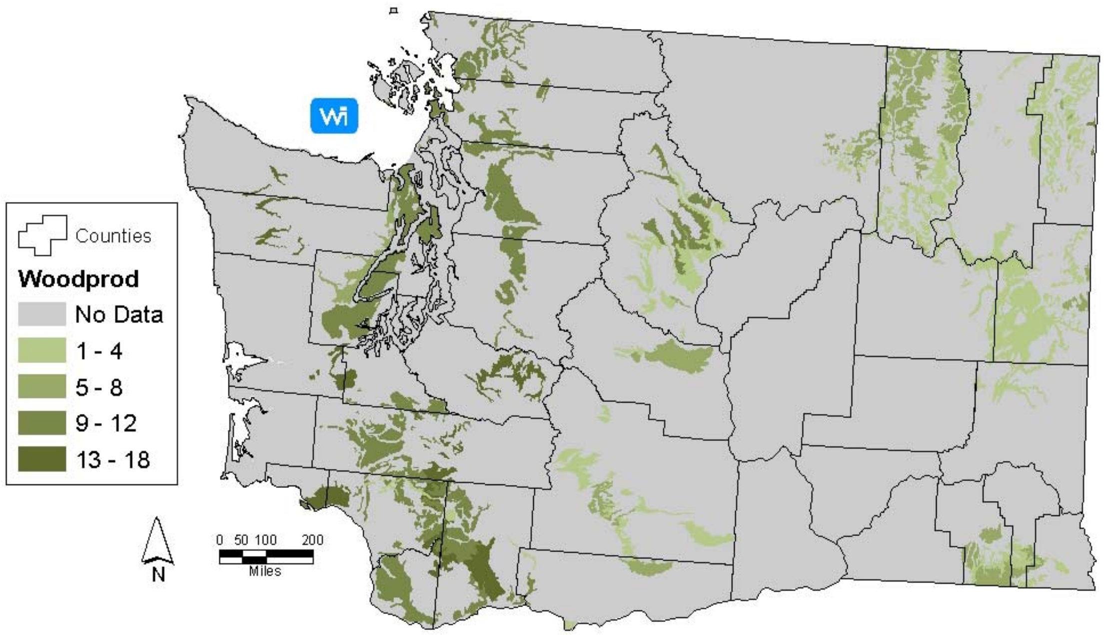


Figure 2-5. Map showing dominant soils components with available STATSGO "woodprod" data

To derive suitability for any area that was not mapped for "woodprod" by STATSGO, a multi-criteria evaluation of pertinent factors was conducted whereby areas of current forest vegetation were used to calibrate a model and predict a score indicating whether or not an area was suitable for growing trees (suitability score). The methods used to derive this suitability score were identical to the methods used the carbon supply report for California (Brown et al. 2004) except that the factor aspect was included in the set of biophysical drivers for Washington. The factors, used to map suitability for forest growth in Washington, were available water content (AWC) in the soil, elevation, slope, mean annual temperature, and annual precipitation.

In this analysis, a constraint was introduced whereby lands that fell into a category of any one of the factor maps where there were no areas of current forest were eliminated as candidate lands for afforestation. In other words, the concept of limiting factors was used. For example, a constrained site might be one where the mean annual precipitation class is one in which forests commonly exist across the state, but there are no forests growing in areas with mean annual temperature values as low as the site in question. In this example, the site would be constrained from candidacy for afforestation because of the prohibiting factor of mean annual temperature despite meeting the suitability constraint for mean annual precipitation. Elevation was another factor that acted as a constraint at some of the state's higher points.

The suitability score was based on the proportion of each factor map's class that is forested throughout the state. For any given cell in a factor map, this proportion value across all of the factor maps was averaged to produce an overall suitability map for forest growth. More details on how suitability scores are calculated using GIS can be found in the California report (Brown et al. 2004) or in conventional GIS suitability analysis discussions such as those found in the Idrisi Kilmanjaro users' manual (Eastman 2003) and with ESRI products (Wayne 2003a, 2003b). In this study, no weighting of factors with respect to each other was used (cell values were averaged), but empirical data on forest area locations were used to weigh the classes in each factor map. This technique is used frequently in land use change modeling (Brown et al. 2007; Pontius et al. 2001; Hall et al. 1995).

The suitability scores for forests cross-referenced to existing land cover classes in Washington are shown in Figure 2-6. It can be seen from this figure that there are relatively large areas of agricultural land and rangeland classes that have high forest suitability scores. To illustrate the case for rangelands in more detail, Figure 2-7 shows the distribution, in acres, of existing rangelands within the forest suitability classes.

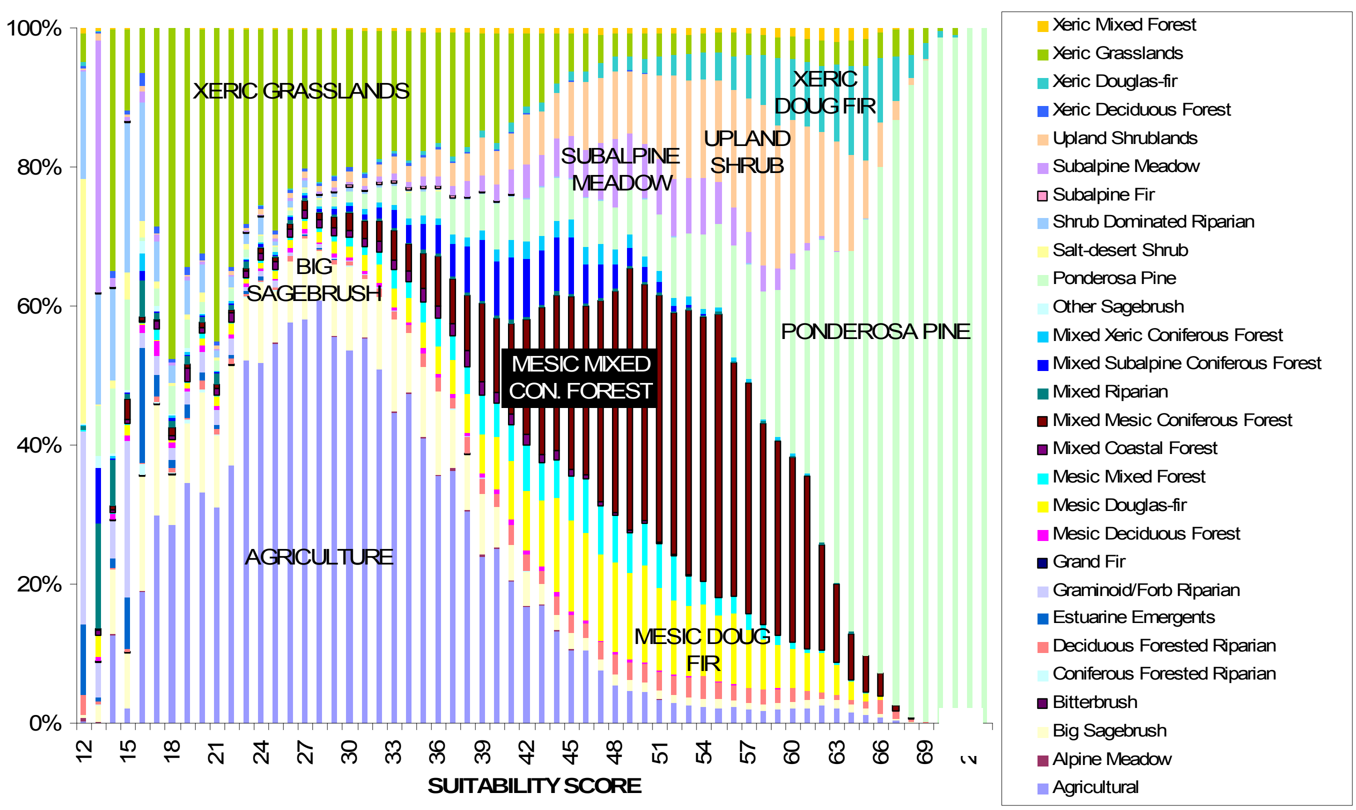


Figure 2-6. Forest suitability scores cross-referenced to land cover classes. The higher the score, the more suitable the site is for forests and vice versa.

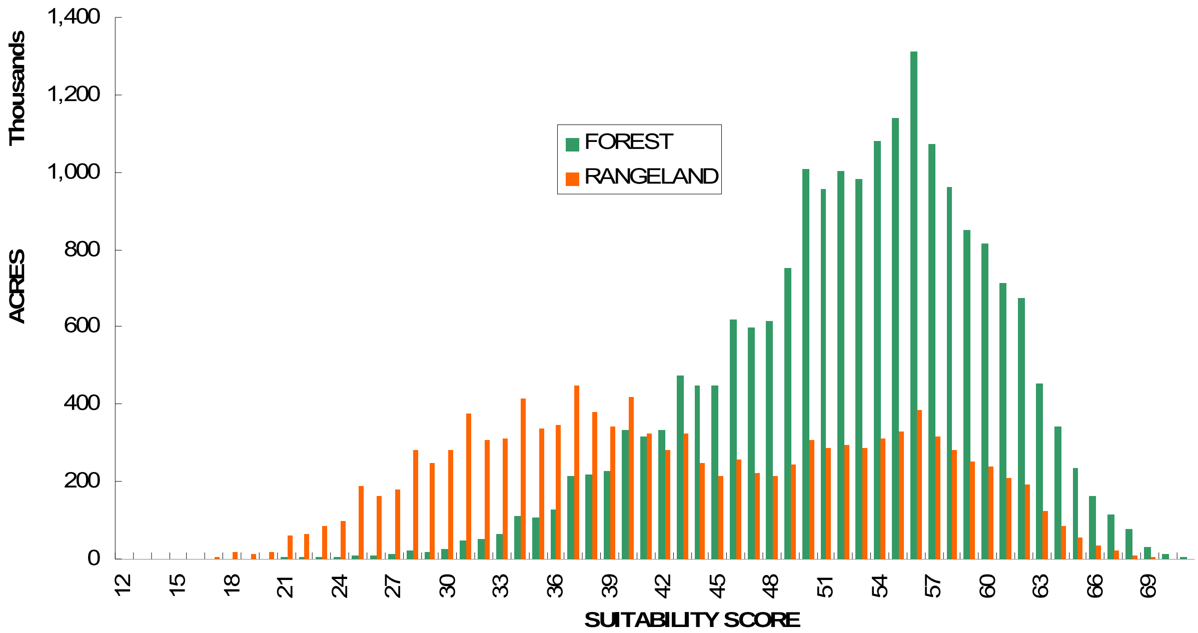


Figure 2-7. Distribution of existing rangelands and all forest classes within the forest suitability classes

It is clear that a substantial area of existing rangelands have high forest suitability scores. When compared to Figure 2-6, these scores correspond to those for mixed mesic coniferous forest, mixed xeric coniferous forests, and ponderosa pine forests. This overlap implies that rangelands could be afforested with species typical of these forest types. Of the total area of existing rangelands, about 9.3 million acres (about 79% with a suitability score >32; Figure 2-7) could be afforested with mesic mixed conifer species and ponderosa pine. In most cases, when overlaps occur for a forest type in a wide range of suitability scores (from low to high), this is reflected in the modeling of the biomass productivity of an afforestation project and is described below. As explained above, in factor map classes where forests do not currently exist in Washington, these classes were flagged and excluded from suitability analysis. Due to the fact that this constraint was introduced, no minimum threshold cutoff in the suitability scores for afforestation candidacy was applied as in the California report (Brown et al. 2004).

2.2.4. Species Selection Analysis

The carbon sequestration potential for any given grid cell was developed by first identifying the dominant forest vegetation types that exist in those suitability classes in other areas of the state. This is the way to select the kinds of tree species that would most successfully be planted on candidate sites. This analysis needed to be constrained because if sites in the northeastern part of the state are in the same suitability class as sites in the southwestern part, they could be assigned the same dominant forest vegetation type, even if this would not be the case in reality. To prevent this, species selection was constrained with a map of Holdridge Life Zone classes of the state (Lugo et al. 1999), shown in Figure 2-8. In this way, the dominant forest vegetation type was mapped for all suitability classes in each Holdridge Life Zone.

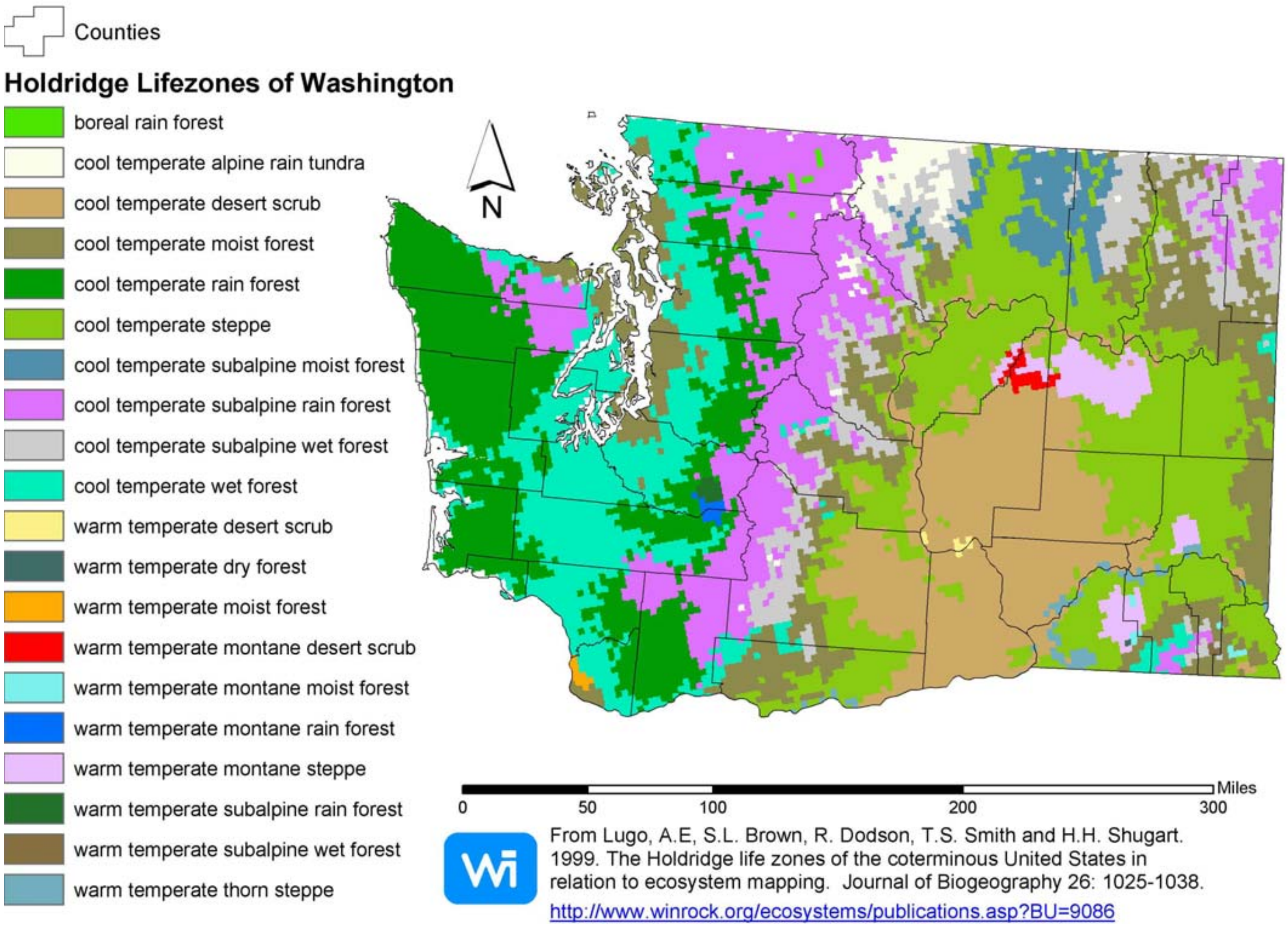


Figure 2-8. Map of Holdridge Life Zones of Washington

Using the Holdridge Life Zone map to stratify the land also allows for another constraint to be applied when estimating site suitability as described in Section 2.2.3. If a suitability class in a Holdridge Life Zone had no dominant forest species when dominant forest species were extracted (meaning that it actually has no forest species), even though the suitability class might have forests in other Life Zones, all of these areas were eliminated from candidacy.

2.2.5. Modeling Forest Carbon Sequestration Potential

Existing models of forest growth were considered, including the CRYPTOS and CACTOS models (Wensel et al. 1986) and the Forest Vegetation Simulator developed by the U.S. Forest Service. Given the data requirements for these models, they were deemed to be less useful for application to the large scale of this effort (both in Washington *and* in the California study). Therefore, models were developed that would directly estimate the rates of forest carbon accumulation on a per-unit-area basis, and that would require a manageable suite of inputs: forest type and forest suitability class. To simplify, other factors influencing forest growth (e.g., site preparation, planting density, management) were held constant.

The carbon accumulation numbers applied to this analysis were prepared to be conservative yet fully transparent and supported. Where possible the numbers are taken from the U.S. Department of Energy's 1605b greenhouse gas reporting program's look-up tables (http://www.pi.energy.gov/pdf/library/AppendixPartIForestry0321.pdf).

Where look-up table values were not applicable, carbon accumulation data were taken from the published literature. For the analysis, carbon stock densities are required for years 20, 40, and 80, so literature values were used in a growth model to derive values for these years.

The Chapman-Richards function (Richards 1959; Pienaar and Turnbull 1973), a popular sigmoid-shaped biological growth model, has been used in related reports and found to be appropriate as it is simple to use, transparent, and data are available for parameterization. The Chapman-Richards function of the following form was chosen to model biomass carbon accumulation over time:

$$yield = a \times (1 - e^{(-k \times age)})^{1/(1-m)} \qquad \text{Eqn. 2-1}$$

where:

- yield is expressed in metric tons of biomass.
- age is expressed in years.
- a (asymptote) is determined from literature.
- m (parameter)is set iteratively at 0.7 (fraction of asymptote [final yield] at which growth rate peaks).
- k (the rate at which the asymptote is approached) is determined by back calculation.

Parameters for Chapman-Richards models were estimated to tailor carbon yield curves for each vegetation class, and pass through the previously determined age:biomass/ha points.

The age at which mean annual increment (MAI) peaks, roughly the age at which stand volume begins to level off (here assumed to be the age at which yield = 80% of the asymptote), was determined in consultation with Josephson (1962), referencing empirically derived yield tables, and the USFS Silvics of North America for species growing in Washington (Burns and Honkala 1990).

All values reported here include the carbon in above- and belowground live biomass.

Where a single forest class had significant coverage across a wide range of forest suitability classes (>10 classes) in a Holdridge Life Zone, the forest class was further broken down into productivity classes (high, medium, and low productivity). The cumulative distribution of the areas across the life zone's suitability classes was then divided into equal-area low-, medium- and high-productivity classes. The carbon sequestration estimates are shown in Table 2-2.

Table 2-2. Estimated rates of carbon sequestration of selected forest vegetation types

Forest Type	Dominant NW Regional Gap Analysis Categories	Example Species	Prod. Class	Biomass carbon (t C/ha) at age:			Source
				20	40	80	
Subalpine forest	Subalpine fir Engelmann spruce Mixed subalpine coniferous forest	Engelmann spruce, Subalpine fir	High	50.65	85.7	159.5	DOE 1605b
			Mid	40.85	62.75	114.65	
Mixed coastal forest	Coastal coniferous forest Coastal lodgepole pine Mixed coastal forest Grand fir	Grand fir, Douglas fir, Sitka spruce, lodgepole pine		116	285	501	Smithwick et al.2002; Calculated from Eqn. 2-1
Jeffrey pine	Jeffrey pine	Jeffrey pine		38.42	134.87	254.09	Burns and Honkala 1990; Smith et al. 2003, Cairns et al.1997
Lodgepole pine	Lodgepole pine	Lodgepole pine		25.2	53.3	95	DOE 1605b
Ponderosa pine	Ponderosa pine	Ponderosa pine		28.8	46	76.1	DOE 1605b
Douglas fir	Mesic Douglas fir	Douglas fir	High	49.6	180.7	391.4	DOE 1605b
			Mid	39.5	132.5	315.5	
			Low	29.3	84.2	239.5	
Western hemlock	Western hemlock	Western hemlock	High	65.5	231	467.7	DOE 1605b
			Mid	51.6	173	399	
			Low	37.7	115	329	
Mixed mesic forest	Mountain hemlock Western redcedar Mixed mesic coniferous forest Coniferous forested riparian Deciduous forested riparian Whitebark pine Mixed mesic forest Mixed riparian	Douglas fir, Mountain hemlock, Western redcedar		57	161	350	Smithwick et al.2002; Calculated from Eqn. 2-1

Table 2 cont.

Forest Type	Dominant NW Regional Gap Analysis Categories	Example Species	Prod. Class	Biomass carbon (t C/ha) at age:			Source
				20	40	80	
Mixed xeric forest	Mixed xeric coniferous forest Western larch Xeric deciduous forest Xeric Douglas fir Xeric mixed forest	Ponderosa pine, western larch, Douglas fir		22	55	96	Smithwick et al.2002; Calculated from Eqn. 2-1
Mesic deciduous forest	Mesic deciduous forest, Deciduous forested riparian	Bigleaf maple, Cottonwood, Aspen		50.2	84.5	161.5	DOE 1605b

2.2.6. Carbon Stock Baselines in Non-tree Vegetation

The rangeland vegetation classes from the Northwest Regional Gap Analysis were combined into categories based on biomass. Biomass values for each of the categories were obtained from Forest Inventory and Analysis data (USDA Forest Service 2002) and from the literature.

The biomass carbon values and the sources of the data are given in Table 2-3. These carbon stocks on existing rangelands represent the baseline that is not considered attributable to afforestation activities on those lands.

Table 2-3. Biomass carbon stocks in rangeland vegetation classes

Vegetation Type	Northwest Regional Gap	Biomass	Source
Wet grasslands	Alpine meadow	5.9	Prichard et al. 2000
Mesic grasslands	Subalpine meadow	2.4	Brown and Archer 1999
Xeric grasslands	Xeric grasslands	0.6	Winrock unpublished
Shrub/tree	Pinyon pine	25.5	FIA analysis
Shrub	Big sagebrush	5.1	Martin et al. 1981

2.2.7. Economic Analyses

All economic decisions involve trade-offs. If activity X is forgone in order to undertake activity Y, then the value of undertaking activity X must be considered as the ***opportunity cost*** of undertaking activity Y. Simply put, the opportunity cost is the most highly valued alternative to the activity being considered. In this case, the activity being considered is afforestation of range- and cropland in Washington. Therefore, the profitability per hectare in Washington represents the opportunity cost of producing carbon on that land (i.e., afforestation). The ultimate cost of producing carbon through afforestation on crop- or rangeland will differ from site to site and county to county primarily based on the quality of the soil and growing conditions, which directly influence both crop and range yields (i.e., opportunity forgone) and carbon yields (i.e., afforestation).

In the economic analysis, the "price" a farmer/rancher would need to receive to take a parcel of land out of agriculture/rangeland and put it in forestland use for increased carbon sequestration needs to be estimated. That "price" must be equal to or greater than the return the farmer/rancher is currently receiving from the agricultural or range use of that land. For a landowner to consider taking an acre of agricultural or range land out of that use for the purpose of afforestation, the "price" will have to be equal to the marginal return to the farmer from the parcel of land under consideration. That marginal return is the estimated revenue less the input costs for the agricultural enterprise in question for putting that last acre into agricultural or range production. Only the variable costs of agricultural or range production are used in this analysis because it is unlikely that a farmer will enroll all land in a carbon sequestration program, but only a smaller proportion thereof. As a result, the allocation of fixed costs over the amount of unit area remaining in agricultural or range land use remains about the same and can be ignored.

The economic analysis methodology for estimating the opportunity costs of afforestation projects on range- and cropland is based on widely available data on prices, costs, and yields of the major crops produced in the state. This methodology was intentionally designed to be easily replicable across states. As such, it foregoes some degree of local specificity regarding costs and prices of crop production, but the simplicity and replicability of this approach outweighs the small margins of error caused by using regional cost and price data.

To calculate the total cost of afforesting rangeland and cropland, the variables considered were opportunity costs, one-time conversion costs, management costs, and measurement and monitoring costs. The economic analysis for rangelands is practically identical to that used for California (Brown et al. 2004) and that for croplands the same as that for the Southern States regional partnership (Brown and Kadyszewski 2005a). The following pages briefly describe the approaches for estimating total costs and the local values used in the analyses.

Rangelands

The most highly valued alternative to afforestation is cattle ranching. (An alternative to afforestation of rangelands could be conversion to urban development, and depending upon the price of real estate, the opportunity cost for this alternative could be high. This alternative was not considered in the analysis.) Therefore, the profitability per acre of cattle ranching in Washington represents the opportunity cost of producing carbon (i.e., afforestation).

The profitability of cattle ranching varies greatly from year to year and from ranch to ranch. This is due primarily to weather conditions and cyclical fluctuations in the price of beef.

Unfortunately, annual enterprise budgets for cattle ranching, which indicate profitability, are not officially kept in Washington. Because of this, the analysis relied on input from recent Cattle-Fax publications and from personal communication with rangeland extension specialists[2] to calculate an average annual profitability value for Washington cattle ranching (Table 2-4). The revenue estimates reported in Table 2-4 reflect long-term average prices received for cattle. After subtracting total costs of production from revenue, an average annual profit per cow is estimated to be $94.75.

Other than the wide swings in the price received for cattle, the most critical variable in determining ranching profitability is the forage production potential of the rangeland. Forage production determines the carrying capacity of the land. Higher forage production can support more cows per acre and therefore results in higher profits per acre. Moisture and soil conditions are the primary predictors of rangeland productivity and are the drivers of the methodology described below.

Table 2-4. Revenue and costs associated with cattle ranching in Washington (data from Cattle-Fax and T. Hudson and D. Nelson, Washington State University, 2005, personal communication)

Economics of Ranching in Washington			
Revenue			
	Total	$/Animal	Assumption
Calf	$600.00	$510.00	85% wean rate
Cull cows	$425.00	$63.75	15% cull rate
Total Revenue		$573.75	
Costs in $/Animal			
Pasture		$130.00	
Supplemental feed		$151.00	
Other operating and fixed costs		$198.00	
Total Costs		$479.00	
Mean annual profit/animal (Revenue – Costs)		$94.75	

Western rangeland specialists use an average of 791 lbs. of forage dry matter (DM) to represent the monthly requirements for cattle being fed on rangeland forages (L. Metz 2003, USDA-NRCS, Davis, CA, personal communication). This monthly requirement is termed an animal unit month (AUM) and is used as a measure of the carrying capacity of a parcel of rangeland. Therefore, if one acre of rangeland produces 791 lbs. of forage DM over the course of one month, that acre is said to produce one AUM of forage. This translates into an annual per-cow

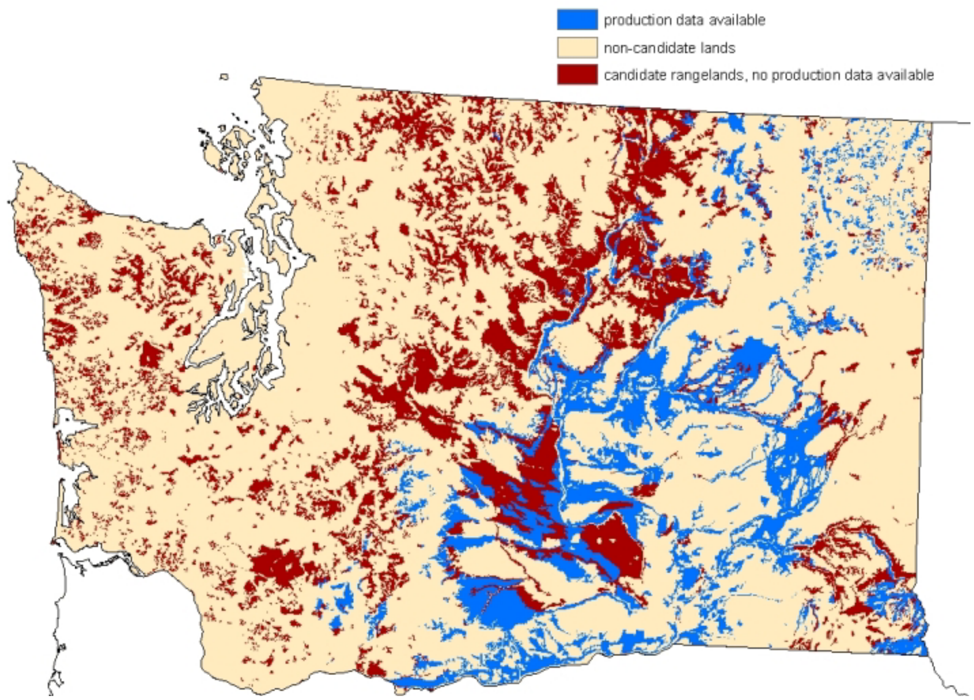
1. From personal communications in 2005 with Don Nelson, Washington State University Extension Beef Specialist for Pacific Northwest; and Tip Hudson, Washington State University Rangeland Extension Specialist.

forage requirement of 9,492 lbs. DM (12 times the AUM). This forage requirement estimate (i.e., AUM of 791 lbs.) and the average annual per-cow profitability of $94.75 were used to estimate the profitability potential (i.e., opportunity cost) for all Washington rangelands, as explained next.

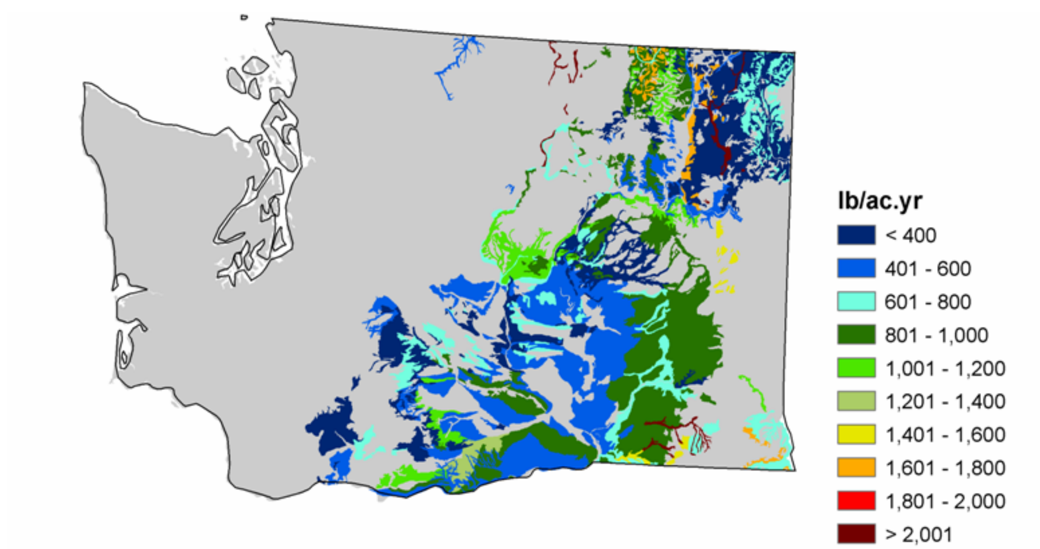
For rangeland that produces only 100 lbs. of forage DM per acre, almost 95 acres will be required to support one head of cattle for a year. The annual per-acre profitability of this low-producing rangeland is estimated to be only $1.00 (i.e., $94.75/95). High-producing rangeland of 2,000 lbs. DM per acre per year will require only 4.75 acres to support one head. In this case the annual per-acre profitability is $19.96 (i.e., $94.75/4.75). The relationship between annual average per-cow profitability and annual average per-cow forage DM requirements yields a constant relationship indicating that each pound of forage DM is equal to $ 0.009982 in ranch profits. This average profitability figure per pound of forage production was used to project the profitability of all Washington rangelands.

The modeling methodology that was developed to estimate forage production for all Washington rangelands used forage production estimates from the State Soil Geographic Database (STATSGO). The forage production estimates were translated into a livestock carrying capacity for the land and combined with the average per-cow profitability (Table 2-4) to estimate the average annual opportunity cost of afforestation for each pixel of rangelands on the map.

Because forage production from STATSGO was not available for the full extent of a state's rangelands, a multivariate regression was run using the variables of aspect, slope, elevation, mean annual precipitation, mean annual temperature, and available water content in the soil (based on the approach developed for California). These data were extracted from 5180 sample locations in both Washington and Oregon where STATSGO data were available for the dominant soil components, and a highly significant relationship as reflected in low P values was derived. Figure 2-9a shows areas where forage production data were unavailable from STATSGO and where the regression analysis was used to fill in the gaps. Figure 2-9b shows the range of forage production in areas where STATSGO data were available. Most of the mapped rangelands have low productivity (less than 600 lb/ac.yr) and would require about 16 acres to support one animal.



(a)



(b)

Figure 2-9. (a) Dominant soils components with available STATSGO "rsprod" (range productivity) data (maroon areas were filled with regression results); and (b) estimates of forage production for areas with "rsprod" data

Conversion costs and ***maintenance costs*** are those associated with establishing tree plantings on rangelands in Oregon; it was assumed given similarities between the two states that the cost for Washington would be the same. Based on information from a range of timber companies, the cost of establishing forests varies from $300 to $600 per acre, with the variability stemming mostly from soil moisture and texture, and slope of the site. The Oregon Department of Forestry (J. Cathcart personal communication) gave an estimate at $550 per acre ($1,360/ha) that was used for this analysis. The maintenance cost is projected to be incurred for a period of five years from the beginning of the activities to ensure that enough tree seedlings survive to generate a well-stocked, free-to-grow stand. Expected maintenance activities (depending upon local conditions) include replanting seedlings that die, weeding (or herbicide application), possibly fertilizing, and installing adequate fencing to control livestock incursion until the trees get established. Annual maintenance costs are estimated to be approximately $70/ac.yr during the first 5 years of activities ($173/ha.yr), as shown in Table 2-5.

Table 2-5. Assumptions in per-acre cost breakdown for afforestation projects (for croplands, "Site prep" was reduced by 50%)

One-time Conversion Costs		Maintenance Costs	
Site preparation	$250	Vegetation management	$130
Seedling costs (436 trees/acres @ 10 ft. x 10 ft. spacing)	$150	Interplanting/contingencies (seedlings and labor)	$120
Planting labor costs	$120	Final release	$90
Administration	$30	Additional administration costs	$10
	$550		**$350**
		Cost per year for first 5 years	$70

The final cost category is the ***cost of measuring and monitoring (M&M) carbon production*** over the life of the activity. The average annual M&M costs associated with carbon production contracts is estimated to equal $1.60/ac for 20-year projects, $1.08/ac for 40-year projects, and $0.80/ac for 80-year projects, based on Winrock's experience with measuring and monitoring many afforestation activities throughout the U.S. Several factors affect the magnitude of the cost, including which pools are measured and monitored (this analysis assumes only aboveground biomass), frequency of monitoring (once every five years over the duration of the project), area, and whether the lands are contiguous or dispersed (assumed here to be contiguous). The area of the activity is an important factor and economies of scale exist for M&M costs; therefore, per-acre M&M costs may be significantly higher for smaller activities.

Because the economic analysis is considering afforestation activities that are 20, 40, and 80 years in duration, the annual opportunity cost estimates were projected into the future (20, 40, and 80 years) and then discounted to obtain a present value (PV) estimate of the annual stream of profits from farming that would be foregone to allow for afforestation. The real discount rate used in this analysis is 4 percent (6% discount rate minus 2% inflation rate). The costs that are incurred only at the beginning of the project are not discounted. These include the conversion cost and the contract cost (currently assumed to be zero because data are not available) and are added to the total present-value costs. The resulting numbers represent the present value of all of the current and future costs (for the life of the carbon project) associated with sequestering carbon on rangelands through afforestation (Table 2-5).

Table 2-6. Present value of current and future costs associated with sequestering carbon on Washington rangelands through afforestation

Forage production lbs/acre.yr	20 year	40 year	80 year
100	$2,310	$2,325	$2,329
500	$2,444	$2,520	$2,565
1000	$2,612	$2,764	$2,860
1500	$2,779	$3,008	$3,155
2000	$2,947	$3,252	$3,450

Croplands

The economic analysis for croplands involves estimating the profitability of crop production for the major relevant crops of Washington using USDA county-level area and yield data. The crops selected for inclusion in the analysis are the crops that meet both of the following criteria: (1) they represent a significantly large area in the state, and (2) they have an average profitability that is low enough to allow carbon projects to be a possible alternative (i.e., commodity crops as opposed to high-value crops). The two crops that meet these criteria for Washington are wheat and hay. Another reason that the higher-value crops were not included in this analysis is that they tend to cover smaller areas and are not distinguished clearly on any land-use or land-cover maps and thus are difficult to identify.

The area and the average yield for each county within Washington were collected from the USDA National Agricultural Statistics Service (NASS) for the years 2000–2004. NASS's annual program focuses on agricultural production for mainstream crops, livestock, and associated inventories. The program is based on a series of sample surveys to collect farm-level data to produce the state and U.S. crop forecasts and estimates published in the NASS Agricultural Statistics Board reports.

In a given year, net returns (NR) to the land, per area of land, can be calculated with the expression:

$$NR = PY - CY + G \qquad \textit{Eqn. 2-2}$$

where:

- P is the price per unit for each commodity received by the farmer.
- Y is the expected yield of that crop.
- C is the variable cost of production per unit.
- G is the amount of money received as government payments or subsidies for producing that crop.

Estimates of the total price (P) received by the farmer are based on estimates of future market prices for the year 2005 through 2014. Estimates of future prices for the major U.S. crops are published by the Food and Agriculture Policy Research Institute (FAPRI). The mean of the actual and projected prices for the years 2005–2014 are used as the price in the opportunity cost calculations for this analysis. The costs of production for each of the major crops in each county were calculated by multiplying the reported average yield for the crop by the variable costs of production. Fixed costs of production were ignored.

The variable costs of production for each of the major crops were taken from the enterprise budgets prepared by the extension specialists for each crop. The yield used for each crop in each county is the average of the reported county yields for the years 2000 through 2004. As mentioned above, these data come from the USDA-NASS database. The county-specific yields for each crop generate the variability in estimated profitability associated with crop production across the state.

For the crops included in this analysis, wheat and hay, government payments (G) are applicable only to wheat. For wheat, like other subsidized crops, G consists of up to three components. These are loan deficiency payments received per unit of production, counter-cyclical payments per unit of production, and direct payments per area of production. The loan deficiency payment and counter-cyclical payment are conditional based on the price received for the crop. The direct payment is received regardless of price or yield. The standard formulae for calculating each of the government payments and the total G are applied in this analysis.

Any given area of cropland is likely to have a rotation of crops produced on it over a number of years for agronomic and economic reasons. This analysis used USDA-NASS data on planted area for each crop in each county to calculate the average percentage of hectares planted to both wheat and hay from 2000–2004. This average for each county was used to estimate a weighted average profitability for crop production in each county. By using county-specific yield and area data, combined with prices and per-unit costs that are constant across the region, this analysis was able to produce relatively specific estimates of opportunity costs with a simplified and replicable analytical framework.

The profitability (i.e., opportunity cost) estimates for each crop in each county are then weighted by the average percentage of cropland planted to each crop in each county from 2000 through 2004. This averaging process is necessary to account for the frequency of crop rotations on agricultural land. Each county then ends up with a unique opportunity cost for foregoing crop production for afforestation. This estimated opportunity cost could be viewed as the minimum amount of return necessary to induce landowners to afforest agricultural land.

Added to the opportunity cost are the costs of converting the land to trees, managing the land for afforestation, and measuring and monitoring carbon production on that land as was done for rangelands and described above. Finally, a present-value analysis was performed using the same time intervals and discount rates as for rangelands described above. The results of this analysis, in terms of present value of the total costs for afforesting croplands in Washington, are shown in Table 2-7.

Table 2-7. Present value of the total costs for afforesting croplands in Washington after different time intervals

	20 years	40 years	80 years
Mean	$3,316	$3,930	$4,334
Median	$3,143	$3,678	$4,028
Minimum	$2,665	$2,982	$3,188
Maximum	$4,190	$5,203	$5,871

2.3. Results: Carbon Supply for Rangelands and Croplands

2.3.1. Carbon Sequestration Potential

Based on the analyses of carbon sequestration potential and productivity across suitability and Holdridge Life Zone classes, carbon sequestration grids were derived for all rangelands and croplands. On candidate areas, new grids of additional carbon that could be sequestered were obtained by subtracting the current carbon stocks (Table 2-3) from the potential carbon stocks after different time intervals (Table 2-2). The amount of carbon sequestered at any of the time intervals is always lower in the drier east side of the state than in the moister west side (Figures 2-10 and 2-11). Even after 80 years, the maximum carbon stocks that can be attained by afforestation of rangelands and croplands in the eastern part of the state range between 50 to 100 t C/ha. In contrast, this value is attained within 20 years on lands in the western, more humid part of the state.

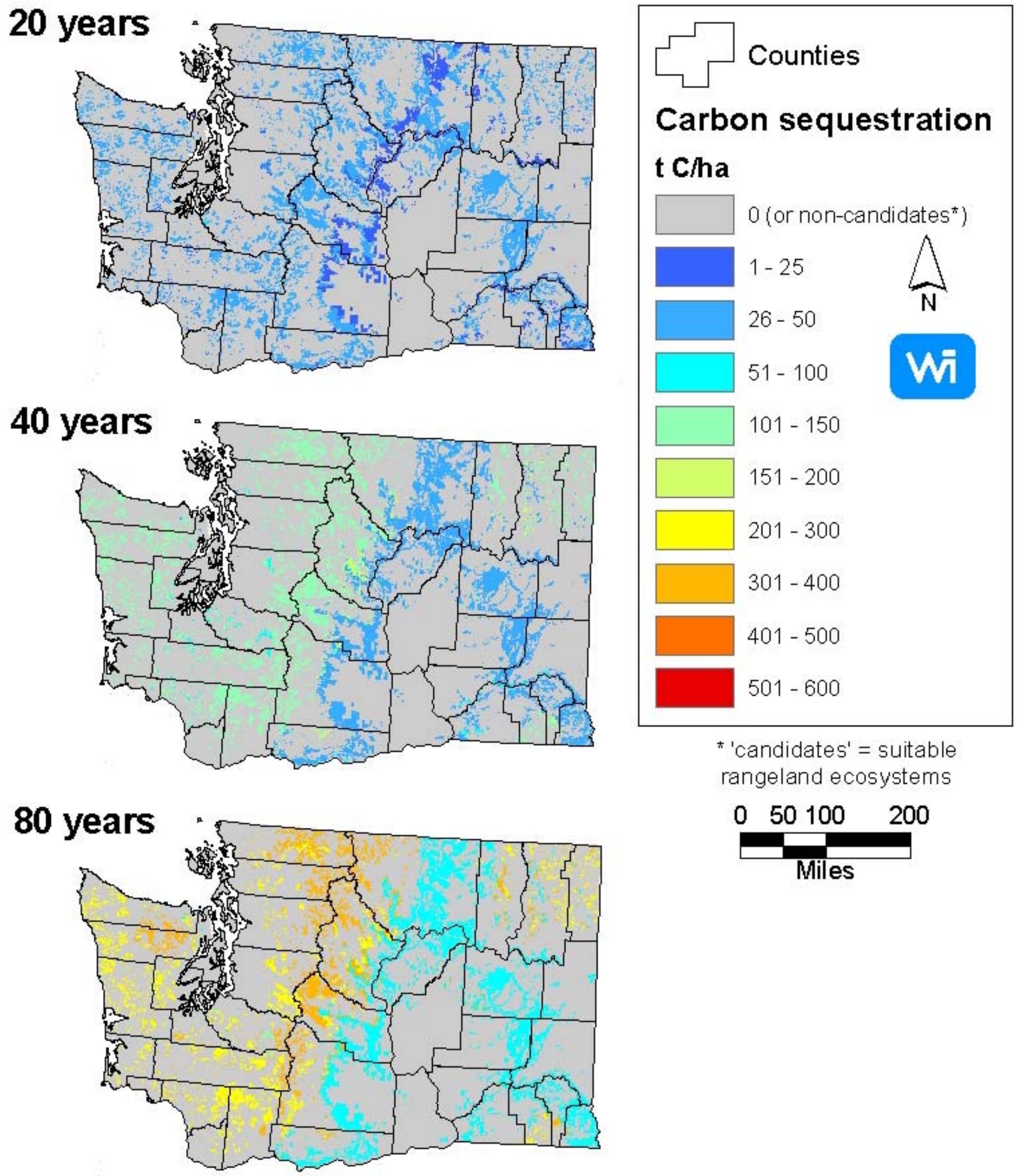


Figure 2-10. Carbon sequestration potential from afforestation with native species on suitable rangelands in Washington

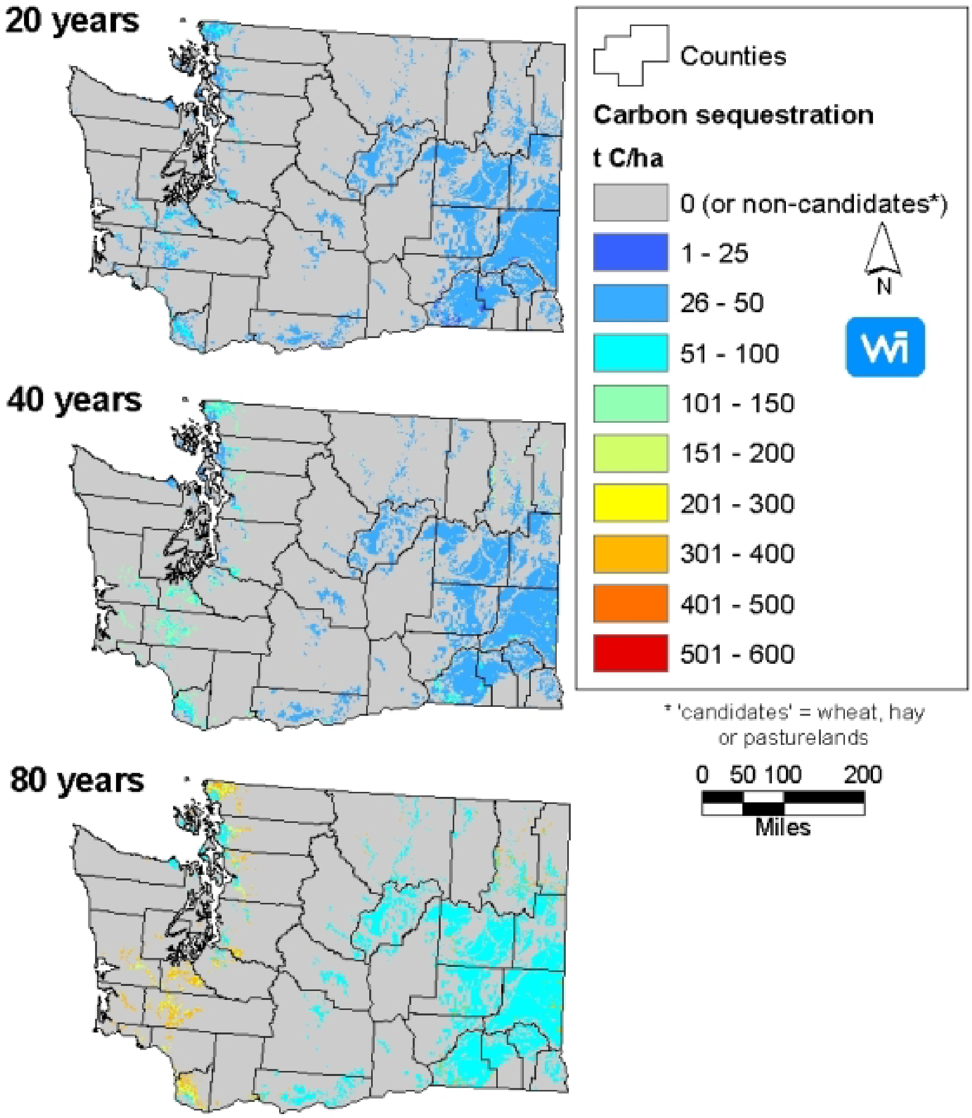


Figure 2-11. Carbon sequestration potential from afforestation with native species on suitable croplands in Washington

2.3.2. Total Present Value of Costs

The total costs in $/ha for afforesting rangelands and croplands are mapped in Figures 2-12 and 2-13. The present value of the costs is higher for the longer-duration scenarios because there is a longer period of time where the rangeland opportunity has been forgone. The present value of the cost hurdle on rangelands tend to be less than $3,000/ha for the 40-year duration period. For a project lasting 80 years, the present value of the cost hurdle is generally below $3,250/ha, except for a few areas where costs reach up to and above $3,500 /ha (Figure 2-12).

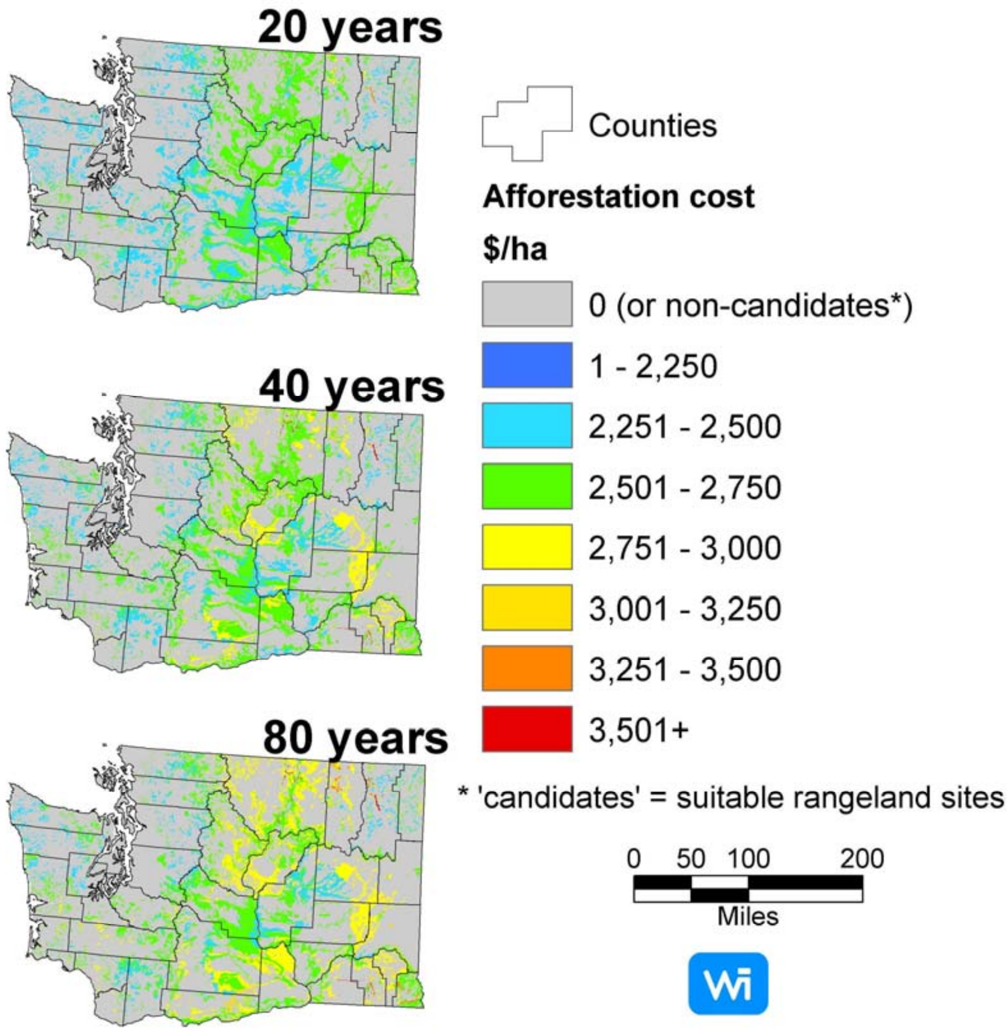


Figure 2-12. The present value of the total cost ($/ha) to afforest candidate rangelands

As expected, the present value of sequestration costs for croplands are considerably higher than for rangelands (Figure 2-13). Half of the cropland costs less than $4,000/ha up to 40 years. After 80 years, costs go as high as $5,000/ha.

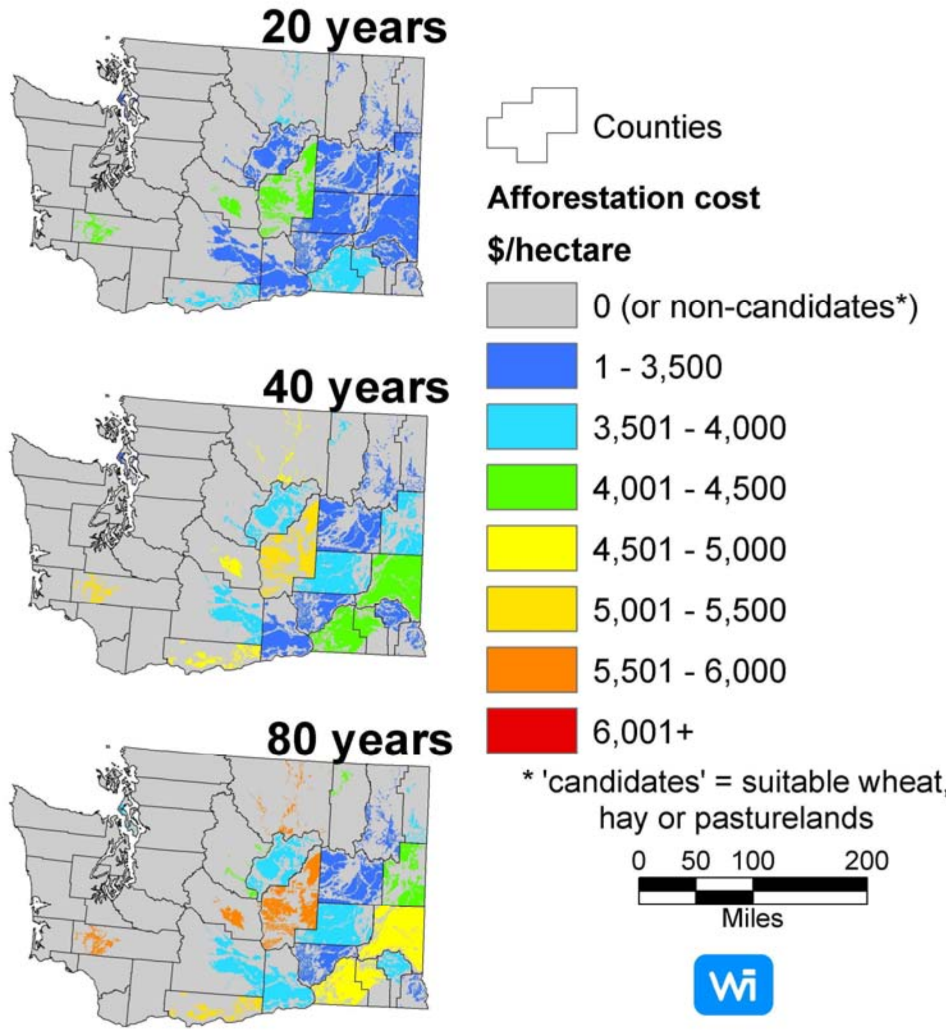


Figure 2-13. The present value of the total cost ($/ha) to afforest candidate croplands

2.3.3. Carbon Supply for Afforestation of Rangelands and Croplands

Figures 2-14 and 2-15 show the spatial distribution (at 30 m resolution) of the cost per tonne of carbon (t C) for afforesting rangelands and croplands for activities lasting 20, 40, and 80 years. After 40 years, much of the rangeland available for afforestation supplies carbon at costs of between $16 and $75/t C. However, for longer projects, the costs per t C decrease because the initial afforestation costs are now spread over more years of sequestration so that the amount of carbon storage is increased due to tree growth. The costs per t C decrease through time, so that after 80 years, much of the rangeland, especially towards the western part of the state, could be afforested and supply carbon at less than $10/t C (or <$2.70/t CO_2).

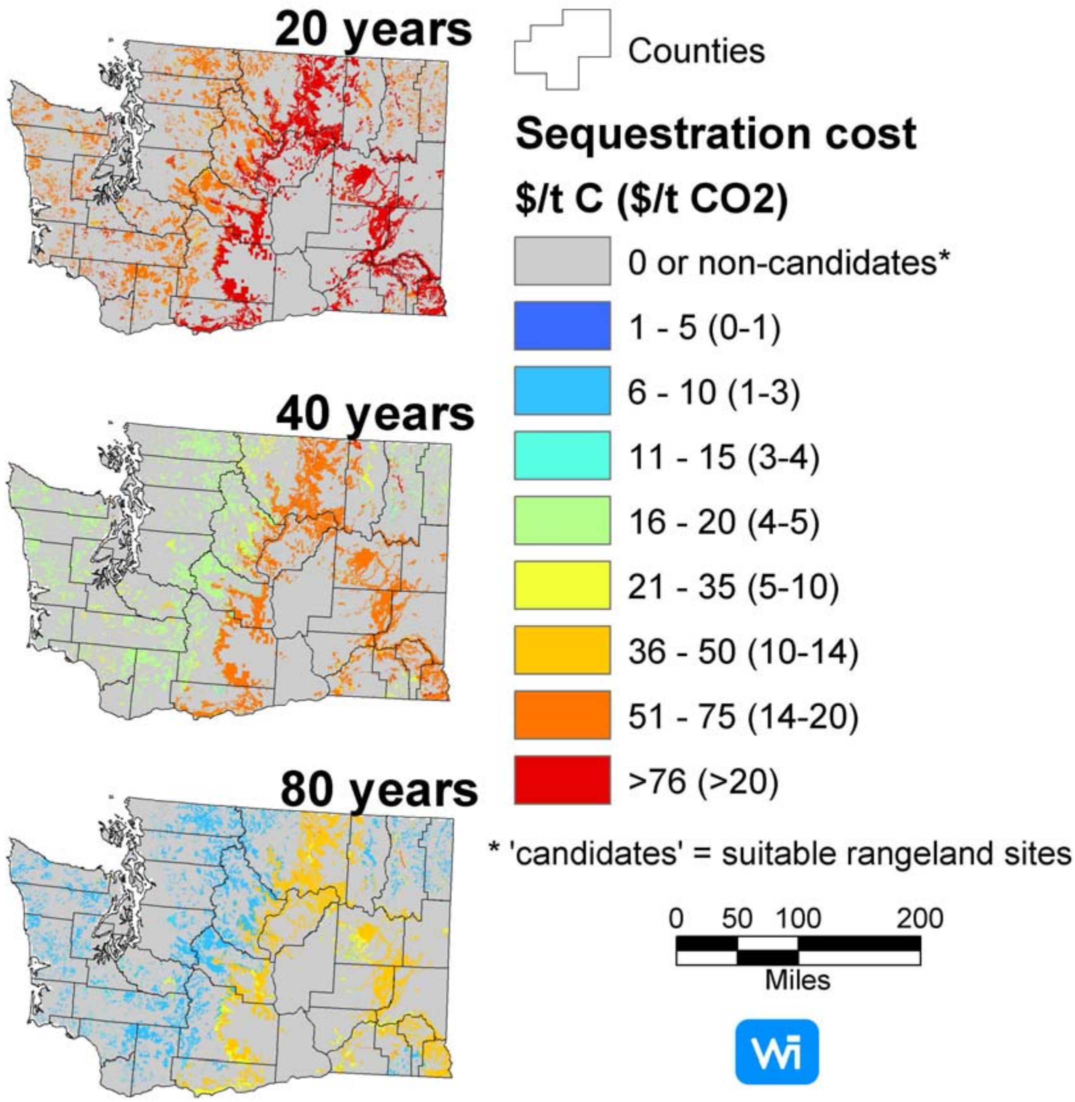


Figure 2-14. Costs of carbon sequestration through afforestation of suitable rangelands of Washington

Similar to the case for rangelands, for activities lasting only 40 years, much of the cropland available for afforestation supplies carbon at costs of more than $50/t C (Figure 2-15). The costs per t C decrease somewhat for longer-lasting projects, but still much of the cropland in the eastern part of the state has the potential to supply carbon mostly in the $36–$75/t C range.

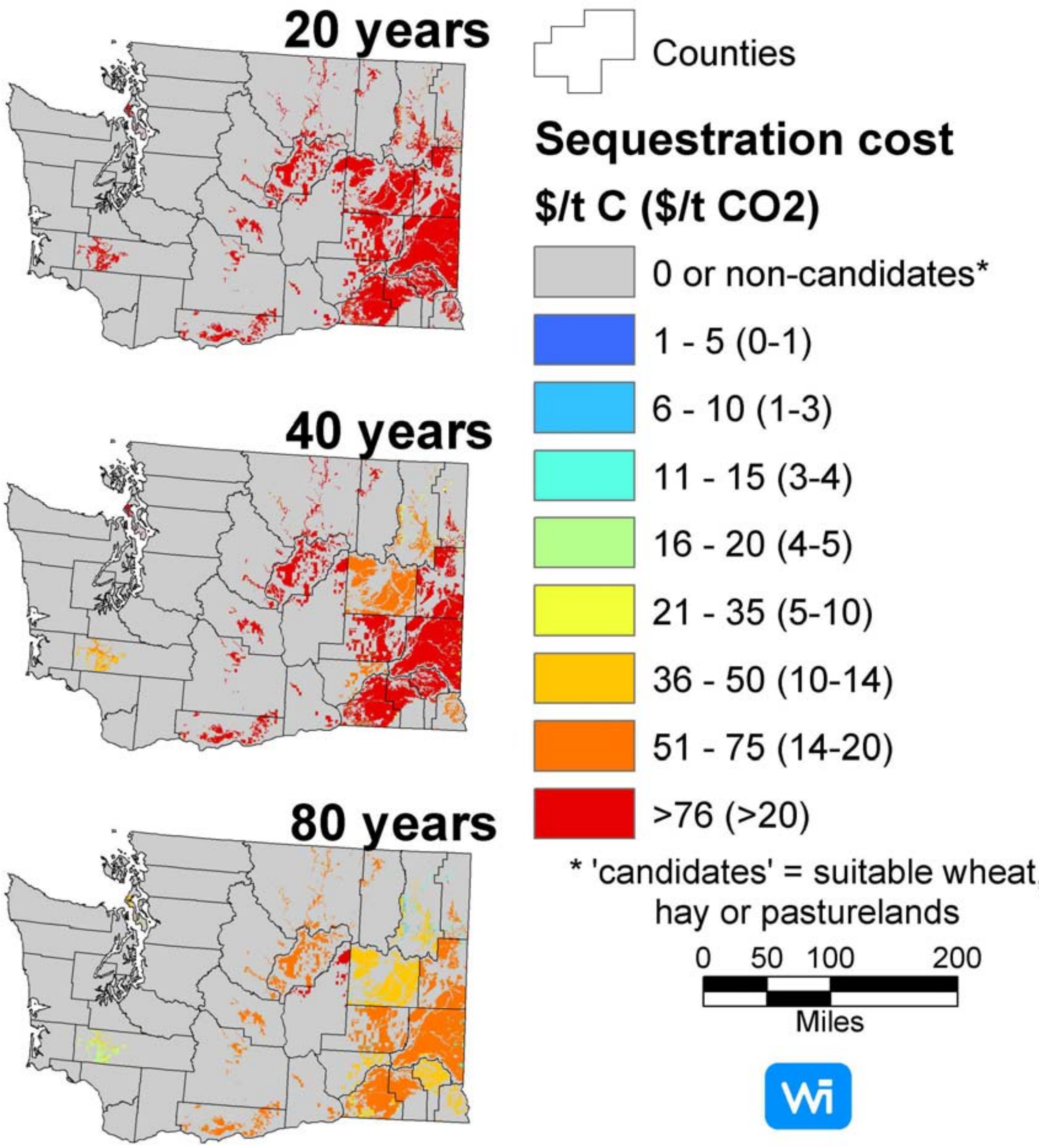
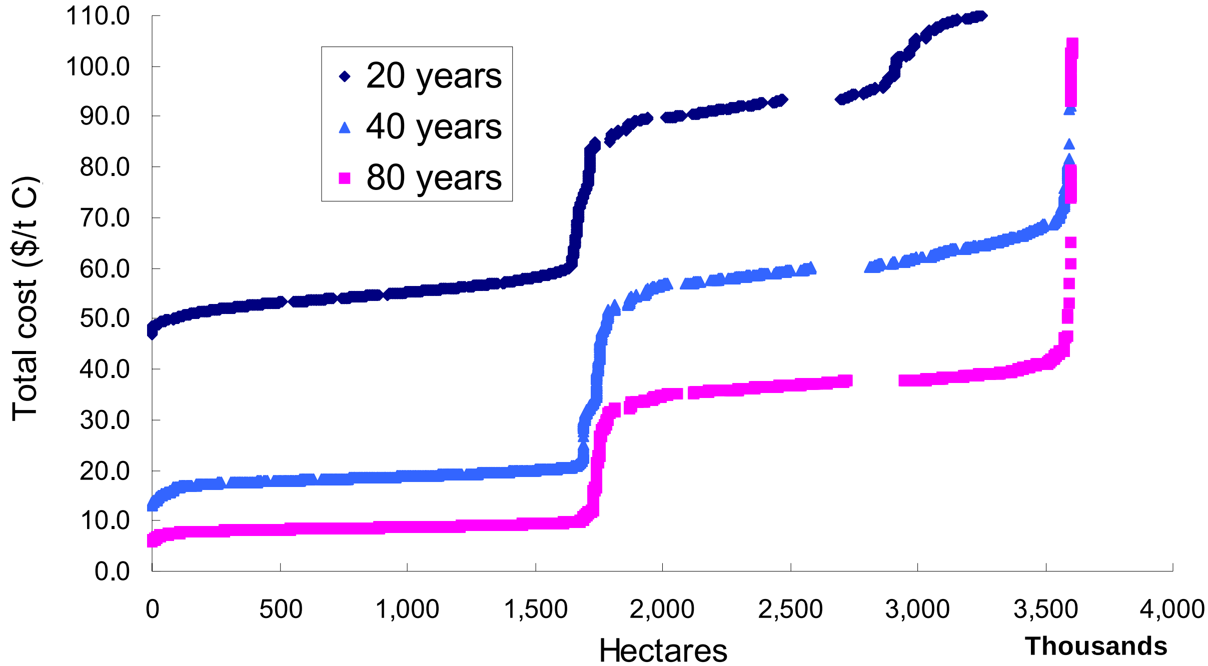


Figure 2-15. Costs of carbon sequestration through afforestation of suitable croplands of Washington

The area of rangeland available for afforestation increases up to about 3.6 million ha at gradually increasing costs for all project durations (Figure 2-16, top). The quantity of carbon available from afforestation of rangelands at different price points below $100/t C and time periods is shown in Figure 2-16 (bottom). At a common carbon price of $36/t C ($10/t CO_2), afforestation of rangelands produces no carbon after 20 years, about 240 million t C after 40 years, and 550 million t C after 80 years.



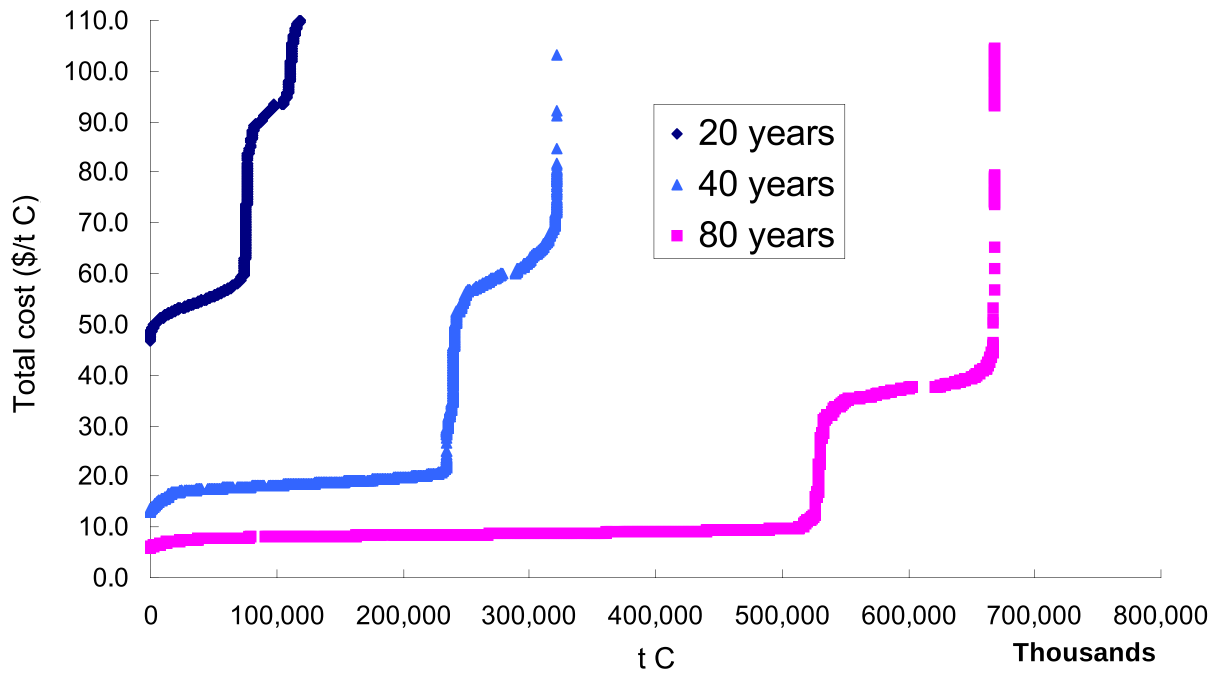


Figure 2-16. Carbon supply curves for afforestation of suitable rangelands in Washington: (top) areas available and (bottom) quantity available at different costs per tonne carbon

The total amount of carbon that could be sequestered by afforestation of rangelands is highest at all three time periods in the counties in the central part of the state, on the eastern side of the Cascades (Figure 2-17). The westernmost counties also have the potential to sequester considerable quantities of carbon at all three time periods. Counties in the southeast part of the state have the lowest potential and do not exceed 8 million t C even after 80 years, whereas most of the central and many of the western counties have the potential to sequester more than 30 million t C after 80 years.

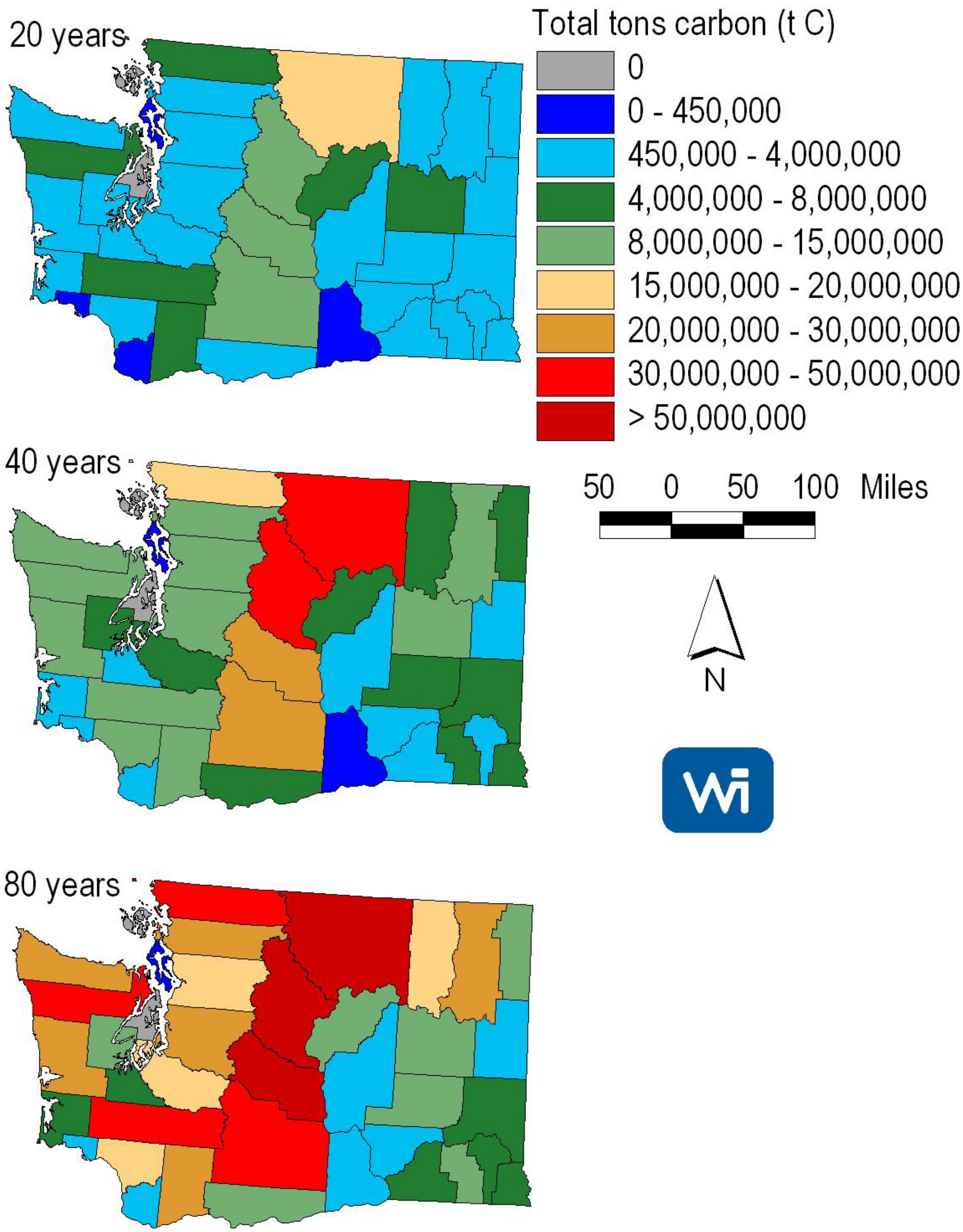
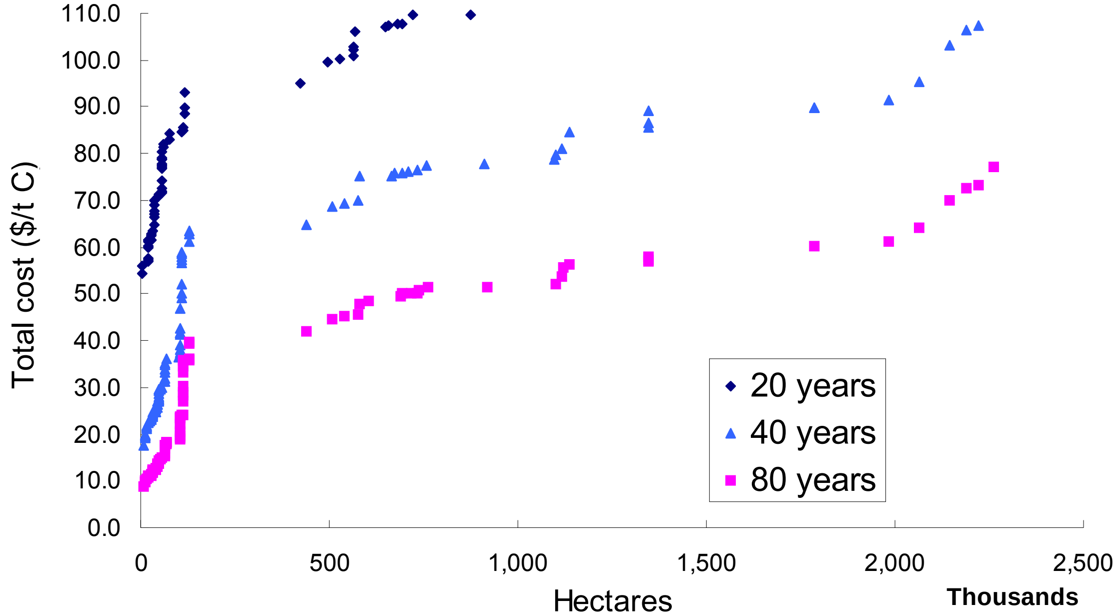


Figure 2-17. Spatial distribution, at the county scale of resolution, of the total amount of carbon that could be sequestered by afforestation of rangelands after 20, 40, and 80 years



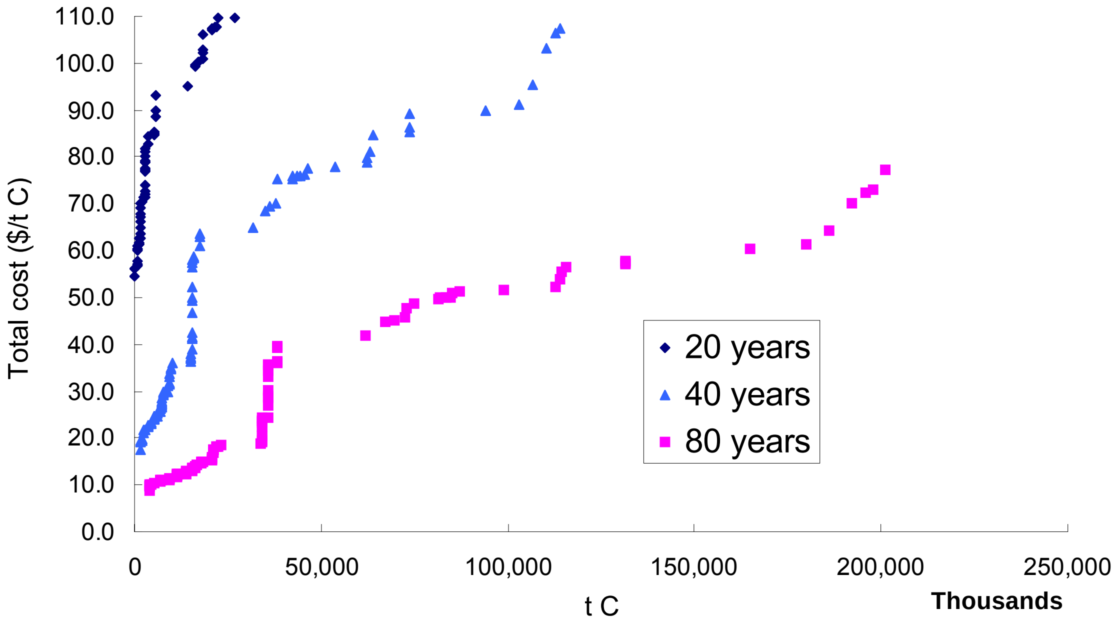


Figure 2-18. Carbon supply curves for afforestation of suitable croplands in Washington: (top) areas available and (bottom) quantity available at different costs per tonne carbon

The area of cropland available for afforestation increases up to about 2.3 million hectares at gradually increasing costs for all time periods (Figure 2-17, top). The quantity of carbon available from afforestation of croplands at different price points below $100/t C and time periods is shown in Figure 2-18 (bottom). At a common carbon price of $36/t C ($10/t CO_2), there would potentially be none after 20 years, 15 million t C after 40 years, and 38 million t C after 80 years.

The total amount of carbon that could be sequestered by afforestation of croplands is highest at all three time periods in the counties in the eastern part of the state (Figure 2-19). Many of these eastern counties have the potential to sequester between 15 and 30 million t C after 80 years. Counties in the central and south central part of the state have the lowest potential and do not exceed 4 million t C even after 80 years.

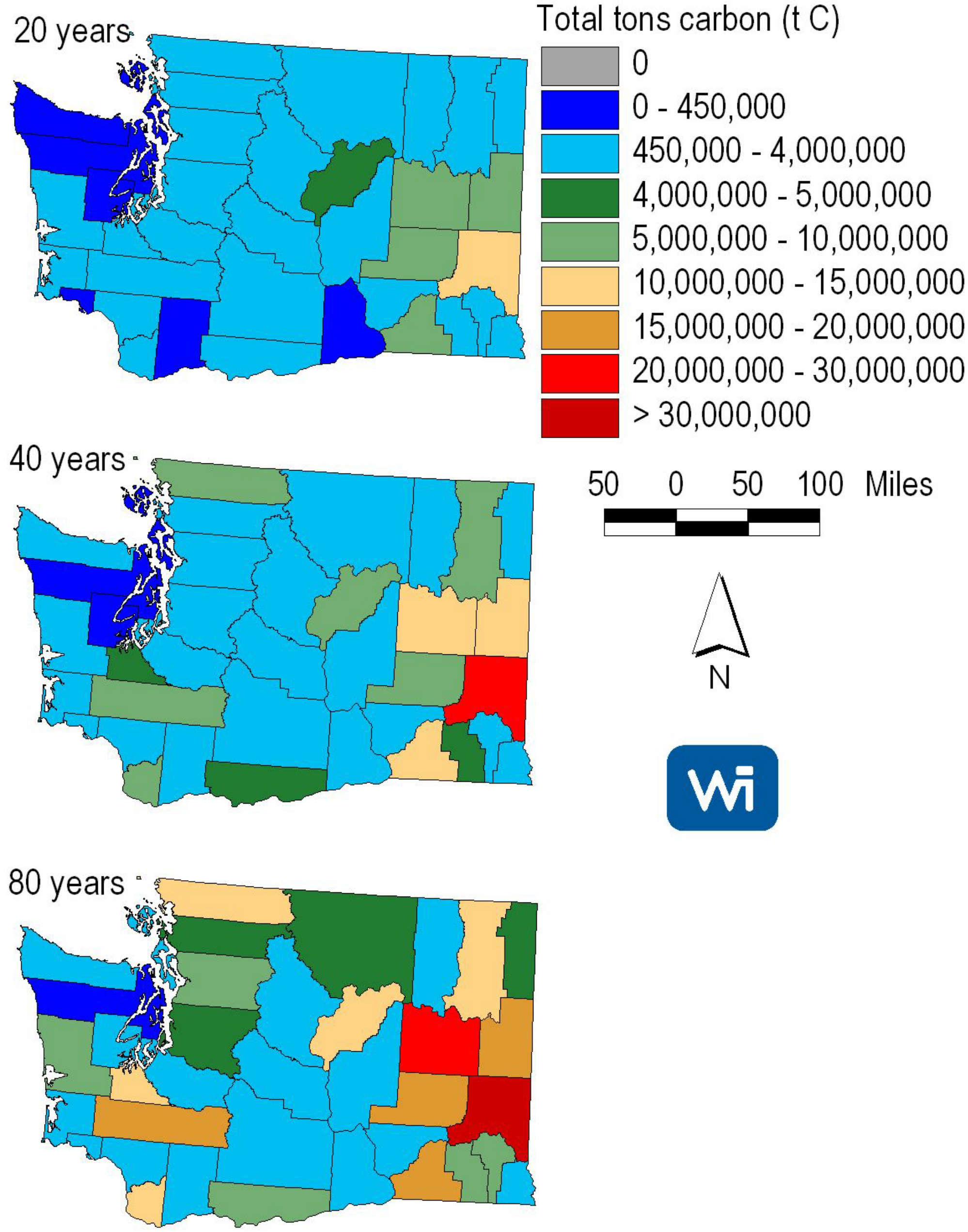


Figure 2-19. Spatial distribution, at the county scale of resolution, of the total amount of carbon that could be sequestered by afforestation of croplands after 20, 40, and 80 years

3.0 Changes in Forest Management

3.1. Background

This chapter presents the potential for, and costs of, carbon sequestration through two potential changes in forest management: increasing rotation ages and increasing the area of riparian zones along streams in Washington. The project developed a model to describe how optimal rotation ages are affected by changes in the value of sequestered carbon. The model was used to estimate the marginal costs of increasing rotation ages 5, 10, and 15 years beyond currently optimal rotation ages. The model was also used to estimate the costs of holding land indefinitely in riparian zones. Estimates of marginal costs were developed for a range of species, site classes, and timber pricing regions in Washington. These costs were then applied to U.S. Department of Agriculture Forest Service Forest Inventory and Analysis (FIA) data to estimate the spatial distribution of carbon sequestration.

The results indicate that there are around 444,000 hectares of private timberland nearing the optimal rotation age in Washington. Up to 12.0 million t C could be stored in 15-year rotation extensions on this land. The average cost per tonne is around $136 per t C, or about $2,862 per hectare. For expanding riparian zone management, there appear to be around 14,100 hectares of land nearing the optimal rotation age, with the potential to store 0.6 million t C for an average cost of $122 per t C.

This section is organized as follows: Section 3.2 describes the methodology used to estimate carbon sequestration costs through aging timberland, and presents estimates of the 5-, 10-, and 15-year extension periods for Washington forests. Section 3.3 describes the approach, data used and results for setting aside timberland in extended riparian zones.

3.2. Extending Forest Rotations

3.2.1. Approach

Previous estimates of carbon sequestration costs through aging timberland have been developed for Winrock International for several Southern states (Brown and Kadyszewski 2004, 2005a) and for California (Brown et al. 2004). The methods used to estimate the costs of carbon sequestration through aging in this report are updated and revised relative to these earlier reports. This report estimates the marginal costs for permanent sequestration of carbon through aging timber, and for permanently setting aside riparian zones along streams.

Several important assumptions underlie this analysis. First, prices for all products and carbon are assumed to be constant over time. Second, for financial analysis, the value of carbon sequestration is discounted, and when calculating potential carbon storage, additional tons gained over time are also discounted. The issue of carbon discounting is discussed in more detail below.

To estimate the marginal costs of carbon sequestration in forests through aging, the optimal rotation period with and without value assigned to carbon storage was calculated. Optimal rotation periods for a range of carbon prices, and the additional (permanent) carbon stored for the alternative rotation periods are calculated. The carbon prices that achieve 5-, 10-, or 15-year aging periods are thus the marginal costs of sequestering carbon, assuming that carbon and timber prices are constant.

To calculate optimal rotation periods under alternative carbon and timber prices, the following function was maximized:

Stand Value = *Eqn. 3-1*

$$W(a) = \frac{(P_S\phi_S + P_P\phi_P)V(a)e^{-ra} + P_C\alpha V(a)e^{-ra} + rP_C\int_0^a \beta(n)V(n)e^{-rn}dn - C}{(1-e^{-ra})}$$

where:

P_S = price of sawtimber products (stumpage, \$/ft^3).

P_p = price of pulpwood products is (stumpage, \$/ft^3).

P_C = price of sequestering a tonne of carbon forever.

$V(a)$ = biomass yield, or growing stock volume (ft^3 per hectare).

Φ_S = proportion of biomass used for sawtimber.

Φ_P = proportion of biomass used for pulpwood.

α = conversion factor converting harvested biomass into "permanently" stored carbon.

$\beta(t)$ = conversion factor converting biomass yield into carbon.

C = harvesting costs.

r = interest rate.

a = rotation period.

The first part of Equation 3-1 represents the value of harvesting the stand and selling products in markets, $(P_S\phi_S + P_P\phi_P)*V(a)e^{-ra}$. The second part of Eqn. 3-1 is the value of storing carbon permanently in markets $P_C\alpha V(a)e^{-ra}$. The term α is calculated as the present value of initial storage in market products less the present value of decay (or replacement rate of products):

$$\gamma\phi_S(0) - \int_0^\infty \delta_S\gamma\phi_S(n)e^{-rn}dn + \gamma\phi_P(0) - \int_0^\infty \delta_P\gamma\phi_P(n)e^{-rn}dn \qquad \textit{Eqn. 3-2}$$

The term γ accounts for wood density and converts wood biomass into carbon. The term α therefore accounts for the proportion of the harvested volume that is carbon as well as the proportion stored permanently in marketed products. Permanent storage is valued at the market price for carbon sequestration, *PC*. The term [$rP_C \int_0^a \beta V(n) e^{-rn} dn$] accounts for the value of carbon sequestered on the stump. Carbon on the stump is rented annually at the rate of *rPC*. Because the volume of carbon on the stump grows over time, the annual value of rental payments for carbon sequestration will increase over time. Consequently, within each rotation, the present value of rental payments must be calculated with the integral in Eqn. 3-1). The term $\beta(n)$ converts timber volume into carbon. As noted in Smith et al. (2003), carbon per unit of timber volume changes over time, so the carbon conversion factor for timber on the stump is a function of time.

For this analysis, Eqn. 3-1 is solved numerically for each timber type and pricing region in the state over a set of constant carbon prices (ranging from $0–$750 per t C). This allows determination of the optimal rotation age, given timber prices and carbon prices. The carbon price, as shown in Eqn. 3-1, represents the marginal cost of carbon storage in forests. For each carbon price (or marginal cost), the optimal additional aging period is calculated.

The additional carbon stored when forests are aged is calculated separately for each aging period. For this analysis, a 300-year period is used to assess carbon gains. Carbon stocks are calculated across this 300-year period for the baseline, and for each increment in rotation ages. The carbon benefit calculated for aging timber is estimated as the net present value of the annual change in the difference in carbon stocks (both in products and stored on the stump) during this period. The annual difference in carbon stocks is given as:

$$CSD_t = CS_t^{ER} - CS_t^B \qquad \textit{Eqn. 3-2a}$$

$$S_t = CSD_t - CSD_{t-1} \qquad \textit{Eqn. 3-2b}$$

$$NPV(Carbon) = \sum_0^{300} S_t (1+r)^{-t} \qquad \textit{Eqn. 3-2c}$$

where CS^{ER} is the carbon stock in each time period under the extended rotation and CS^B is the carbon stock in each time period under the baseline. Stands are assumed initially to be at the optimal rotation period (the baseline rotation period, "*B*"). In the baseline scenario, stands are assumed to be continuously harvested at the economically optimal rotation age. In the scenario of extended rotations with carbon prices, stands are also assumed to be harvested continuously at optimal rotations, but the optimal rotations will be longer due to carbon prices.

Throughout this study, present-value techniques are used to discount carbon flows. While most economists recognize the importance of discounting monetary flows over time, Equations 3-2a–3-2c discount a non-monetized flow of carbon, rather than carbon values. Discounting carbon flows like this is appropriate for benefit-cost analysis under the following conditions.

Suppose a company considers investing in a project that has a stream of costs, C_t, a stream of annual carbon sequestration, S_t, and a stream of the benefits of sequestering a tonne of carbon in each year, P^c_t. P^c_t is the price of carbon that would evolve in a carbon market, thus it represents the marginal costs of abating carbon in the next-best alternative for the company—i.e., it is the opportunity cost for sequestering carbon. A company would choose to invest in projects where the following condition holds (where r is the discount rate):

$$\sum_{0}^{X} C_t (1+r)^{-t} < \sum_{0}^{X} P_t^c S_t (1+r)^{-t} \qquad \textit{Eqn. 3-3}$$

Assuming that the price of carbon rises at a rate of "g" over time, this equation becomes:

$$\sum_{0}^{X} C_t (1+r)^{-t} < \sum_{0}^{X} P_0^c (1+g)^t S_t (1+r)^{-t} \qquad \textit{Eqn. 3-3a}$$

$$\sum_{0}^{X} C_t (1+r)^{-t} < P_0^c \sum_{0}^{X} S_t \left(\frac{(1+g)}{(1+r)} \right)^t \qquad \textit{Eqn. 3-3b}$$

Under this assumption, one would invest in the project if the discounted costs divided by the net discounted carbon gains are less than the current price of carbon.

$$\frac{\sum_{0}^{X} C_t (1+r)^{-t}}{\sum_{0}^{X} S_t \left(\frac{(1+g)}{(1+r)} \right)^t} < P_0^c \qquad \textit{Eqn. 3-4}$$

Note that for this analysis, no salvage value is assumed, thus the landowner retains the rights to the carbon. Further, the company that purchased the sequestration over the period of time in question must continue to hold sequestered tons beyond the project period, X, equal to the undiscounted stream of S_t. Companies may choose to renegotiate their contracts with existing landowners, purchase new contracts, or abate carbon on their own, depending on the relative costs of other alternatives, at the end of the contract term.

As can be seen in Equation 3-4, if g is 0, carbon flows can be discounted at financial discount rates and the costs per tonne can be compared to the current opportunity costs of carbon sequestration. Alternatively, one could assume that carbon is discounted with social discount rates to determine the present value of carbon. Social discount rates for carbon could be appropriate for long-term problems like climate change where damages occur in the very far distant future. The carbon analysis uses a social discount rate of 3% for carbon. Costs are discounted at 6%.

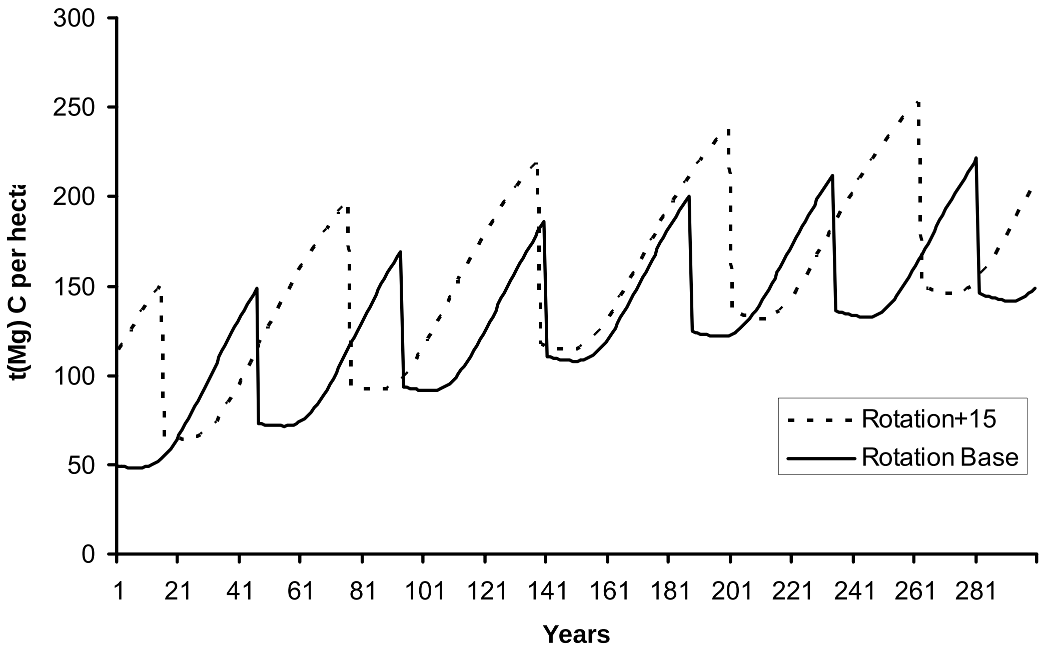


Figure 3-1. Comparison of total carbon storage on the landscape and in forest products over a 300-year period for a high-site Douglas fir stand in western Washington

To get a sense for the potential carbon flows associated with projects that might arise in Washington, Figure 3-1 compares the baseline rotation with the 15-year extended rotation for a high-site Douglas fir stand in western Washington. Carbon gains are calculated by comparing the differences in the stocks with these two rotations, and then calculating the annual change in this difference. This credits the lengthened rotation for maintaining the stock initially and avoiding an emission, and it credits future storage of timber products. It also debits the lengthened rotation for delaying the faster earlier growing period, and for emitting some carbon at harvest time. The stream of incremental carbon gains or losses are discounted to determine the net present value of the gain in carbon associated with aging a forest additional years.

3.2.2. Data Used in the Analysis

Inventory and Yield Function Parameters

These data were obtained from the USDA Forest Service Forest Inventory and Analysis database (USDA Forest Service, FIA), FIA Mapmaker version 1.7. The most recent complete periodic inventory for Washington was used, namely, data from cycle 3 collected in 1991. The data are unfortunately somewhat dated; however, the 1991 periodic inventory is the most recent complete inventory for the state. Data were downloaded on the age class distribution of forest types, and the proportion in different site classes.

Individual yield functions for timber types in the region were estimated based on information on growing stock and acres in different age classes. Timber types are aggregates based on dominant species. Many stands will contain additional species. The values of these additional species can have important effects on site value, thus corrections for the mix of species present in each RPA timber type were carried out when the marginal value of stands (i.e., the price) was calculated. All yield information was originally estimated in m³ per hectare. The functional form of the yield function was assumed to be as follows:

$$Yield\ (m^3/hectare) = exp(a - b/age) \qquad \text{Eqn. 3-5}$$

Yield function parameters for Washington used in this analysis are shown in Table 3-1.

Table 3-1. Estimated yield function parameters for Washington. Yield at 120 years using the parameters and the maximum yield observed in FIA data are shown.

Forest Type*	Parameter a	Parameter b	Yield at 120 yrs. from Parameter	Maximum Yield in FIA Data
			m^3/ha	
Douglas Fir High	7.20	70	747.4	662.4
Douglas Fir Med.	6.85	60	572.5	626.3
Douglas Fir Low	6.35	80	293.9	280.5
Ponderosa Pine Med.	5.90	60	221.4	240.5
Ponderosa Pine Low	5.45	50	153.4	184.9
Fir/Spruce Med.	5.70	50	197.0	304.0
Fir/Spruce Low	6.00	50	266.0	385.7
Hemlock/Spruce High	6.95	40	747.4	978.0
Hemlock/Spruce Med.	6.80	55	567.7	518.9
Hemlock/Spruce Low	6.30	58	335.9	466.8
Lodgepole Avg.	5.85	75	185.9	306.5
Hardwood Avg.	6.15	35	468.7	429.2

*High, medium, and low refer to productivity classes as designated by the US Forest Service FIA database.

In addition to determining the growing stock volume, it is important to estimate the proportion of growing stock used for sawtimber and pulpwood. For this, the analysis utilized USDA Forest Service FIA data that defines the proportion of growing stock that is sawtimber quality to develop the relationship between stand age and sawtimber proportion. The relationship used in this analysis is:

$$Sawtimber\ \% = 0 \qquad if\ Age < C\ (yr) \qquad \text{Eqn. 3-6}$$

$$= A*(1-EXP(-B*(Age-C)))^4 \qquad if\ Age > C\ (yr)$$

where A, B, and C are parameters given in Table 3-2.

In addition to the information presented in Equation 3-6, the analysis imposed an additional constraint that the sawtimber proportion cannot exceed 85%. Parameters used to estimate the sawtimber proportion are given in Table 3-2.

Table 3-2. Parameters used to calculate sawtimber proportion of stands for Washington

Forest Type	Parameters A	B	C
Douglas Fir	3	0.05	20
Ponderosa Pine	3	0.03	20
Fir/Spruce	2.5	0.03	20
Hemlock/Spruce	3	0.03	20
Lodgepole	2.5	0.02	20
Hardwood	1	0.02	20

Price Data

Prices were obtained from the Washington Department of Natural Resources (Tony Ifie, personal communication) for the year 2005. Prices were available for a number of different species and for a range of grades. This analysis assumed that an average price for each species is approximated by grade "3S." To determine stumpage prices, it was assumed that logging and hauling costs are $200 per thousand board feet (MBF; approximately $34 per m^3). As noted above, the analysis is based on timber types which are often composed of multiple species. That is, stands likely have multiple species within them, although they may be classified into a "dominant type." Because prices for individual species were known, the weighted average prices for timber types were estimated by using information on the proportion of each species within each timber type. The resulting weighted average prices for Washington timber types are shown in Table 3-3.

Table 3-3. Timber prices for timber types in Washington (2005)

	R1 (West Side)	R2 (Columbia)	R4 (East Side)
		$ per m^3	
Douglas Fir and Larch	$52.63	$59.21	$44.57
Ponderosa Pine	$30.14	$31.46	$40.30
Fir - Spruce	$33.75	$36.19	$33.53
Hemlock - Sitka	$36.56	$46.89	$36.68
Lodgepole	$31.75	$42.49	$33.40
Red Alder	$55.06	$57.51	$53.57
Other Hardwoods	$54.97	$57.42	$53.48
Pulp and Miscellaneous	$1.83	$1.83	$1.83

Cost Data

Costs for regeneration and timberland management in Washington were estimated to be approximately $1,396 per hectare on average for industrial and nonindustrial private land. These data were obtained from sources in Oregon (Jim Cathcart, personal communication), and were approved for use in this Washington analysis by Tony Ifie (Washington Department of Natural Resources). Specific cost categories are shown in Table 3-4.

Table 3-4. Regeneration cost estimates for Washington

	$$/acre	$$/ha
Private Industrial		
Site Preparation	$90	$222
Seedlings	$110	$272
Planting Labor	$110	$272
Vegetation Management	$130	$321
Interplanting/Contingencies	$10	$25
Administration	$20	$49
TOTAL	$470	$1,161
Private Nonindustrial	$660	$1,630
Average	$565	$1,396

Taxes

There are three "taxes" on forestland in Washington, according to the Washington Department of Revenue. First, the state levies an excise tax on forests when they are harvested. The excise tax is 5% of the value of the stumpage harvested. Second, the value of bare forestland is taxed at the local millage rate. Bare-land values for forestland, as well as county-level average land tax rates ($ per $1000 value) were obtained from the Washington Department of Revenue to estimate annual average taxes on each hectare of forestland in different regions. Third, there is a special fire assessment, amounting to approximately $0.72 per hectare on the west side of the Cascades and $0.67 per hectare on the east side of the Cascades. Based on the last two categories of taxes, the annual per-hectare tax rate is shown in Table 3-5. The excise tax is incorporated into the spreadsheet used to calculate opportunity costs and is not shown in the table.

Table 3-5. Tax rates used in Washington ($ per hectare per year)

Site Class	West Side WA	Columbia	East Side WA
High	$5.84	$6.04	$5.97
Med	$4.04	$4.17	$4.13
Low	$1.89	$1.94	$1.92

Biomass/Carbon Data

Biomass conversion factors from Smith et al. (2003) are used in this analysis. Only aboveground carbon in live biomass was counted. The functional form used to estimate biomass is given in Equation 3-7. Parameters (E, F, and G) for the equation for different species are provided in Table 3-6.

$$Carbon\ (tonnes/hectare) = 0.5*(E*(F+(1-EXP(-Yield/G)))) \qquad Eqn.\ 3\text{-}7$$

Table 3-6. Carbon biomass parameters (from Smith et al. 2003). All parameters are specific to the timber type for all of Washington, although specific site classes are used to calculate growing stock volume (GSV) and carbon at 70 years.

Forest Type*	E	Parameters F	G	GSV at 70 Years	Carbon at 70 Years
				m^3/ha	t/hectare
Douglas Fir (Med)	984.2	0.0185	1251.5	362.4	132.8
Pond. Pine (Med)	312.80	0.02	331.20	109.9	46.9
Fir/Spruce (Med)	658.80	0.02	757.60	146.3	63.2
Hemlock/Spruce (Med)	658.80	0.02	757.60	462.1	155.7
Lodgepole (Med)	303.40	0.02	390.50	134.3	47.1
Hardwood (Med)	2318.00	0.01	4085.20	284.3	90.8

*Med=medium-productivity class

Carbon stocks in products are tracked using rates suggested by Row and Phelps (1996) and Winjum et al. (1998). First, it was assumed that when a softwood stand is harvested, 43% of the carbon enters products and 57% is emitted immediately, either on site through decomposition of deadwood or through use in the energy sector. Second, solidwood products were assumed to turn over at a rate of 0.5% per year and release carbon, while pulpwood was assumed to turn over at a rate of 1% per year.

3.2.3. Results: Estimated Marginal Costs of Carbon Sequestration Through Extending Rotations

Table 3-7 presents the marginal costs and the carbon gains associated with holding carbon for 5, 10, or 15 years longer than the optimal rotation period for permanent changes in rotations. The results are shown for all site classes and a single pricing region in Washington. Differences in marginal costs arise from differences in initial rotation ages, prices, and yield functions for different site classes and species. The total amount of carbon available for sequestration on private timberland in Washington is shown in Table 3-8. The total was derived by summing the marginal costs and t C/ha for each site class and timber type in each county. Only softwood timberland that is 40–60 years old according to the USDA Forest Service FIA database was included in the analysis. Future contracts could be established on younger stands, but currently merchantable age classes were deemed to be the most appropriate for aging at the current time. Only private and non–Forest Service lands are analyzed here, as Forest Service lands are excluded from the forest inventories.

Briefly, the results indicate that 443,665 hectares of private land in Washington are nearing the economically optimal rotation period. If all of this land were contracted to increase rotation ages by 15 years, 12.0 million t C could be sequestered for average costs of $136 per t C (Table 3-8). The calculation for public land in Washington does not include USDA Forest Service land, but indicates that 147,625 hectares of public land are nearing economically optimal rotation ages and could be contracted for extending rotations. Contracts for 15-year extensions on these lands could provide up to 4.8 million additional tonnes of carbon for similar average costs (Table 3-8).

Table 3-7. Net carbon sequestered and $ per tonne for increasing rotation ages 5, 10, and 15 years above economically optimal rotation ages in Washington (west side of Cascades)

Forest Type*	t C per Hectare			$ per t C		
	5 years	10 years	15 years	5 years	10 years	15 years
Douglas Fir High	18.0	32.1	43.2	$95	$110	$125
Douglas Fir Med.	15.0	26.6	35.6	$100	$115	$120
Douglas Fir Low	7.8	14.2	19.2	$60	$70	$80
P. Pine** High	7.3	12.9	17.2	$65	$70	$70
P. Pine Med.	5.5	9.6	12.8	$70	$70	$75
Fir/Spruce High	7.5	13.0	17.2	$60	$85	$85
Fir/Spruce Low	9.7	16.7	22.0	$60	$80	$80
Hem/Spr. High	18.7	32.0	42.2	$150	$155	$160
Hem/Spr. Med.	16.6	29.0	38.6	$115	$120	$125
Hem/Spr. Low	11.3	19.8	26.4	$95	$100	$102
Lodgepole	6.3	11.0	14.6	$10	$60	$65
Red Alder	7.6	13.2	17.4	$15	$15	$15

* High, medium, and low refer to productivity classes as designated by the US Forest Service FIA database.
P. pine = ponderosa pine; Hem/Spr. = hemlock/spruce.

Table 3-8. Aggregate estimated carbon potential from holding timber past economically optimal rotation periods for Washington

	Extension of Rotation		
	5 years	10 years	15 years
Private Land Potential Hectares	443,665		
Million tonnes	5.1	9.0	12.0
Million $$	$460	$894	$1,270
Average $$ per tonne	$111	$125	$136
Average $$ per hectare	$1,036	$2,014	$2,862
Average tonnes per hectare	11.5	20.3	27.0
Public Land Potential Hectares*	147,625		
Million tonnes	2.0	3.6	4.8
Million $$	$203	$394	$564
Average $$ per tonne	$111	$125	$136
Average $$ per hectare	$1,378	$2,672	$3,820
Average tonnes per hectare	13.8	24.2	32.3

* Note that public land omits Federal USDA Forest Service lands.

Figure 3-2 presents a marginal cost curve for carbon sequestration through forest aging on private lands. There are relatively few opportunities for less than $50 per t C. The least-cost options overall tend to be red alder stands that are nearing economically optimal rotation ages. Figure 3-3 presents the distribution of carbon sequestration costs for 15-year rotation extensions in Washington. Lower-cost opportunities tend to occur on the east side of the Cascades due to relatively lower site values for forests overall.

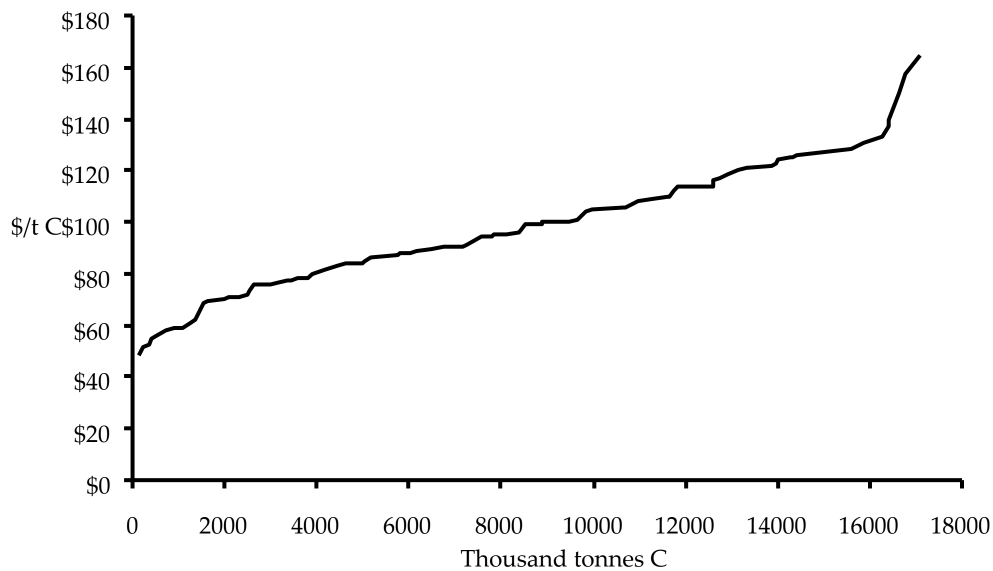


Figure 3-2. Marginal cost curves for carbon sequestration through aging, including 5-, 10-, and 15-year rotation extension periods in Washington

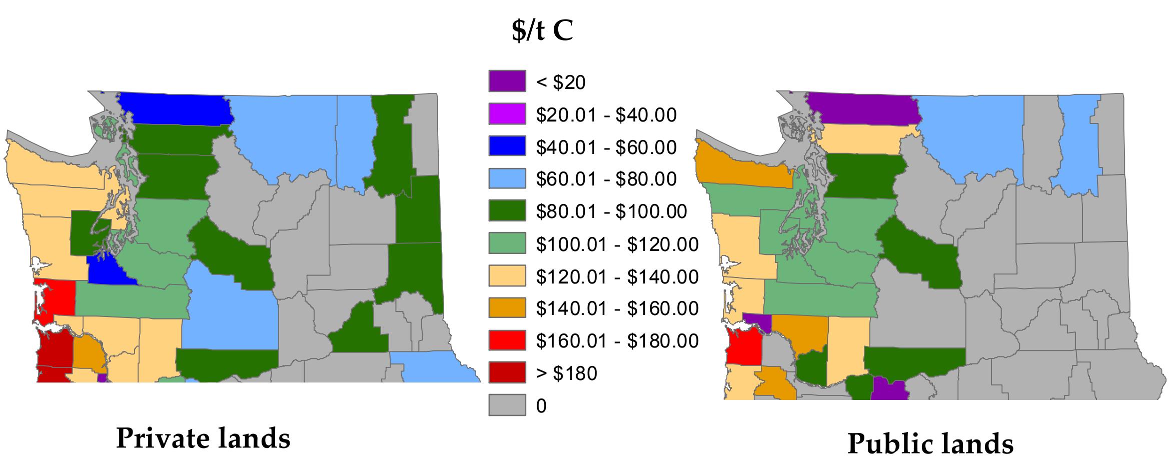


Figure 3-3. Distribution of the costs of carbon sequestration for extending rotations 15 years in Washington

3.3. Conservation of Timber Land in Extended Riparian Buffers

3.3.1. Methods and Analyses

This section examines the potential for riparian zone management to increase carbon sequestration. This analysis assumed that 200 foot (61 meter) riparian buffers are required on all Washington timberland. The costs of excluding currently mature timber from harvesting for the indefinite future were estimated. The new riparian zones were treated as set-asides, and only economically mature timber at the current time was considered.

The potential carbon sequestration associated with setting aside timberland can be seen through Figure 3-4, which presents the carbon situation for a riparian zone set-aside (red line) versus harvesting that stand in the same rotation period indefinitely (blue line). For a stand that is initially near the rotation age of 47 years, if the stand is set aside, carbon accumulates along the red line from the year of the set-aside forward. If the stand is harvested, some carbon is stored in wood products and some is emitted initially. Over the entire time period analyzed, the set-aside stand holds more carbon than is held by the harvested stand. Although storage occurs in wood products, holding stands in set-asides appears to sequester more carbon in the long-run than harvesting forests—at least for these relatively productive Douglas fir stands in Washington.

In this analysis, the carbon is discounted such that early carbon gains are more valuable than future carbon gains. Thus, the set-aside stand holds more "present value" carbon than the harvested stand, even though these stands have similar average carbon storage in the longer run (i.e., > 400 years). The set-aside stand shown in Figure 3-4 is estimated to hold approximately 89 t of "present value" carbon.

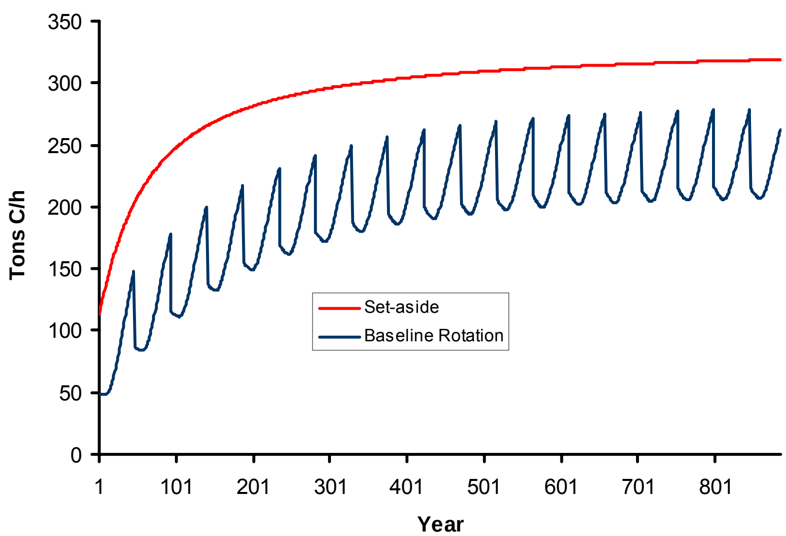


Figure 3-4. Tonnes carbon per hectare stored in aboveground biomass and products for the baseline (blue) and set-aside (red) for high-site Douglas fir stands in Washington Region 1

Table 3-9 presents estimates of the tonnes of carbon gained and the costs for riparian zone protection in Washington. These estimates assume that the land would otherwise be harvested at economically optional rotation ages, and that the harvests would occur in the relatively near future (i.e., the next 5–10 years). Carbon gains depend only on the site class, and thus are the same for each region (assuming the same site classes). The estimates of costs, however, differ due to differences in stumpage prices estimated for the different regions.

Table 3-9. Net carbon sequestered and costs in $ per tonne for setting aside mature forests in riparian zones in Washington

Forest Type*	T C per Hectare	$ per t C		
	All Regions	Region 1	Region 2	Region 4
Douglas Fir High	89.2	$130	$148	$115
Douglas Fir Med	69.6	$154	$175	$129
Douglas Fir Low	44.0	$99	$113	$83
Pond. Pine High	28.7	$114	$119	$156
Pond. Pine Med	20.5	$111	$116	$153
Fir/Spruce High/Med	28.1	$99	$100	$98
Fir/Spruce Low	35.7	$102	$110	$101
Hem/Sp Med	57.0	$238	$306	$239
Hem/Sp Med	62.0	$164	$211	$165
Hem/Sp Low	45.3	$127	$164	$127
Lodgepole	26.0	$59	$77	$62
Red Alder	25.3	$64	$66	$62

* High, medium, and low refer to productivity classes as designated by the US Forest Service FIA database. Pond. Pine = ponderosa pine; Hem/Sp = hemlock/spruce.

The total costs per hectare of setting aside timberland are estimated as the current stumpage value of mature timber on each hectare, assuming the timber is near the optimal rotation age, plus the present value of bare land. These estimates provide a lower-bound estimate of what it would cost individuals interested in purchasing set-asides to negotiate with landowners for the rights to hold the timber on the land indefinitely—for example through a conservation easement. The costs per tonne are estimated by dividing total tonnes gained into the total costs.

It is also useful to estimate how much land is available in riparian areas for protection. To accomplish this, stream lengths through different types of land uses in each county in the two states were estimated. The stream lengths through forested areas were extracted from these data and used to estimate the total area of land in a set-aside encompassing an additional 100 feet (30.5 meters) of land on each side of the stream. The data included information on the types of forests, allowing the economic value and carbon sequestration estimates from the tables above to be attached directly to specific stream segments.

The estimates of costs and carbon sequestration assume that land is currently of merchantable age; however, the riparian area data did not distinguish age classes. It was therefore assumed that the riparian zones have the same distribution of age classes as the rest of forests in each county. Thus, the total stream length within in each county was adjusted to reflect the proportion in the county that is merchantable, according to the USDA Forest Service FIA data.

3.3.2. Results: Marginal Costs of Carbon Conservation in Riparian Buffers

The results of the analysis of potential costs of sequestering carbon through riparian zone set-asides are shown in Table 3-10. It is estimated that there are currently 14,119 hectares of mature forests in riparian zones within Washington. If these areas were set aside, the estimated costs would be approximately $5,268 per hectare, or $74.4 million in total. Approximately 610,000 t C could be sequestered with this action, for an average cost of $122 per t C. The distribution of costs by county is shown in Figure 3-5. As with holding timber longer than optimal rotation periods, costs tend to be lower in counties on the east side of the Cascades due to lower overall site values, lower productivity, and thus lower opportunity costs of not harvesting the timber.

Table 3-10. Estimated total area of riparian zones and total cost of protecting currently mature areas in Washington

	Washington
Riparian stream lengths (million meters)	23.2
Total potential area (hectares)	141,469
Mature potential area (hectares)	14,119
Total carbon (million tons)	0.61
Total cost (million $)	$74.4
Average cost per tonne ($/t C)	$122.33
Average cost per hectare ($/ hectare)	$5,268

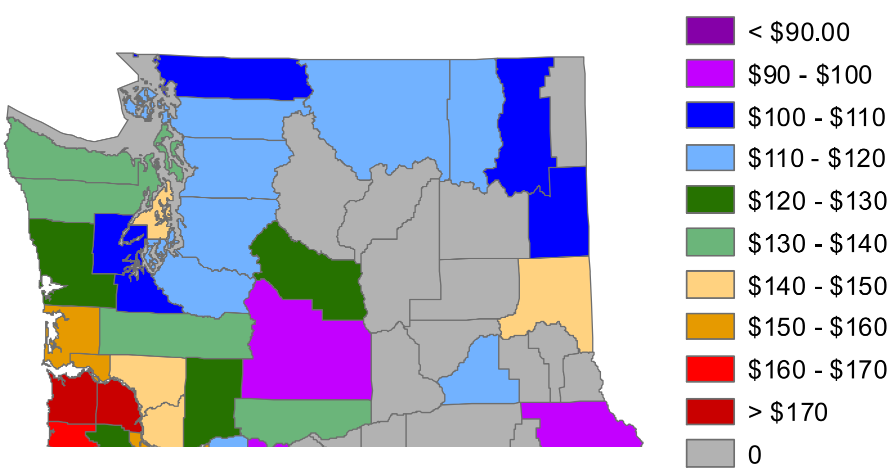


Figure 3-5. Costs (in $/t C) of sequestering carbon through expanding riparian zones in Washington.

4.0 Fuel Load Reduction on Wildfire-Prone Areas

4.1. Introduction

Fires have a significant effect on carbon stocks in forests. Fire management techniques that reduce carbon emissions by reducing the risk of wildfire through removal of biomass fuels potentially offer an opportunity to reduce emissions and thus provide carbon dioxide emission reduction credits (henceforth, carbon credits). Not only would reductions in catastrophic forest fires reduce carbon and non-CO_2 greenhouse gas emissions from burning, but the use of the biomass to generate electricity would offset emissions from fossil fuel–generated energy. The objective of this section is to produce a first-order approximation of the areas and carbon stocks of forests suitable for fuel reduction to reduce their fire risk, as well as their location relative to existing power plants.

4.1.1. Magnitude of the Problem

The last century has seen the transformation of many Western forest ecosystems from relatively open, healthy forests in which periodic low-intensity ground fire played an important ecosystem function, to densely stocked, fire-prone forests in which catastrophic crown fires burn hundreds of thousands of acres each fire season. This has resulted in escalating fire suppression budgets; loss of timber, wildlife, and recreational and ecosystem values; lost property values; skyrocketing insurance costs; and loss of life. Fires appear to be increasing in size and intensity, resulting in greater losses of forest area and billions of tax dollars spent each year for fire control. As reported by the National Interagency Fire Center, 103,387 fires consumed 4.5 million acres in 1960; by the year 2000, 122,827 fires burned almost twice as much—8.4 million acres—while federal expenditures rose from $845 million in 1994 to $1.7 billion in 2002 (Figure 4-1).

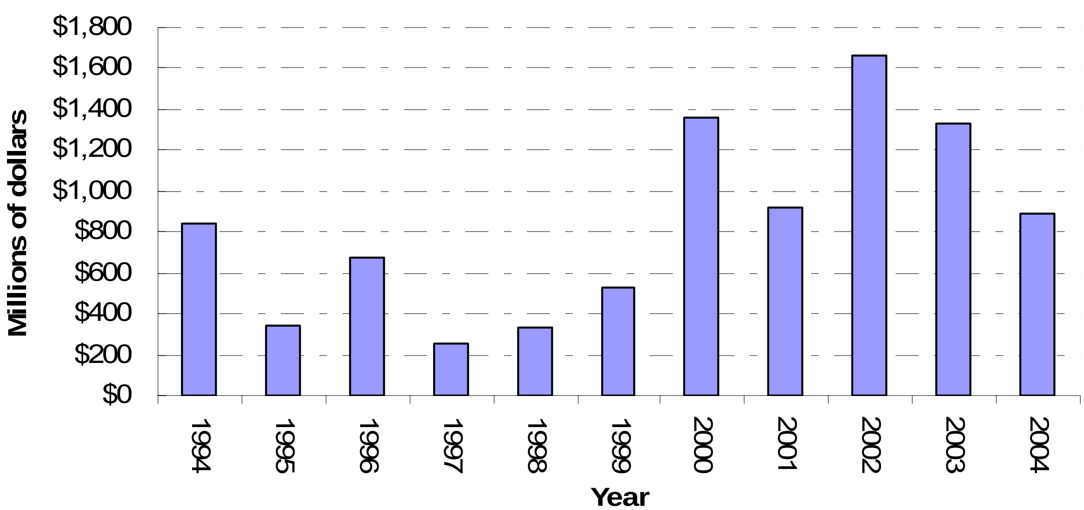


Figure 4-1. National Interagency Fire Center statistics showing federal expenditures in millions of dollars from 1994 to 2004

In 1937 the USDA Forest Service (USFS) adopted policy of "fast, energetic and thorough suppression of all fires in all locations" (Chase 1989). A more recent scientific consensus suggests that low-intensity ground fire played a natural and important role in many Western forest ecosystems (e.g., Schoennagel et al. 2004). Instead of having a healthy fire return interval of 15 or 20 years depending on forest type, a combination of logging, fire suppression, and other factors have altered fire regimes and resulted in a fundamentally different forest landscape in which accumulated woody fuels create conditions for infrequent but intense and large-scale fires that can permanently alter ecosystems (Pyne et al. 1996). This has led to a debate among landowners and public land managers about how to manage fire across boundaries, and how to return natural low-intensity fire to these forest ecosystems—starting from a present condition of accumulated fuels that makes it impossible simply to forego fire suppression, let fires burn, or introduce prescribed fire without first undertaking treatments to reduce fuel loads. A national consensus is beginning to develop among government, industry, community, and environmental stakeholders that something must be done to reduce fuel loads and return forests to more natural fire regimes; nonetheless, the problem is complex and the barriers to a large-scale solution are political, administrative, environmental, and perhaps most significantly economic. The necessary fuel reduction treatments tend to be labor intensive and very costly, the value of the material removed relatively low, and agency budgets to pay for treatment increasingly constrained. Creative utilization strategies for understory biomass and small-diameter timber are needed, together with a broad portfolio of approaches and sources of revenue to offset the costs of fuel treatment.

A recent assessment of forests across 15 Western states, conducted under the auspices of the National Fire Plan, found that approximately 67 million acres are at moderate to high risk of wildfire (Fire Regime Condition Class 2 and 3) and 28 million acres at the highest risk level (FRCC 3) [3]. These figures include only those acres considered accessible for some type of treatment to reduce hazardous fuels. The 28 million acres in FRCC 3 could yield 345 million bone dry tons (BDT) in removals, with most (70%) of the *volume* in larger-diameter classes (over 7" considered merchantable sawtimber), but the *greater number of stems* in the < 7" submerchantable biomass category (USDA Forest Service Research and Development/Western Forestry Leadership Coalition 2003). This hints at both the scale of the wildfire risk/hazardous fuels problem in the West, and one of the key economic barriers: a huge quantity of submerchantable material requiring treatment and/or removal to reduce fire risk, but constituting relatively little volume or value to pay the high cost of handling such a large number of stems.

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3. Fire Regime Condition Class (FRCC) is a measure of how much a forest has departed from natural wildland fire conditions (Schmidt et al. 2002). The fire regime in Class 2 areas is moderately altered from the historical range; moderate levels of restoration treatments such as fire or mechanical treatments would be required to begin managing a more natural fire cycle. In Class 3 areas, fire regimes have been significantly altered and there is a high risk of losing key ecosystem components in a wildfire. Due to high fuel loadings, mechanical treatments are expected to be needed before the reintroduction of fire (USDA Forest Service Research and Development/Western Forestry Leadership Coalition 2003).

In Washington alone, 8.5 million acres in FRCC 2 and 3 require hazardous fuel reduction and would yield an estimated 242 million BDT, of which 2.5 million acres are in FRCC 3 and would yield an estimated 63 million BDT (USDA Forest Service Research and Development/Western Forestry Leadership Coalition 2003).

4.1.2. Approach and Analysis of Hazardous Fuel Reduction Treatments

Decades of fire suppression practices, resulting in unnatural fuel accumulation and severe wildfire in Western forests, are particularly associated with the dry ponderosa pine forest type (Schoennagel et al. 2004). According to Schoennagel et al., dry ponderosa pine forests are in urgent need of ecological restoration and fire mitigation. Historically, frequent and low-severity fire maintained open stands in low-elevation ponderosa pine; the surface fuel layer, dominated by grasses and needles, usually dries easily, resulting in frequent low-intensity surface fires. Disturbing this historical fire regime in these forests through fire suppression has resulted in buildup of ladder fuels at intermediate heights that carry ground fires into the crown, where they can lead to large, catastrophic fires. Mixed-severity fire regimes occur mostly at mid-elevation, in forest stands with variable tree species and densities defined as mixed conifer forests. In these forests, accumulated fuel and climate affect the frequency, severity, and size of fires. The impact of suppression practices on fuel loads in these forests varies depending on the tree composition of the forest stand. To restore historical stand structure of ponderosa pine and mixed conifer forests, mechanical methods of hazardous fuel reduction (HFR) are recommended.

A broad range of HFR treatments and technologies is available to address the fire risk problem. Prescribed fire is a relatively low-cost way to reduce fuel loading and is ultimately perhaps the preferred treatment if the goal is to reintroduce fire into forest ecosystems. Prescribed fire is fairly constrained in its use today because of the potential for fire escape (especially at the wildland-urban interface), relatively short windows of appropriate conditions, and air quality and sediment yield concerns. Indeed, to treat FRCC 3 forestlands, prescribed fire is probably an option only following some mechanical treatment to reduce fuel loads (USDA Forest Service Research and Development/Western Forestry Leadership Coalition 2003). One could envision a range of available HFR treatments, each with different constraints, costs, yield of merchantable and submerchantable material and thus revenues, air quality impacts, ground impacts, and greenhouse gas emission impacts (Figure 4-2, Table 4-1).

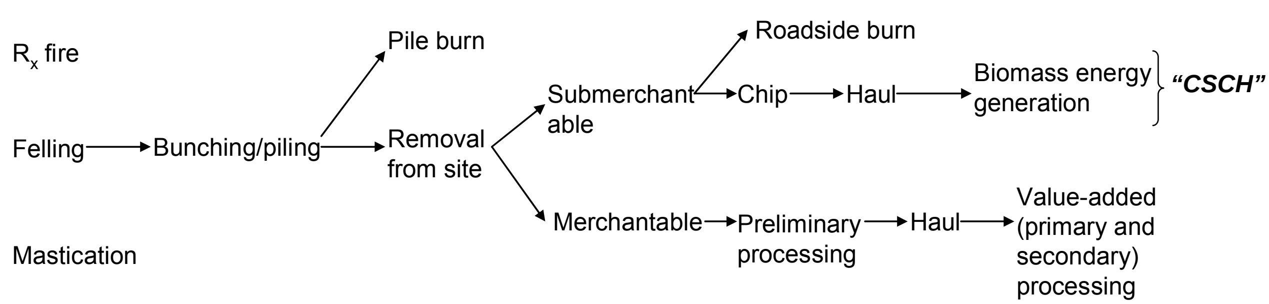

Figure 4-2. Schematic of potential HFR treatments (adapted from USDA Forest Service Research and Development/Western Forestry Leadership Coalition 2003).

Table 4-1. Benefits, constraints, and representative costs for HFR treatments

Hazardous Fuels Reduction Treatment	Product Yield	Benefits	Constraints	Representative Costs
R_x fire	No	Less expensive; re-introduces fire	Air quality; ground impacts; fire escape at wildland-urban interface; seasonal restrictions; immediate CO_2 emissions to atmosphere	$35–$300/acre, average $92/acre[a] $23–$223/acre[b]
Masticate—leave on site	No	Efficient; useful for less-accessible sites where fuel removal not a goal	Leaves fuel on site; gradual CO_2 emissions to atmosphere	$100–$1,000/acre[c]
Cut-pile-burn	No	Less expensive; can be used on inaccessible or steep sites	Leaves fuel on site; air quality; immediate CO_2 emissions to atmosphere	$100–$750/acre[c]
Cut-lop-scatter	No	Less expensive; can be used on inaccessible or steep sites	Leaves fuel on site; gradual CO_2 emissions to atmosphere	$105–$280/acre[d]
Cable yarding for biomass removal	Yes	Makes less-accessible or steeper sites treatable	Expensive; ground impacts	$80–$130/CCF[b]
Cut-skid-chip-haul (for sub-merchantable biomass) "CSCH"	Yes	Removes fuel from site; some product value to offset costs; allows renewable energy generation; greatest CO_2 benefit	More expensive; limited to gentler slopes and areas closer to roads for removal; limited haul distance to biomass plant	$34–$48/BDT + haul cost $0.35/BDT.mile[e] $560–$1,634/acre[e]
Cut-skid-process-load-haul (for merchantable biomass)	Yes	Greatest product value to offset costs; removal of merchantable material may be necessary to reduce fire risk (Crowning Index) and meet spacing or forest health goals	More expensive; limited to gentler slopes and areas closer to roads for removal; limited haul distance to processing facility; environmental controversy/frequent litigation	Variable

a. USDA 2005.

b. Chalmers and Hartsough, no date.

c. Fight et al. 2004.

d. Barbour et al. 2004.

e. Fried et al. 2003b.

The present analysis is confined to a single HFR treatment—cut-skid-chip-haul, or CSCH—because this appears to be the most practical way to remove fuel from the forest while making the fuel available for transportation to a biomass energy power plant. The analysis attempts to estimate:

- The total area of Washington forestlands with historically low-severity and mixed-severity (HLS-HMS) fire regimes.
- How much of this area meets a series of constraints making it feasible to treat using CSCH.
- How much biomass could be removed from this area using CSCH and be available to existing biomass power plants.
- The economics of using CSCH on those forested acres.

Thus the focus is primarily on submerchantable biomass and the use of forest fuels for generating heat and power in biomass energy facilities.

The approach chosen here is necessarily a simplification of the reality of HFR as practiced today, in which a variety of treatments can be applied for different locations, terrain, slope, or other conditions. Perhaps most importantly, most HFR prescriptions call for a mix of submerchantable and merchantable material removal, both for economic reasons and to target a desired future forest condition that is defined in terms of residual spacing or basal area, residual fuel loading, reduced ladder fuels to prevent ground fires from moving into the crown, and reduced crown density or crown-touching to prevent crown fires from being sustained or spreading over long distances (Fried et al. 2003). While diameter limits are sometimes applied, it is rarely appropriate to exclude all merchantable material to meet these desired future conditions. Accordingly, different treatment types, technologies, and product yield dictate different economics of HFR and different types of sites that become treatable either in technical terms (e.g., treatments available for steep slopes) or in economic terms (e.g., treatments that yield more merchantable material, offsetting costs and allowing the contractor to remove more submerchantable biomass to reduce ladder fuels or treat lands on the margin of the maximum haul distance from a biomass energy facility). There is extensive literature focused on the economics of different treatments, as well as models to estimate costs of treatment (STHARVEST and others), and models to estimate quantities of biomass available from a given area or the best locations to site biomass energy facilities (FIA Biosum, Coordinated Resource Offering Protocol, and others). (See Fight et al. 2003, 2004; Fried, Barbour and Fight 2003; Fried et al. 2002, 2003; Barbour et al. 2001, 2004; Christensen et al. 2002; Chalmers and Hartsough, no date; Mater 2005.)

4.1.3. Objectives

The four primary objectives of this study are to:

1. Identify areas of forestland in the state with HLS-HMS fire regimes.
2. Conduct a multi-criteria evaluation to identify forestlands with HLS-HMS fire regimes suitable for fuel removal. This analysis assigns a Suitability for Potential Fuel Reduction (SPFR) score to all forested areas, based on criteria affecting the feasibility both of treating these lands and of removing and transporting the fuels for biomass energy generation.

3. Identify forested areas at risk for catastrophic wildfire that could be treated with Cut-Skid-Chip-Haul HFR treatment to mitigate potential extreme fire behavior and to restore these forests to their historical fire regime.
4. Assess how much biomass fuel this Cut-Skid-Chip-Haul HFR treatment might generate for use in power plants, and at what cost.

4.2. Forested Land with Historically Low-Severity and Mixed-Severity Fire Regimes

The first step in the analysis was to identify forest areas with HLS-HMS fire regimes that were suitable for fuel removal to restore their historical fire regimes. Forested areas were extracted from the Washington GAP analysis layer (USGS, GAP Analysis Program 2005). There were fifteen forest types recognized in the GAP data set, dominated by mixed mesic coniferous, mesic Douglas fir, and ponderosa pine forests (Table 4-2, Figure 4-3).

Table 4-2. Distribution of forest area (in hectares) by forest type

Forest Type	Northwest Regional GAP Analysis Category	Area (ha) Statewide
Mixed Mesic	Mixed Mesic Coniferous Forest	3,088,400
	Mesic Mixed Forest	652,500
	Mesic Mixed Forest	652,500
	Deciduous Forested Riparian	321,500
	Mixed Riparian	68,600
	Coniferous Forested Riparian	4,800
Douglas Fir	Mesic Douglas Fir	1,301,500
Ponderosa Pine	Ponderosa Pine	1,108,900
Subalpine	Mixed Subalpine Coniferous	620,600
	Subalpine Fir	20,400
Mixed Xeric	Xeric Douglas Fir	283,900
	Mixed Xeric Coniferous	236,400
	Xeric Mixed	106,400
	Xeric Deciduous	32,300
Mixed Coastal	Mixed Coastal	172,300
Mesic Deciduous	Mesic Deciduous	66,700

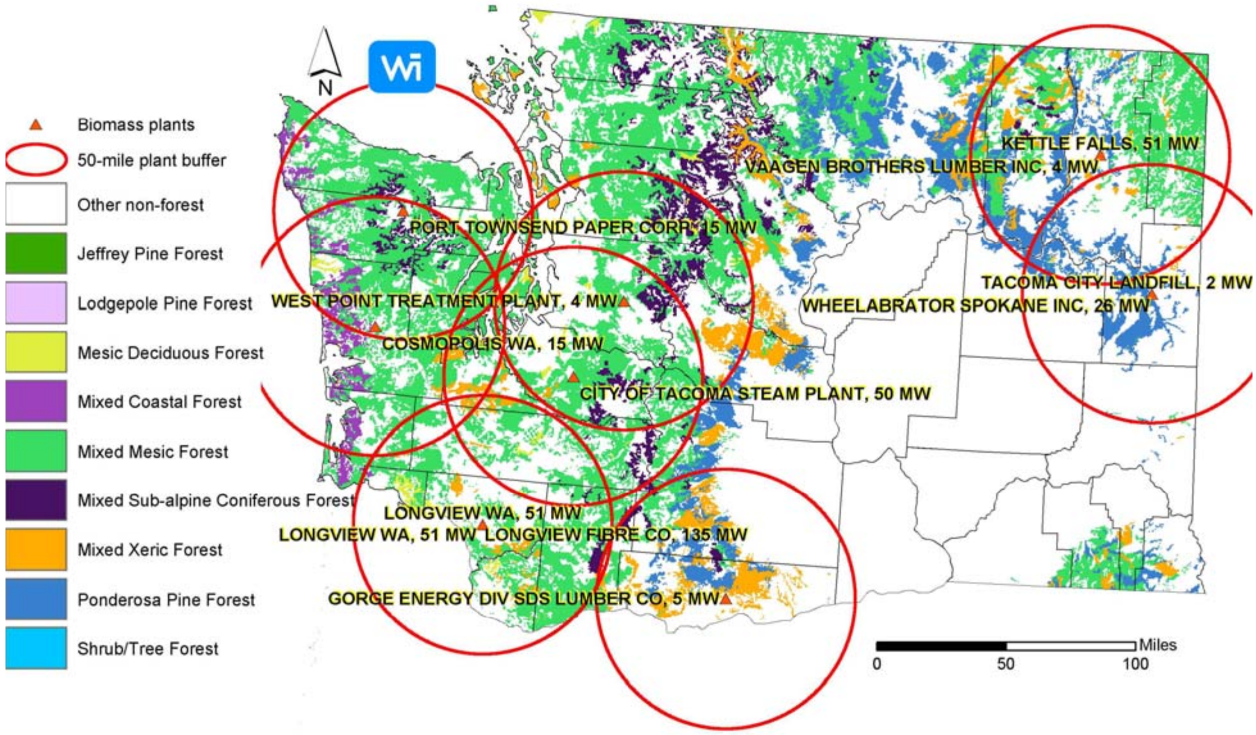

Figure 4-3. Map showing the forest classes for this analysis and names of Washington's biomass power plants with their electric power outputs (in megawatts)

Forest areas with HLS-HMS regimes were identified based on a reclassification of the NW Regional GAP's classification used above. Two forest categories were recognized from the GAP analysis data: ponderosa pine forest and mixed xeric coniferous forest. The total area of ponderosa pine and mixed xeric coniferous forests in Washington was estimated at approximately 1.3 million hectares (Figure 4-4).

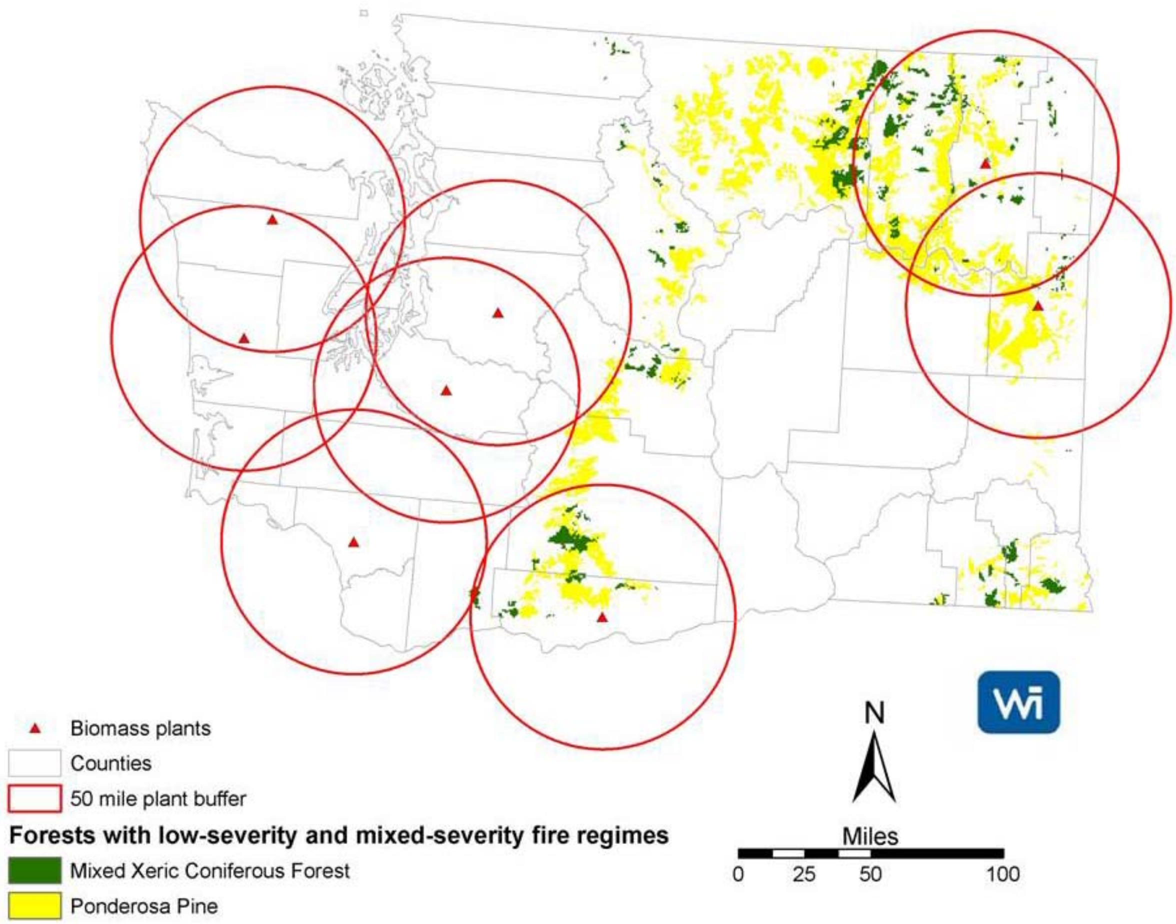

Figure 4-4. Map showing forestlands with low-severity and mixed-severity fire regimes and locations of the biomass power plants in Washington state

4.3. Suitability for Potential Fuel Reduction

A multi-criteria evaluation was conducted to identify forestlands suitable for fuel removal. Three factor maps were used in the decision support tool for a Multi-Criteria Evaluation module (MCE, a module in the Idrisi software package): distance from roads, distance from power plants, and slope. The analysis was constrained to a radius of 50 miles from existing power plants, representing a general rule of thumb for maximum hauling distance for low-value biomass fuel. These factor maps were combined to create a single raster map showing Suitability for Potential Fuel Removal (SPFR) scores.

The first factor analyzed was distance from roads. A GIS data layer for roads—the Census 2000 TIGER Line—was downloaded from the ESRI website,[4] including all major state and interstate highways and local roads statewide. Also, a railroad layer at scale 1:24,000 was downloaded

4. http://arcdata.esri.com/data/tiger2000/tiger_download.cfm

from the Washington State Department of Transportation (WSDOT 2005). Both transportation layers were combined to create a layer representing all roads. The Euclidean distance module in ESRI's ArcView software was used to create a distance map from the linear features of all roads. This map was standardized into a range from 0 to 255 using the "FUZZY" module in the GIS software Idrisi Kilimanjaro (Eastman 2003), so that the starting point for most suitable areas was 100 meters away from the roads to avoid a risk of fire close to roads. The greatest travel distance to reach a road was assigned the lowest suitability score (0), and the least travel distance the highest suitability score (255), indicating that as yarding distance increases, the cost of removal increases and suitability for fuel removal thus decreases (Figure 4-5).

The second factor analyzed was slope. A slope map in degrees at 1,000 m resolution (same resolution as the FCCS layer[5]) for the state of Washington was derived from a 30-meter Digital Elevation Model (GeoCommunity 2005). Slope in the state of Washington ranges between 0.0 and 32.30 degrees, and was standardized with a fuzzy classifier to range of 0 to 255, with 255 representing the gentlest slope (easiest access and least ground impact from fuel removal, thus most suitable) and 0 the steepest slope (least suitable), as illustrated in Figure 4-5.

The third factor analyzed was distance from existing power plants. The locations of electricity generating facilities within the state of Washington with greater than 0 MWh annual biomass/wood net generation in 2000 were obtained from the Emissions & Generation Resource Integrated Database (eGRID—U.S. Environmental Protection Agency 2003). A point file was created using the latitude and longitude information for each plant, then the Euclidean distance module in ArcView was used to create a distance map from the point locations of the power plants. The distance map was standardized to a scale of 0 to 255, with the greatest travel distance to reach a power plant assigned the lowest suitability score (0) and the least travel distance the highest suitability score (255), indicating that as the distance to the nearest power plant increases, the cost of hauling fuel increases and suitability for fuel removal thus decreases (Figure 4-5).

All three factor maps were used as inputs for the MCE module, a GIS decision-making tool in Idrisi Kilimanjaro software. The output of this module was an SPFR score map on a standard scale from 0 to 255, where 0 represents the least suitable areas and 255 the most suitable areas for potential fuel reduction accounting for distance to roads, slope, and distance to power plants (Figure 4-5).

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5. Fuel characteristic class system

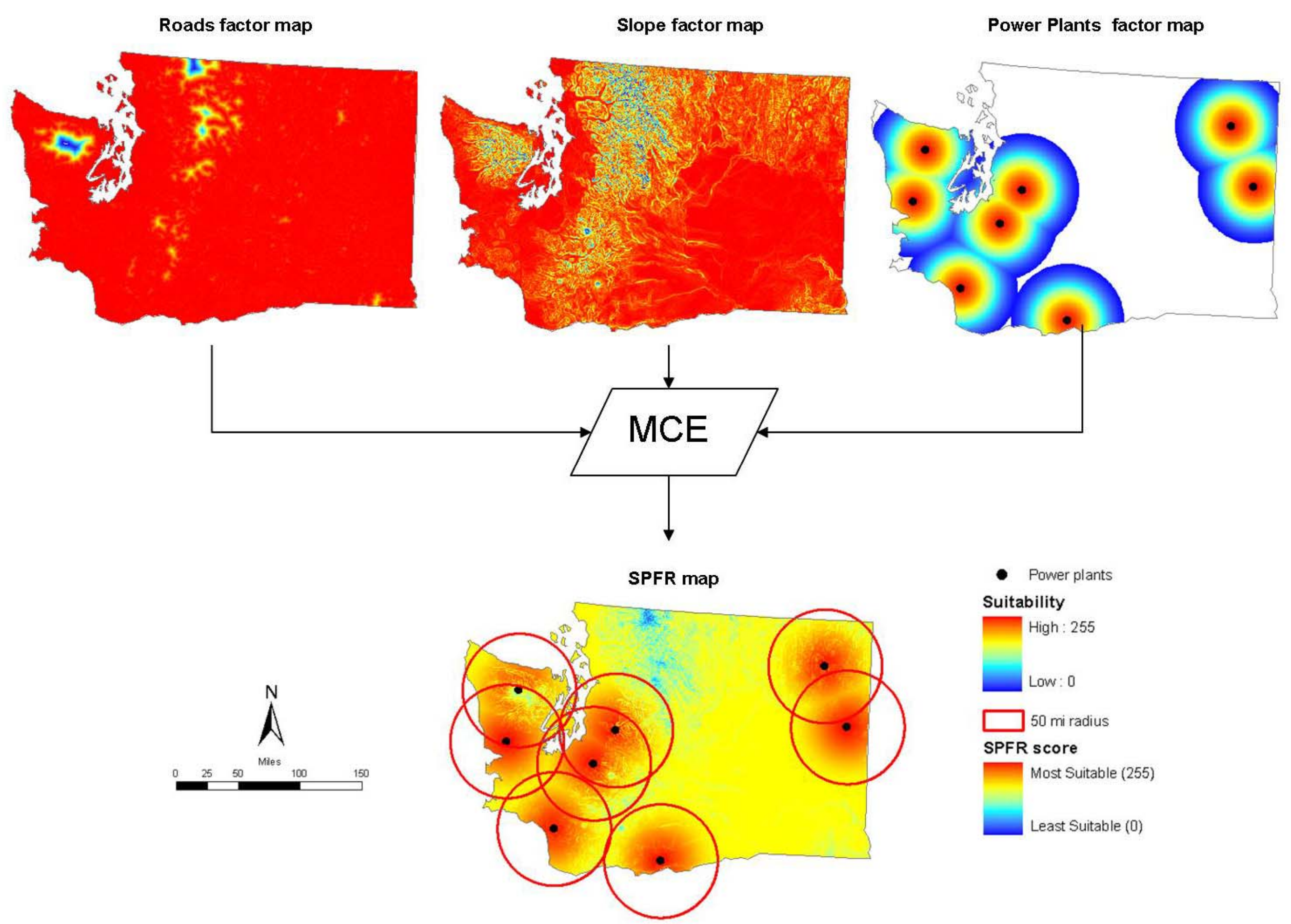

Figure 4-5. Suitability for Potential Fuel Removal (SPFR) scores for Washington, with highest suitability assigned to areas close to roads, on gentle slopes, and close to existing power plants

The ranges of the SPFR scores for the forests with HLS-HMS fire regimes, and locations of the existing eight power plants in Washington and the buffer zone of 50 miles around them, are shown in Figure 4-6. The SPFR scores for Washington forests with HLS-HMS fire regimes indicated the suitability for treating these forestlands, then removing and transporting the fuels to the nearest biomass energy generation facility, based on three factors: slope, distance from roads, and maximum distance of 50 miles from a power plant. The highest suitability is assigned to forest close to roads and power plants, and on gentle slopes.

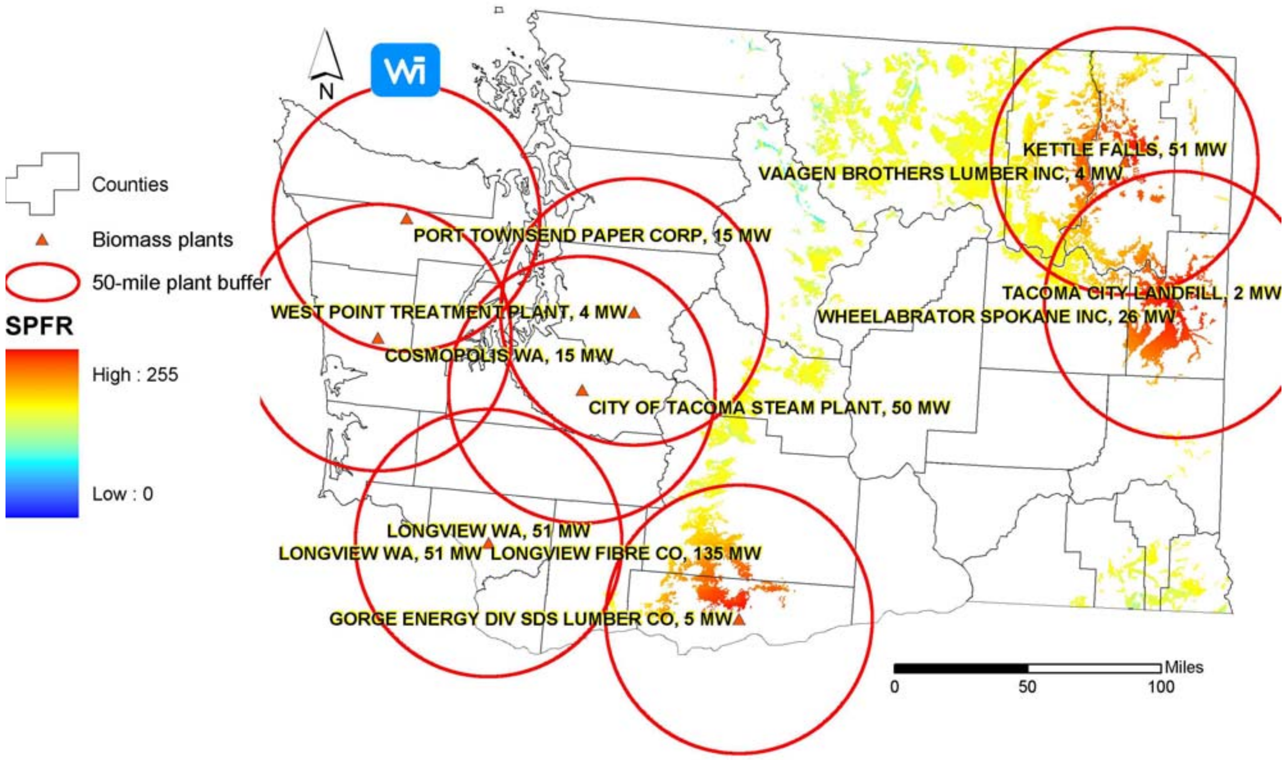

Figure 4-6. Suitability for Potential Fuel Reduction (SPFR) scores for Washington's forests with low-severity and mixed-severity fire regimes. The map also shows the 50-mile radii and power outputs of existing biomass power plants.

4.4. Forests with Historically Low-Severity and Mixed-Severity Fire Regimes Deemed Treatable with CSCH

4.4.1. Estimated Biomass Yield

The third component of this analysis looked in more detail at one type of hazardous fuels treatment, Cut-Skid-Chip-Haul (CSCH), a treatment in which hazardous fuel is harvested in the woods, bunched and skidded to a landing, chipped into a chip van, and hauled to a biomass energy facility for electricity and/or heat generation. The objective was to assess the area of Washington forestland with HLS-HMS fire regimes to which this treatment could be applied, how much biomass fuel this might generate for use in power plants, and at what cost.

The following crucial constraints for CSCH treatment were considered for CSCH:

- **Maximum slope**. Assumes only lands of < 40% slope may be treated with CSCH (Fight et al. 2003; Fried et al. 2002; Fried et al. 2003; Fried, Barbour, and Fight 2003). Steeper slopes may be treated in other ways (e.g., cut-pile-burn), but do not allow CSCH due to poor machinery and equipment access, difficulty of removal, and ground impacts from harvest and skidding.

- **Maximum yarding distance.** Assumes only lands within 0.25 miles (400 meters) of existing roads may be treated with CSCH. This is used as a general rule of thumb for the maximum distance low-value material would be skidded to a landing where a chipper and chip van are parked (Bob Rynearson, W.M. Beaty & Associates, personal communication, September 2005).
- **Maximum haul distance.** Assumes only lands within 50 miles of existing power plants may be treated with CSCH due to transport cost. This maximum haul distance may be considerably affected by the volume/value of merchantable material in the prescription, but for a simplified CSCH treatment targeting only low-value submerchantable material, it is assumed that haul distance cannot exceed 50 miles.
- **Minimum block size to justify move-in costs of equipment and personnel.** A general rule of thumb is that a treatment block must be at least 80–100 acres to justify move-in costs, although this number may be slightly less if equipment is already sited nearby for another project (Bob Rynearson, W.M. Beaty & Associates, personal communication, September 2005).

Constraints were applied sequentially so that only lands meeting all constraints were available for CSCH treatment. Forests with HLS-HMS fire regimes were superimposed on a slope map and all forestlands of >40 % slope were excluded (Figure 4-7A). To meet the requirement of maximum 0.25-mile yarding distance, a buffer layer was created, rasterized, and overlaid with the HLS-HMS fire regime forests on gentle slopes to exclude any lands further than 0.25 miles from roads (Figure 4-7B). Finally, the constraint map of 50 mile radii from existing power plants was overlaid on the earlier maps to exclude forests beyond this haul distance (Figure 4-7C).

The fourth constraint of minimum block size proved difficult to apply when the analysis was conducted. In theory it would be possible to exclude as uneconomic all lands that meet the three above constraints but lack sufficient contiguous area to meet the 80–100 acre minimum treatment block constraint. However, the 1,000-meter level of resolution that the analysis was originally conducted at meant that a single pixel represented 100 hectares or 247 acres, so it was not possible to exclude blocks of only 80–100 acres. Only at a later date would the 1,000-meter pixel data be eliminated from the analysis,[6] allowing analysis at 30-meter resolution. The WESTCARB Phase II project anticipates application of this constraint in further characterization of opportunities at the finer-scale analyses of the pilot project sites.

Applying sequential factors of slope, yarding distance, and 50-mile radius from existing power plants to forestlands with HLS-HMS fire regimes resulted in an estimate of approximately

6. A 1,000-meter grid cell "fuel characteristic class system" (FCCS) GIS layer, developed by the Fire and Environmental Research Applications team (FERA) of the USDA Forest Service's Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, was originally used to identify fuelbeds that had moderate and high fire behavior potential and were at high wildfire risk. Subsequent and later reviews indicated that assumptions about forest species compositions as supported by Schoennagel et al. (2004) were sufficient for mapping fire risk.

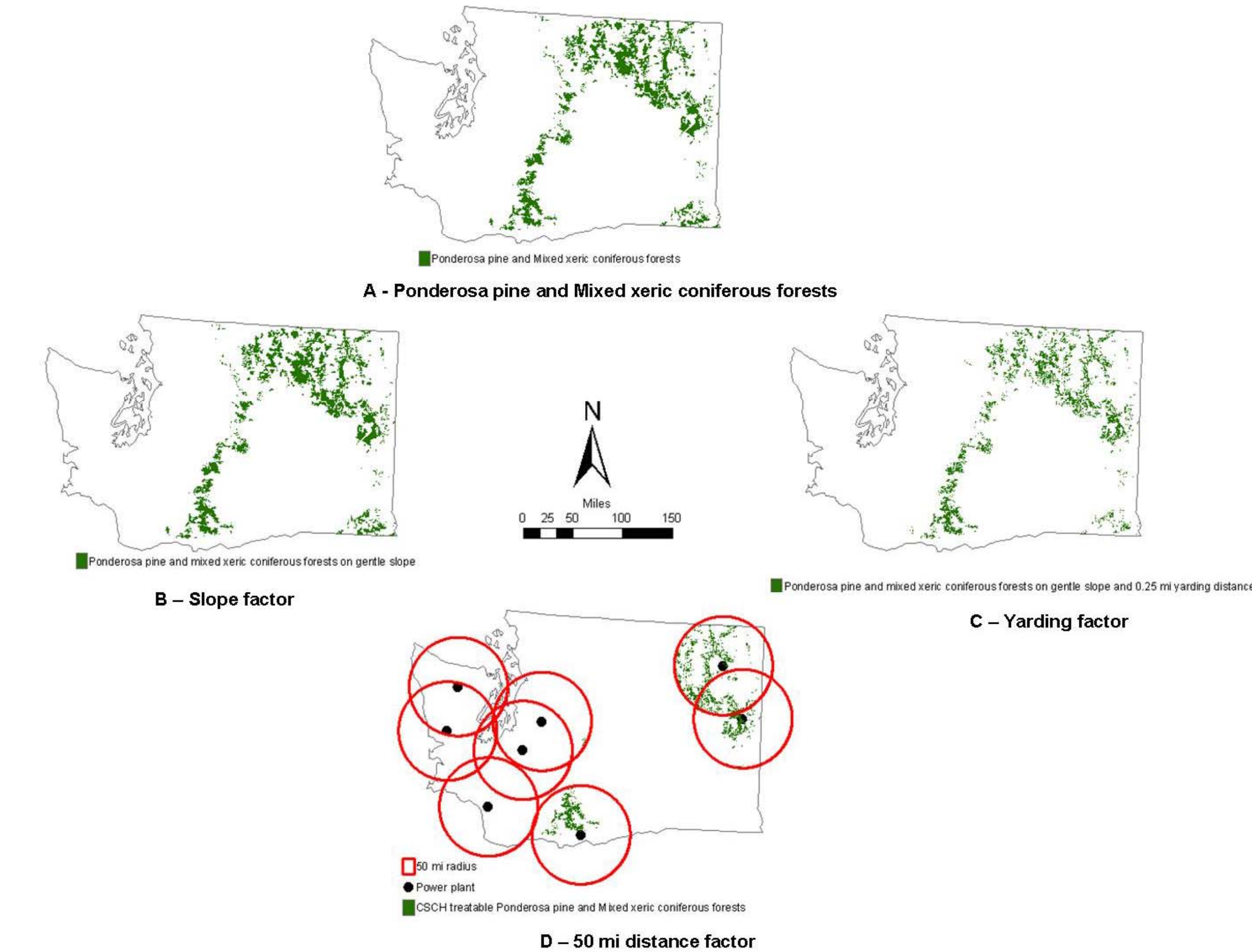

Figure 4-7. Critical factors to determine forestlands with low-severity and mixed-severity fire regimes, suitable for CSCH fuel treatment: A–Ponderosa pine and mixed xeric coniferous forest in Washington; B–Slope less than 40%; C–Yarding distance less than 0.25 miles; D–Distance from existing biomass power plants less than 50 miles.

500,000 hectares of dry ponderosa pine and mixed xeric coniferous forests that would be available for CSCH treatment (Figure 4-7. Available biomass (short tons/acre) for each fuelbed was calculated from the FCCS data set using the Available Fuel Potential Index (dimension/scaled) multiplied by 10 (David Sandberg, USDA Forest Service's Pacific Northwest Research Station, personal communication, August 2005; see also Sandberg et al. 2001 and Ottmar et al. 2003). The available biomass (short tons/acre) was multiplied by 1.016 to convert to metric tons, and then divided by 0.4 to convert to available biomass (BDT/ha).[7] The total biomass stocking, including trees, accessible for CSCH treatment, would be approximately 39 million BDT.

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7. All numbers are reported in hectares. To convert ha to acres, multiply by 2.47. To convert BDT/ha into BDT/acre, multiply by 0.4.

The total fuel available for removal would be much less than this quantity, as not all biomass on the land would be removed through treatment. Actual percent removal is highly variable by stand, pre-treatment condition, and desired future condition (D. Goehring and D. McCall, PG&E Natural Resources, personal communication, September 2005), making it difficult to assign a percent removal across a broad scale such as a state or region. Over the landscape as a whole, more than 50% removal of the pre-treatment fuel loading may be needed to significantly reduce fire risk (Torching Index and/or Crowning Index; Fried et al. 2002, 2003). Furthermore, more than 50% removal, as a landscape average, is likely to be needed to reach a stand-level residual basal area of 80–125 ft^2/acre, often used in HFR prescription scenarios (Fried et al. 2002). A 15-state strategic assessment of fuels reduction assumed a removal prescription of reducing stand density to 30% of the maximum Stand Density Index (SDI) for a given stand, or averaged across the landscape, a 70% reduction in SDI (USDA Forest Service Research and Development/ Western Forestry Leadership Coalition 2003).

Given the uncertainty in fuel available for removal, two scenarios were considered to help understand the relationship between potential fuel removal and the subsequent carbon benefits associated with that removal. The first scenario assumed that regardless of pre-treatment condition and desired future condition of the forest stand, CSCH treatment removes 10 BDT biomass per hectare (4 BDT/acre). The second scenario assumed that 20 BDT biomass per hectare (8 BDT/acre) are removed.

In the first scenario, biomass of **approximately 5 million BDT** would be available to biomass energy facilities from CSCH treatments on approximately 500 thousand hectares of Washington forestland. This implies an initial loss of forest carbon due to HFR treatment of approximately 2.5 million t C—although this initial loss is obviously offset by potentially great savings in CO_2 and non-CO_2 greenhouse gas emissions due to reduction in the probability, severity, and extent of wildfire attributable to the HFR treatment.[8] The second scenario results in **approximately 10 million BDT** available biomass associated with approximately 5 million t C initial removals. The total carbon stocks for Washington forest with HLS-HMS fire regimes is approximately 18.5 million t C for the forest area with information from the FCCS data set on the Available Fuel Potential Index.

4.4.2. Economic Analysis and Potential Role of Carbon Emission Reduction Credits

Costs for CSCH range widely depending on the treatment prescription, presence or absence of merchantable material in the prescription, region of the country, and the factors identified above (slope, yarding distance, haul distance, etc.). Here the values quoted in a recent broad-scale strategic assessment covering 15 states and a wide range of experience with HFR were used as a guide: the treatment analogous to CSCH had a cost range of $34–$48/BDT (USDA Forest Service Research and Development/Western Forestry Leadership Coalition 2003). Assuming from above that biomass of approximately 5 million BDT would be removed from the forest in scenario 1, treating all these forestlands would have a total cost of approximately

8. Carbon stocks are calculated as 50% of biomass.

$168 million (low) to approximately $238 million (high). Treating these forestlands in scenario 2 would have a cost of approximately $337 million (low) to approximately $475 million (high).

The value of this biomass for purchase by biomass facilities may be estimated at $36/BDT (Fried et al. 2003), although market prices for fuel will vary somewhat by region depending on the number of biomass plants in operation and thus competition for fuel. For both scenarios, the analysis estimated the amount of revenue that CSCH on the forestlands in question would generate, and/or subsidy required, to remove the available biomass to biomass energy facilities.

In the first scenario, with removal of approximately 5 million BDT biomass from Washington forestlands with HLS-HMS fire regimes, the fuel would have a value of approximately $178 million, and thus range from generating a net revenue of approximately $10 million (if value = $36/BDT and cost = $34/BDT), to requiring a total subsidy of approximately $59 million to treat all these lands (if value = $36/BDT and cost = $48/BDT). In the second scenario, with removal of approximately 10 million BDT biomass, the fuel would have a value of approximately $357 million, and thus range from generating a net revenue of approximately $20 million (if value = $36/BDT and cost = $34/BDT), to requiring a total subsidy of approximately $119 million to treat all these lands (if value = $36/BDT and cost = $48/BDT).

To ascertain whether removal of hazardous fuel that results in reduced fire intensity and reduced carbon emissions (i.e., conservation of forest carbon stocks) makes economic sense, the following first-order calculations are presented. Assuming the higher costs for biomass removal as described above, treating the 500,000 hectares estimated to be treatable with CSCH would require a per-hectare subsidy of $120 ($59 million total subsidy divided by 500,000 ha) for removal of 10 BDT/ha, or $240 ($119 million divided by 500,000 ha) for removal of 20 BDT/ha. Assuming commonly used prices of CO_2, would emissions reductions attributable to HFR activities be sufficient so that the sale of carbon credits from these projects could cover the per-hectare subsidy required?

Depending upon the price of carbon assumed (two commonly used values are $2.40/t CO_2 and $10/t CO_2), the quantity of carbon emissions that would need to be reduced through HFR to cover the per-hectare subsidies needed—essentially, to make high-cost CSCH a break-even activity—varies from as little as about 3 t C/ha to as much as 27 t C/ha (Table 4-3). Whether HFR could produce this order of magnitude of emissions reductions depends on baseline emissions from fires of varying intensities, and whether HFR prior to fire reduces the intensity of fires. In a related analysis conducted for the WESTCARB effort, the differences between net carbon emissions from medium-intensity fires and low-intensity fires across all forest types in Washington ranged from 8 to 30 t C/ha; the difference in emissions between high-intensity and low-intensity fires ranged from 16 to 80 t C/ha (Brown and Kadyszewski 2005b). In other words, if HFR resulted in low-intensity forest fires rather than medium-intensity fires, there would be a reduction in carbon emissions attributable to HFR of 8–30 t C/ha; if HFR treatment reduced fire severity from high-intensity to low-intensity, the emissions reduction would be 16–80 t C/ha. The reduction in emissions attributable to HFR in order to cover the per-hectare subsidies required, 3–27 t C/ha, is well within this range for a change from medium- to low-intensity fires, and much lower for a change from high- to low-intensity fires.

Thus it appears, in a preliminary analysis, that the order of magnitude in emissions reductions attributable to HFR, assuming commonly used prices for carbon offsets, is within the realm of practicality to cover subsidies needed for HFR—adding support to the argument for qualifying fuel reduction activities as carbon offset projects. It should be emphasized that this preliminary analysis needs further research and discussion, including collection of additional data on emissions from wildfires of varying severity, and what reductions in fire severity and/or emissions should be attributable to pre-fire HFR treatment.

Table 4-3. Quantity of CO_2 emissions reductions (t CO_2/ha and t C/ha) that would need to be produced by HFR activities to cover estimated per-hectare subsidies needed for CSCH

Subsidy	\$2.4/t CO_2		\$10/t CO_2	
	t CO_2/ha	t C/ha	t CO_2/ha	t C/ha
\$120/ha	50	14	12	3
\$240/ha	100	27	24	7

5.0 Next Steps

This report has presented the results of carbon supply analyses for several potential activities in Washington: afforestation of rangelands, afforestation of croplands, changes in forest management including extending rotations and widening riparian buffers, and hazardous fuel reduction to reduce emissions from wildfire in fire-prone forest ecosystems. This final section outlines further characterization work that is needed, both to refine these analyses and to evaluate additional carbon sequestration opportunities for the state and region. The focus is on refinements to the analysis of fuel load reduction, and on afforestation using fast-growing species such as hybrid poplar as a means to sequester carbon and/or provide fuel for biomass energy generation.

5.1. Refinements to the Analysis of Carbon Supply from Fuel Load Reduction

The preliminary analysis presented in Chapter 4 highlights needs for further research, policy discussion, and consensus-building among the diverse stakeholders with an interest in forests and fire. Further research and analysis is needed, particularly in the following two areas.

5.1.1. Refinement #1: Analysis of Other HFR Treatment Types

In reality, a much greater range of treatment types than only CSCH (as used in this report) is available for fuel reduction and/or removal. Each treatment type has its own ideal conditions for use, constraints on use, costs, product yield and thus revenue to offset costs, and environmental (air quality, sedimentary, and greenhouse gas emission) implications. Some treatments leave the fuel on site or simply change its form, but may be applied on sites that are relatively more inaccessible either from a technical (terrain, slope, distance to roads) or economic (hauling distance) point of view. Thus a more comprehensive model is needed to answer the following questions:

- In addition to slope, yarding distance, and distance to biomass plants, what factors determine the choice of treatment type and technology?
  - Minimum size of treatment block to justify move-in costs?
  - Mix of diameter classes to be removed?
  - Volume and number of stems in the submerchantable and merchantable categories?
  - Distance to processing facilities for merchantable material?
  - Other factors?
- What is an appropriate decision rule for each factor? In treating the slope factor, this analysis assumed CSCH could be applied on slopes < 40%. An analysis based on meeting constraints ignores the other side of each decision rule: excluding lands of > 40% slope or > 0.25 miles yarding distance only means these lands are not available for CSCH, not that they are excluded from all HFR treatment. On slopes > 40% or at greater distance from roads, other treatments might be available that leave fuel on site but still reduce fire hazard (cut-pile-burn, cut-lop-scatter, prescribed fire, etc.).

- What are commonly accepted cost ranges for each treatment type and technology, in \$/acre or \$/bone dry ton (BDT) for submerchantable material and \$/MBF or \$/CCF for merchantable?
- What revenues are available from utilization of submerchantable and merchantable material from these projects? What effects do revenues have on the factors and decision rules used to select treatments? For example, by how much will a greater volume of merchantable material in the prescription increase the yarding distance or distance to a processing facility that is economically feasible?

Most HFR treatments involve a mix of submerchantable and merchantable material, with the value of merchantable material sometimes "subsidizing" the high cost of removing a large number of submerchantable stems, and both submerchantable and merchantable being part of the prescription to achieve a desired condition of spacing, residual basal area per acre, improved forest health, improvement in Torching Index and Crowning Index, etc. Including merchantable material would make more acres accessible for treatment. Thus the estimates here, focusing only on one objective and a single treatment targeting the submerchantable biomass fuel, can be taken as conservative.

5.1.2. Refinement #2: GHG Emissions from Wildfire, and Eligibility of HFR as a Carbon Offset Activity

The suggestion that HFR might produce sufficient emissions reductions to pay for currently uneconomic CSCH treatments, if these emissions reductions were marketable at commonly used prices for CO_2 credits, is a starting point for further study. This suggestion was based on first-order estimates of the difference in CO_2 emissions between low-, medium- and high-intensity fires, and the assumption that HFR treatment might be credited with turning what would have been a high- or medium-intensity (perhaps crown) fire into a low-intensity (perhaps ground) fire. If so, the emission reductions could be credited to the HFR treatment and potentially marketed as a carbon-offset project.

To substantiate this hypothesis, several areas of study are needed. First, work is needed to develop baselines for various wildfire-prone forest types. These baselines will serve as the reference case against which activities to reduce fires would be compared to estimate the potential carbon credits. Such baselines need to include field data and models to quantify the likelihood of fires occurring (e.g., fire return interval) as well as the effects of different fire intensities on greenhouse gas emissions for different forest types (how much of carbon stock is burned with a given fire intensity and stand structure). Field data might include measurements of post-fire forest carbon stocks for comparison to unburned areas; measurements from past fires of varying intensities; measurements of areas where fuel loads were reduced prior to fire to quantify how much treatment reduced the loss of carbon stocks; and evaluation of non-CO_2 greenhouse gas emissions such as CH_4 and N_2O, also likely to be released in wildfires, though to varying extents depending on the type and intensity of the fire.

Second, further scientific research as well as policy discussion and consensus-building are needed around the question of what reductions in fire intensity and/or greenhouse gas emissions should be attributable to pre-fire HFR treatment. Intuitively, it seems reducing ladder fuels or crown density should reduce the probability, intensity, and extent of wildfires and thus the loss of forest carbon stocks and other greenhouse gas emissions; but by how much? With a probabilistic phenomenon such as fire, it is not possible to demonstrate that an area treated with HFR would have burned in the absence of treatment, and released X tons of CO_2 equivalent to the atmosphere; nor in the with-treatment scenario is the goal necessarily to avoid fire and its associated emissions, only to reduce the intensity of fire or its extent. Many fire models are currently in use to evaluate the probability and impacts of fire under different assumptions, but these models produce highly variable outputs, and consensus among models is lacking; moreover, most do not address greenhouse gas emissions from fire. Therefore the process of deciding what types of HFR treatments should be eligible to qualify as carbon offset projects, and assigning values to the greenhouse gas emission reductions attributable to HFR, will involve considerable scientific as well as political consensus-building—even among stakeholders who more or less agree it would be desirable to reduce fuel loads and treat more acres by improving the overall economics of HFR through qualifying these projects for CO_2 credit markets.

Combining this second refinement with the first, different HFR treatments and technologies could be evaluated in terms of their greenhouse gas emission impacts: for example, CSCH would be assigned a triple emission reduction benefit through reduced emissions from wildfire, reduced emissions from fossil fuel–generated electricity due to electricity generation in biomass facilities, and enhanced carbon sequestration in the residual forest stand. Prescribed fire or cut-pile-burn could be assigned a quantifiable benefit for reducing the incidence or intensity of wildfires, but would still put a greater portion of the forest carbon removed in the treatment into the atmosphere.

When potential utilization of both submerchantable biomass and merchantable material from HFR treatments is considered, emissions reduction credits become one of a set of values—along with merchantable material, biomass fuel value, green power incentives, and even other marketed ecosystem services enhanced by these treatments—that would improve the overall economics of HFR and help federal, state, and private landowners to mount a more effective response to the wildfire problem.

Finally, further work would then be needed to develop carbon accounting methods and field protocols for actually quantifying the potential carbon credits for a variety of fuel treatments by forest types. This calculation would include the reduction in greenhouse gas emissions from displacing some quantity (MWh) of electricity that would otherwise be generated using fossil fuels. Such methods and protocols would need to be cost-effective, transparent, and reproducible.

These refinements will be addressed through additional field data collection, modeling, analysis, and stakeholder discussions in the second phase of the West Coast Regional Carbon Sequestration Partnership.

5.2. Evaluation of Carbon Sequestration Potential Through Afforestation Using Fast-Growing Species and Other Forest Management Methods

In the first phase of this work, the analysis of afforestation potential on rangelands and croplands looked only at the use of planting native species for forest restoration (see Section 2 above). Two other possibilities exist that will be investigated in Phase 2 of the West Coast Regional Carbon Sequestration Partnership.

5.2.1. Use of Fast-Growing Species

Instead of considering only native species for afforestation activities, fast-growing tree species such as hybrid poplar will be investigated. Land suitable for planting such species will be assessed based on existing data, other publications in the region, and partners. Hybrid poplar is already being grown in parts of Oregon and Washington, and its extent could be increased. Plantations of hybrid poplar grow quickly with up to about 100 t C/ha after 10 years. The potential carbon supply for planting fast-growing species on rangelands and croplands will be investigated, including estimating the opportunity costs (as described in Chapter 2), the costs for planting and managing the plantations, and the revenues from the products (pulp, timber, or biomass fuel). The analysis will be done in a geographic information system as done for native species, and the carbon supply from native versus fast-growing species will be compared.

5.2.2. Other Forest Management Methods: Timber Harvest

In Phase 1 of this work, afforestation of rangelands and croplands considered only the planting of native species for forest restoration. However, it is possible that forest could be grown for timber products. Simulating the growing of trees for timber production affects two components of the carbon supply analysis: the quantity of carbon sequestered and the costs. Phase 2 will investigate the effects on the quantity of carbon and costs across the region.

The quantity of carbon sequestered in the living component of forests grown for timber production will be less than that for forest grown for restoration. However, this decrease in the long-term average in living trees can be made up in part by the carbon in the harvested wood that is converted to long-term wood products. The balance between these two main pools of live and wood products will vary by forest type and will be investigated in detail in Phase 2. Cost will also be different between forests grown for timber and for restoration. When grown for timber, there will be revenues from the sale of timber as well as for the carbon. The analysis of the potential carbon sequestration for the region by afforestation for timber species will incorporate all these factors to arrive at new estimates of the carbon supply, and the results will be compared to those generated in this report.

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7.0 Glossary

AUM	animal unit month: the forage requirement for one head of cattle for one month, which serves as a measure of the carrying capacity of a parcel of rangeland
BDT	bone dry tons
C	carbon
CO_2	carbon dioxide, the principal greenhouse gas
CSCH	cut-skid-chip-haul, a method of hazardous fuel reduction
DM	dry matter, as in forage dry matter
FCCS	fuel characteristic class system
FIA	Forest Inventory and Analysis (USFS data)
FRCC 2	Fire Regime Condition Class 2, a designation for an area with a fire regime moderately altered from its historical range
FRCC 3	Fire Regime Condition Class 3, a designation for an area where fire regimes have been significantly altered and there is high risk of catastrophic wildfire
GHG	greenhouse gas
GIS	geographic information system
HFR	hazardous fuel reduction
HLS	historically low severity (fire regime)
HMS	historically mixed severity (fire regime)
NASS	National Agricultural Statistics Service of the USDA
NLCD	National Land Cover Dataset, a USGS land cover mapping project conducted in 1992
SPFR	Suitability for Potential Fuel Reduction, an index developed for this project
STATSGO	State Soil Geographic Database
USDA	United States Department of Agriculture
USFS	USDA Forest Service
USGS	United States Geological Survey
WESTCARB	West Coast Regional Carbon Sequestration Partnership