USING SATELLITE IMAGERY TO DETECT FOREST DISTURBANCES IN NORTHWEST WASHINGTON AND SOUTHWEST BRITISH COLUMBIA FROM 1973 TO 1995

BY

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Abstract

A series of Landsat satellite images are used to detect and map forest disturbances in a 2 million hectare area of southwest British Columbia, Canada, and northwest Washington State, United States, from 1973 to 1995. During this 22 year period the rates and patterns of disturbance are examined by protected status across two countries and by land ownership within Washington for five time intervals. The total amount of disturbance in protected forest areas has been minimal. In contrast, disturbance affected 8.97% of the unprotected forest and appeared to be primarily the result of clearcut harvest activity. The rate of disturbance was greatest in the interval from 1985 to 1988 before declining to 1973 levels. The disturbance rate was larger for unprotected forest land in Washington (9.99%) as compared to British Columbia (7.43%) yet disturbance patterns in both countries displayed smaller mean patch sizes and less patch shape complexity over time. Within Washington, the rates of disturbance varied by federal, state and private ownership. Decreased rates of disturbance on unprotected federal lands occurred simultaneously with increased rates on state and private forests. Results therefore demonstrate that the rates and patterns of disturbance within this complex region of political and administrative boundaries have been influenced by changing forest management practices and policies during this 22-year period.

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Introduction

In recent decades the historically dense and productive lowland forest ecosystems of the Pacific Northwest, including western Washington State, United States and British Columbia, Canada have been altered primarily as a result of forest harvest activity. Forests at higher elevations are protected within National Parks, Provincial Parks, and Wilderness Areas and remain largely untouched by timber harvest. Harvest activity in unprotected forests has been an important component of forest management practices and policies since the early 1970's. Recently, new perspectives in forest management have focused on the ecological as well as the economic value of forest resources at the landscape and ecosystem scale. This requires consistent and complete information on forest cover and forest change (Cohen *et al.* 1996; FEMAT 1993; Sachs *et al.* 1998). Satellite remote sensing and Geographic Information Systems (GIS) are the technologies best suited to provide data and perform landscape analyses which facilitate the examination of ecological relationships and the detection of forest disturbance at the landscape scale (Cohen *et al.* 1996; Iverson *et al.*1989). The historic rates and patterns of disturbance vary across the landscape over time depending on forest ownership but have not yet been mapped. The change detection study presented here uses multi-temporal satellite imagery to examine forest change along the Washington and British Columbia border during five time periods between 1973 - 1995. This is the first large scale analysis of disturbance activity within this region where forests exist in a complex array of boundaries defined by an international border, protected status, and land ownership.

Forest Management

Legislation permitting the designation of wilderness areas in Washington state was adopted by the U.S. Congress through the Wilderness Act of 1964 and by the State of Washington in 1984 (Mueller 1994). Wilderness areas were created from roadless areas that are impacted only impacted by natural disturbance regimes. The North Cascades National Park Complex is composed of the National Park, two National Recreation Areas, and a Designated Wilderness Area which had all been established by 1988. Limited logging activity occurred in the National Park prior to its establishment in 1968 (Agee and Kertis 1987). In B.C., Provincial Parks and Recreation Areas were first established in the 1930's and have been managed for the protection of the natural resource base since the revised Park Act of 1965 (B.C. Ministry of Environment, Lands, and Parks 1998). Historical logging activity also took place in accessible areas within Provincial Parks including one of the province's largest railroad logging operations located in the Alouette Valley of Golden Ears Provincial Park in the 1920's.

On unprotected lands in Washington and B.C. forest management has traditionally focused on timber harvests for economic returns. The United States Forest Service (USFS) has allowed timber harvests in forests of Washington and Oregon at historically high levels since the 1980's (Anderson 1984). The Washington State Department of Natural Resources (DNR) has managed forests as state trust lands which have generated approximately $250 million per year in recent years and more than $4.5 billion since 1970 (DNR 1997). On Washington's private lands industrial and small scale operations have harvested timber for revenue and accounted for the majority of state's total timber harvest since 1980 (FEMAT 1993). In British Columbia, forestry is the key contributor to the provincial economy, accounting for over 50% of the total manufactured shipments in the 1990's (COFI 1998; Kimmons and Lavender 1992).

To maximize available forest resources, management practices have focused on short rotation periods (40 to 80 years) and clearcut harvesting techniques (FEMAT 1993). The cumulative effects of forest disturbance have created fragmented landscapes of forest cover with altered landscape patterns (Franklin and Forman 1987; Ripple *et al.* 1991; Spies *et al.* 1994) that display characteristics far different than those associated with natural disturbance regimes for this region such as fire or disease (Wallin *et al.* 1996b). Changing landscape patterns also have wide ranging environmental implications. The fragmentation of forest landscapes impacts biological diversity (Franklin 1993; Harris 1984; Rosenberg and Raphael 1986; Lehmkuhl *et al.* 1991), climate (Bonan *et al.* 1992), hydrology (Jones and Grant 1996), and the release of carbon to the atmosphere (Dixon *et al.* 1994; Harmon *et al.* 1990; Houghton *et al.* 1983; Wallin *et al.* 1996a).

In response to these issues forest management has been redefined to examine forests at the ecosystem or landscape scale using an approach where economic benefits are balanced with ecological considerations (Cohen *et al.* 1998). As of 1995, timber harvest activity on unprotected forest lands in Washington and British Columbia were governed by new forestry guidelines that were designed to consider the cumulative impacts of harvest practices in forests at the ecosystem scale. In 1992, the Washington State Forest Practices Act was adopted to regulate forestry activity including timber harvesting, road construction, chemical application, and reforestation on state and private lands (Washington State Forest Practices Board, 1992). On federal lands within Washington, the Northwest Forest Plan was introduced in 1994, to address ecosystem management using guidelines that control activities within specific management areas and provide greater benefits to late-successional forest-related species (Anderson 1994). In British Columbia, The Forest Practices Code came into effect in 1995 to provide provincial and regional standards for managing forests using environmentally sound forest practices (COFI 1998). These new forest management plans are designed to more adequately protect a variety of forest resources at larger spatial scales; however, data on the historic rate and patterns of forest disturbance remain unavailable for much of the region.

Satellite Imagery

Satellite remote sensing is uniquely suited to gather data on forest cover and disturbance throughout the world (Cohen *et al.* 1996; Iverson *et al.* 1989). In tropical forests, for example, remote sensing-based studies have examined decreases in forest cover in Costa Rica (Sader and Joyce 1988), the spatial characteristics of forest clearings in Guatemala (Sader 1995), and the amount of deforestation and forest fragmentation in Brazil (Skole and Tucker 1993). In temperate regions changing forest cover and landscape patterns that have resulted from forest management activities have been investigated in the Russian Far East (Cushman 1997), along the border between China and North Korea (Zheng *et al.* 1997), in Western Oregon (Ripple *et al.* 1991), and interior British Columbia (Sachs *et al.* 1998). With few exceptions forest change has been examined over several years or decades, and few studies have divided longer time periods into smaller intervals to increase temporal resolution. In one example, Miller *et al.* (1998) examined forests of northern New England from 1973 - 1991 using four time periods. Other studies have examined and documented the variability in forest change that occurs across multiple forest ownership groups during smaller time periods. In the Pacific Northwest, Turner *et al.* (1996) examined watersheds on the Olympic Peninsula of Washington for three time periods between 1975 - 1991 on both public and private lands. In western Oregon, Spies *et al.* (1994) examined a landscape consisting of public, private and wilderness ownership groups from 1972 - 1988 using four time periods.

Objectives

An examination of the historic rates and patterns of disturbance during a period of changing management practices and policies across a landscape that displays complex ownership boundaries is an excellent opportunity to demonstrate the capabilities of using satellite imagery and GIS. Results will provide baseline data to support research and resource management which will be able to examine historic trends of disturbance to gain a more holistic view of forest management at the landscape scale. The specific objectives of this research are to: 1) use a temporal series of Landsat satellite images to detect and map forest disturbances (harvest activity and fire) for a 2.03×10^6 hectare study area in southwest British Columbia and northwest Washington from 1973 - 1995 (Figure 1); 2) evaluate the rates and patterns of disturbance for five consecutive time intervals (1973 - 1979, 1979 - 1985, 1985 - 1988, 1988 - 1992, and 1992 - 1995) on forested lands as defined by the international border, protected vs. unprotected status, and management patterns in Washington (Figure 2); 3) assess the accuracy of the disturbance map

Methods

Study Area

This project examines approximately 2.03×10^6 hectares of southwest British Columbia and northwest Washington State (Figure 1). In British Columbia, the majority of the forest area is managed by the Vancouver and Kamloops forest regions of the B.C. Ministry of Forests. The remaining forest is protected within a number of provincial parks and recreation areas that include portions of Golden Ears and Mount Judge Howay to the west and all of Manning, Skagit Valley, and Cascade provincial parks to the east (Figure 2). In Washington state, unprotected commercial forest lands (lands outside National Parks, National Recreation Areas, and designated Wilderness Areas) are divided between federal, state, and private management (Figure 2). The majority of the federal land is managed by the Mount Baker-Snoqualmie National Forest. The Washington State Department of Natural Resources (DNR) manages all state forest lands while the majority of remaining forest is privately owned. Protected areas within Washington state cover almost all of the North Cascades National Park Complex, as well as a number of wilderness areas including the Mount Baker, Noisy-Diobsud, and Boulder River wilderness in addition to portions of the Glacier Peak and Pasayten Wilderness.

Dominant physical features within the region include coastal areas of the Puget Sound lowlands from Whidbey Island north to the Fraser River Valley, and the rough topography, deep valleys, and glaciated peaks of the Cascade Range. Elevations within the region range from sea-level to over 3000 meters. Climate and vegetation vary considerably within the study area especially between areas east and west of the Cascade crest. Lower elevations to the west are marine influenced and have a moderate climate where temperatures are mild, ranging from 5(C in winter to 20(C in summer with annual precipitation falling almost entirely as rain. At higher elevations winter temperatures are colder and the majority of precipitation falls as heavy snow that covers most areas above 1000 meters in the months from November to May. Average annual precipitation typically ranges from approximately 89 cm along the coast to over 356 cm in the higher elevations. To the east of the Cascade crest temperatures are warmer in the summer and colder in the winter. Annual precipitation ranges from approximately 84 cm to as little as 38 cm in the northeast portion of the study area in British Columbia (Canadian Meteorological Centre 1996). The region is heavily forested and includes lower elevation forest zones of Western hemlock / Douglas-fir along the western slopes of the Cascades. At higher elevations forest zones shift to silver fir and subalpine forest zones. In the smaller eastern portion of the study area forest zones include subalpine fir, Engelmann spruce, interior Douglas-fir, Ponderosa pine and mixed conifer forests (Franklin and Dyrness 1973; Mueller 1994).

Satellite Image Processing

A total of six satellite images are used to examine forest disturbance from 1973 - 1995 (Table 1). The four most recent satellite images (1995, 1992, 1988, and 1985) are Landsat Thematic Mapper (TM) images which contain six non-thermal spectral bands and were obtained with a 25-meter pixel size. The two older images (1979 and 1973) are Landsat Multispectral Scanner (MSS) images which contain four spectral bands obtained with a 50-meter pixel size.

Table 1 : Landsat Satellite Image Descriptions

Date	Sensor	WRS Path / Row	Satellite #
1995 / 7 / 18	TM	46 / 26	5
1992 / 8 / 10	TM	46 / 26	5
1988 / 8 / 31	TM	46 / 26	5
1985 / 8 / 23	TM	46 / 26	5
1979 / 7 / 20	MSS	50 / 26	2
1973 / 9 / 16	MSS	50 /26	1

Georeferencing

The 1995 TM image is georeferenced to a vector coverage of hydrologic features created from GIS digital data. Data were obtained from United States Geological Survey (USGS) 1: 100,000 Digital Line Graph (DLG) files, the British Columbia Ministry of Environment, Lands, and Parks Watershed Atlas 1: 50,000 Stream Network Layer, Washington State Department of Natural Resources 1: 24,000 hydrology, and Mount Baker-Snoqualmie National Forest 1: 24,000 hydrology. The remaining TM and MSS images are georeferenced to the 1995 TM image and the intersection of the six georeferenced images determine the maximum extent of the study bounds. All georeferencing uses a minimum of 30 Ground Control Points (GCPs) in a first order polynomial transformation with an Root Mean Square (RMS) error less than 1 pixel. The two MSS images are resampled during this process from a 50-meter pixel size to a 25-meter pixel size imagery using nearest neighbor resampling rules to match the resolution of the TM imagery.

Tasseled Cap Transformation

The Tasseled Cap transformation is used to calculate two new spectral components from the original MSS and TM data. The Tasseled Cap transformation is a Spectral Vegetation Index (SVI) which enhances the vegetation components in a scene by contrasting them against other scene components such as soil (Cohen *et al.* 1996). Previous remote sensing studies have demonstrated the usefulness of the Tasseled Cap transformation for examining both forest cover (Cohen *et al.* 1995; Sachs *et al.* 1998; Turner *et al.* 1996) and forest disturbance (Cohen *et al.* 1998; Sachs *et al.* 1998) in the PNW and British Columbia. For the MSS Tasseled Cap (Kauth and Thomas 1976) and the TM Tasseled Cap (Crist *et al.* 1986) data are transformed into brightness and greenness features, which typically contain greater than 95% of the variability of the original data. Although calculated differently for the MSS and TM sensors the brightness and greenness features are equivalent and therefore comparable (Lillesand and Kiefer 1979).

Change Detection

Image Differencing

The six satellite images define five consecutive time periods which range in length from three to six years (Table 2). To detect areas of change between time periods change detection procedures apply computer algorithms to raw or transformed data to examine a given location over time (Cohen *et al.*1996). Image differencing is one common change detection approach which is used to subtract brightness and greenness images for one date from the more recent date (Cohen *et al.* 1998, Lillesand and Kiefer 1979). Difference images identify areas of forest disturbance as patches of increased brightness and decreased greenness (Figure 3). Increased brightness results from an increase in reflectance due to soil exposure while decreased greenness results from a loss of coverage in the amount of green vegetation (Lillesand and Kiefer 1979). The gross vegetation change detected using image differencing has been shown to offset the radiometric, spectral, and spatial differences associated with using images from different dates and different sensors (Cohen *et al.*, 1998; Sachs *et al.*, 1998).

Table 2 : Change Detection Time Periods and Descriptions

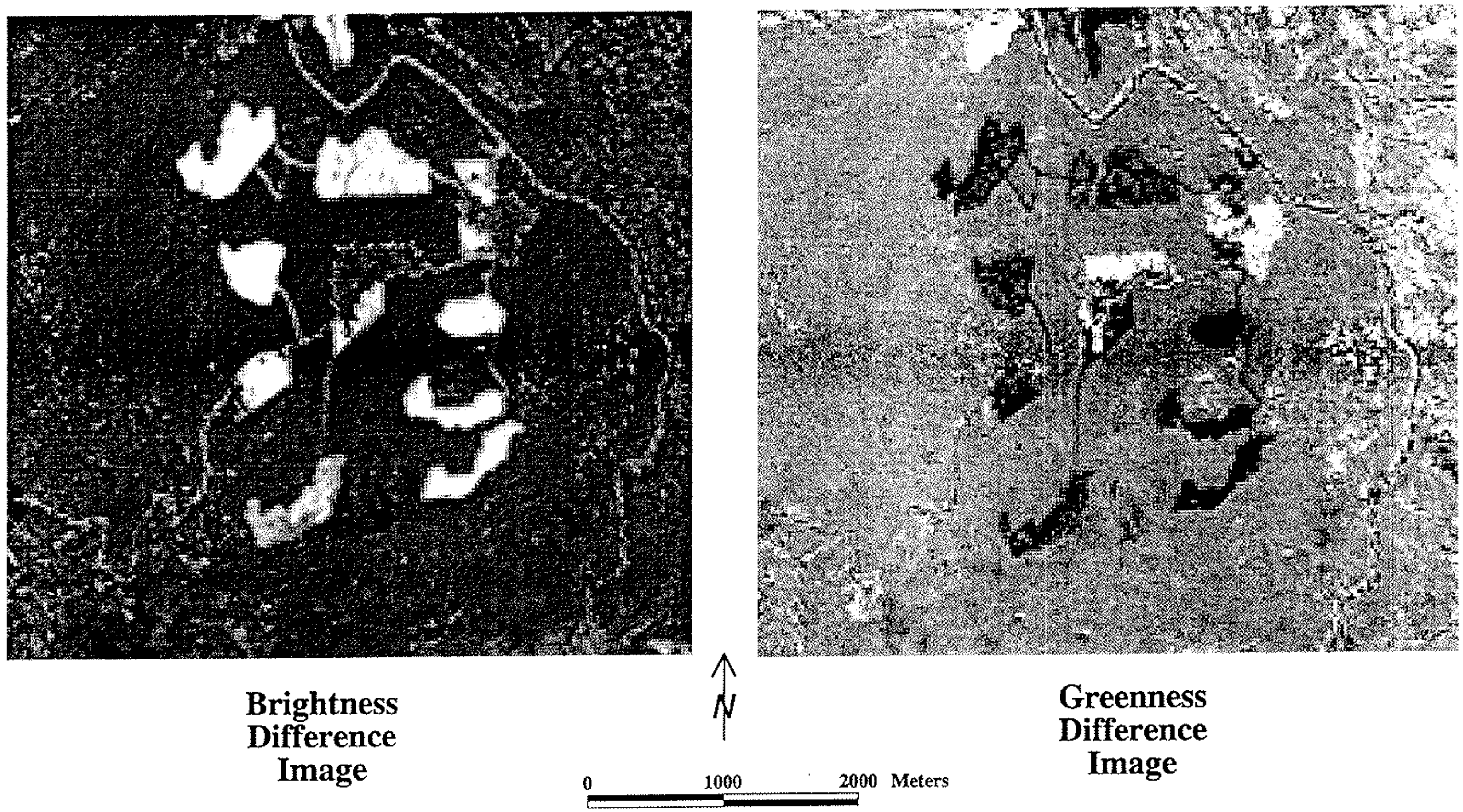
Time Period	Sensor Type	Number of Years
1995 - 1992	TM - TM	3
1992 - 1988	TM - TM	4
1988 - 1985	TM - TM	3
1985 - 1979	TM - MSS	6
1979 - 1973	MSS - MSS	6

Unsupervised Classification

All ten image difference channels, five images each for brightness and greenness difference per time interval, are input simultaneously in an ISODATA unsupervised classification algorithm (Cohen *et al.* 1998). The unsupervised classification procedure uses statistical clustering to group pixels based upon the similarity of their brightness and greenness difference values (Cohen *et al.* 1996). The resulting output image contains numerous classes that represent clusters of change for the five time periods or no change within the image (Lillesand and Kiefer 1979). The results are viewed interactively on screen with the raw satellite imagery to visually interpret and aggregate the results by labeling and assigning clusters to classes representing areas of change within a specific time period or areas of no change.

Figure 3 : Difference Images for Detecting Forest Disturbances

Harvest patches visible using brightness and greenness difference images for an area located in British Columbia from 1992 - 1995.



Post-Processing of Change Detection Results

Filtering

Geometric rectification is inexact with error tolerances measured and reported as an RMS value. Therefore, a slight spatial misregistration is possible and may have a large influence on change detection results (Cohen *et al.* 1996). The aggregated output image is therefore "smoothed" with a majority filter using a 5x5 pixel moving window to account for any slight spatial misregistration between images. Although this filter size approximated a 2 hectare minimum mapping unit a number of small clusters remained which are indistinguishable from background noise. Therefore, after the filtering procedure all clusters with an area less than 2 ha (32 pixels) are eliminated.

Removing Non-Forest Disturbances

The change detection procedure examines the entire study area and as a result detects areas of disturbance in forest as well as non-forest areas. In non-forest areas disturbances are detected in areas where changes occur due to changing snow cover, water levels, and agricultural land cover. It is therefore necessary to "mask" non-forest areas from the disturbance map using available data on forest cover and elevation. Forest cover prior to 1973 is necessary to remove non-forest disturbances without eliminating actual forest change. Forest cover was determined using 1: 250,000 scale Land use / Land cover (LULC) data from the United States Geological Survey (USGS) and the B.C. Ministry of Environment, Lands, and Parks. The USGS LULC data was created in 1973, however the B.C. LULC data was created using satellite imagery from as recently as 1993. To estimate 1973 forest cover in B.C. all disturbance classes, identified as either recently logged or burned, are reclassified back to forest cover. Clouds were a unique scene feature that would falsely appear as forest change but would not be masked using forest cover. Therefore, a vegetation / non-vegetation image is created from the TM 1995 scene (the only scene to contain cloud cover) and incorporated into the forest coverage to remove clouds but retain forest cover.

Elevation also provides useful information for masking disturbances in non-forest areas. A visual examination of satellite imagery and aerial photography indicates that areas below 100 meters were dominated by urban and agricultural land use while high elevation areas above 1700 meters are primarily above timberline consisting of rock, snow, and ice. An elevation cover is created from USGS 1 : 24,000 Digital Elevation Model (DEM) data and B.C. 1 : 20,000 DEM data to mask all areas below 100 meters and higher than 1700 meters in elevation. The final coverage or masking image is created by combining the forest and elevation data (Figure 4).

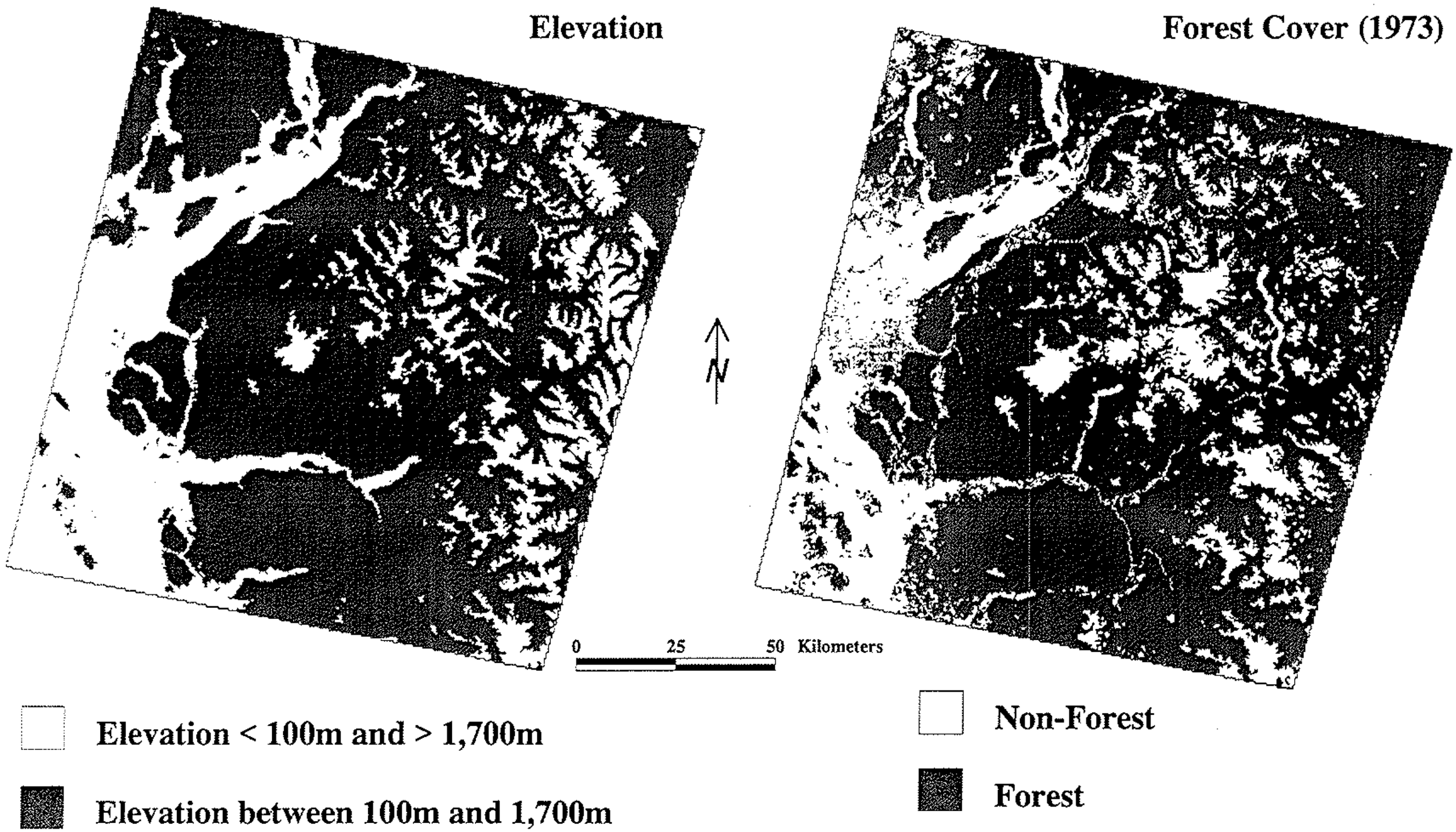
The masking image and the change detection results are converted from a raster to vector format to use a GIS polygon overlay procedure designed to identify change detection polygons that have the majority of their area outside of the mask. The area for each individual disturbance polygon is either completely within the mask, completely outside the mask, or split between mask and non-mask zones. Change polygons that have the majority (> 50%) of their area outside the mask are selected for continued analysis while the remaining polygons (with > 50% of their area within the mask) are discarded.

Determining the Rates and Patterns of Change by Land Ownership

Land Ownership

Land ownership within the study area is determined using GIS data from a variety of sources to examine disturbance by country, protected status, and land ownership. Within B.C., the forest area is divided between provincial parks and unprotected lands, which are primarily Provincial Crown ownership, and are delineated using a GIS coverage of B.C. Protected Areas. In Washington, federally administered forests and protected areas are delineated using 1:24,000 scale Mount Baker-Snoqualmie National Forest bounds in addition to 1: 2,000,000 scale federal land data. State lands are identified using 1:24,000 scale DNR ownership bounds while remaining forest areas outside of unprotected federal and state managed lands are assigned as private ownership.

Figure 4 : Forest Cover and Elevation used to Create the Masking Image



Private forest lands may be owned by large industrial operations, small independent companies, and tribes.

Disturbance Areas, Rates and Patterns

Forest disturbances are analyzed by calculating the amount of disturbed area, the rates of disturbance, and the disturbance patterns by time periods for forests defined by political, administrative, and protected status (Table 3). Time periods included the entire 22-year period from 1973 - 1995 in addition to the five individual time periods: 1973 - 1979, 1979 - 1985, 1985 - 1988, 1988 - 1992, and 1992 - 1995. Disturbance statistics are calculated for the entire study area and by political bounds (Washington and B.C.), protected and unprotected status, and administrative bounds in unprotected forests in Washington (federal, state, and private ownership).

Table 3 : Temporal and Spatial Disturbance Analyses
Disturbance Area and Rates: 1973 - 1995
Study Area
Washington and British Columbia
Protected and Unprotected Forests: Total, Washington and B.C.
Washington Ownership: Federal, State, & Private
Disturbance Rates by Time Period
Study Area
Washington and British Columbia
Protected and Unprotected Forests: Total, Washington and B.C.
Washington Ownership: Federal, State, & Private
Disturbance Patterns: 1973 to 1995
Study Area
Washington and British Columbia
Protected and Unprotected Forests: Total, Washington and B.C.
Washington Ownership: Federal, State, & Private
Disturbance Patterns by Time Period
Study Area
Washington and British Columbia
Protected and Unprotected Forests: Total, Washington and B.C.
Washington Ownership: Federal, State, & Private

The amount of disturbed area and the rate of disturbance are calculated using tools within GIS and summarized as the percent forest area disturbed and the percent forest area disturbed per year, respectively. The amount of area disturbed and rate of disturbance are normalized by forest area to facilitate comparisons between forest ownership groups that vary in size. The spatial characteristics or patterns of disturbance patches are also examined by disturbance classes which are defined as disturbances identified by time periods and forest ownership. Landscape indices can be used to examine the relationships between landscape patterns and ecological phenomena and the spread of disturbance (O'Neill *et al.* 1988). Two class level indices are calculated using the FRAGSTATS spatial analysis program to describe the spatial patterns of disturbance patches (McGarigal and Marks 1995). Mean patch size (MPS) is calculated by dividing the total amount of disturbed area by the number of patches or polygons. The area-weighted mean shape index (AWMSI) measures the complexity of patch shapes in comparison to a standard shape (a circle). The AWMSI is the average shape index of patches weighted by the patch areas and has a value of 1 when all patches within a class are circular and increases with increasing patch shape complexity patches (McGarigal and Marks 1995).

Accuracy Assessment

Pixel Level Assessment

To assess the accuracy of the change detection procedure, including the visual interpretation and classification of output classes, a pixel level assessment was conducted using 100 randomly selected pixels from both the disturbed and non-disturbed classes (Cohen *et al.* 1998, Sachs *et al.* 1998). These pixels are examined simultaneously with the raw satellite imagery (brightness and greenness difference images by time period) to record disturbance status and time interval.

Independent GIS Disturbance Data

Change detection results are compared to available independent GIS data delineating disturbance polygons using a GIS polygon overlay procedure. Accuracy is measured as the number of change detection polygons that overlapped with polygons from the independent GIS disturbance data. In B.C., GIS data for disturbance polygons (harvest and fire) were extracted from the LULC coverage. The LULC coverage has a much larger minimum mapping unit (15 hectares as compared to 2 hectares for the change detection results) and no information on the date of disturbance. Therefore, accuracy can only be measured by this coarse level of spatial agreement but not by time period or amount of area disturbed. For areas within Washington State, fire history polygons from the Mount Baker-Snoqualmie National Forest are examined in conjunction with change detection results.

Independent Rate of Harvest Data

Tabular data describing harvest activity from two separate sources are compared to change detection results for areas within Washington State. The DNR quantified the rate of timber harvest from 1988 - 1991 (Collins 1996) and from 1991 - 1993 (Collins 1997) on federal, state, and private forest lands in Whatcom and Skagit counties. The DNR rate of harvest data were obtained as part of change detection analysis using satellite imagery to map disturbance on all commercial forest lands. The reports provide data for time periods that do not directly coincide with the time intervals for the change detection results; however, the DNR data are used to estimate the accuracy of change detection harvest amounts. In addition to the DNR data the amount of area harvested during the period from 1988-1992 within Whatcom county is also compared to areas recorded on Forest Practice Applications for DNR and private lands.

Results

Disturbance Area and Rates: 1973 to 1995

Study Area

The resulting change detection map displays disturbance patches by time period from 1973 - 1995 (Figure 5). Disturbances cover only a small portion of the entire study area; 4.40% of the total area and 6.10% of the original forest cover in 1973. The annual rate of disturbance on forest lands, measured as the percent of the original forest area disturbed per year, is 0.28% (Table 4) and results in a reduction of forest cover in the study area from 72.07% in 1973 to 67.67% in 1995 (Table 5).

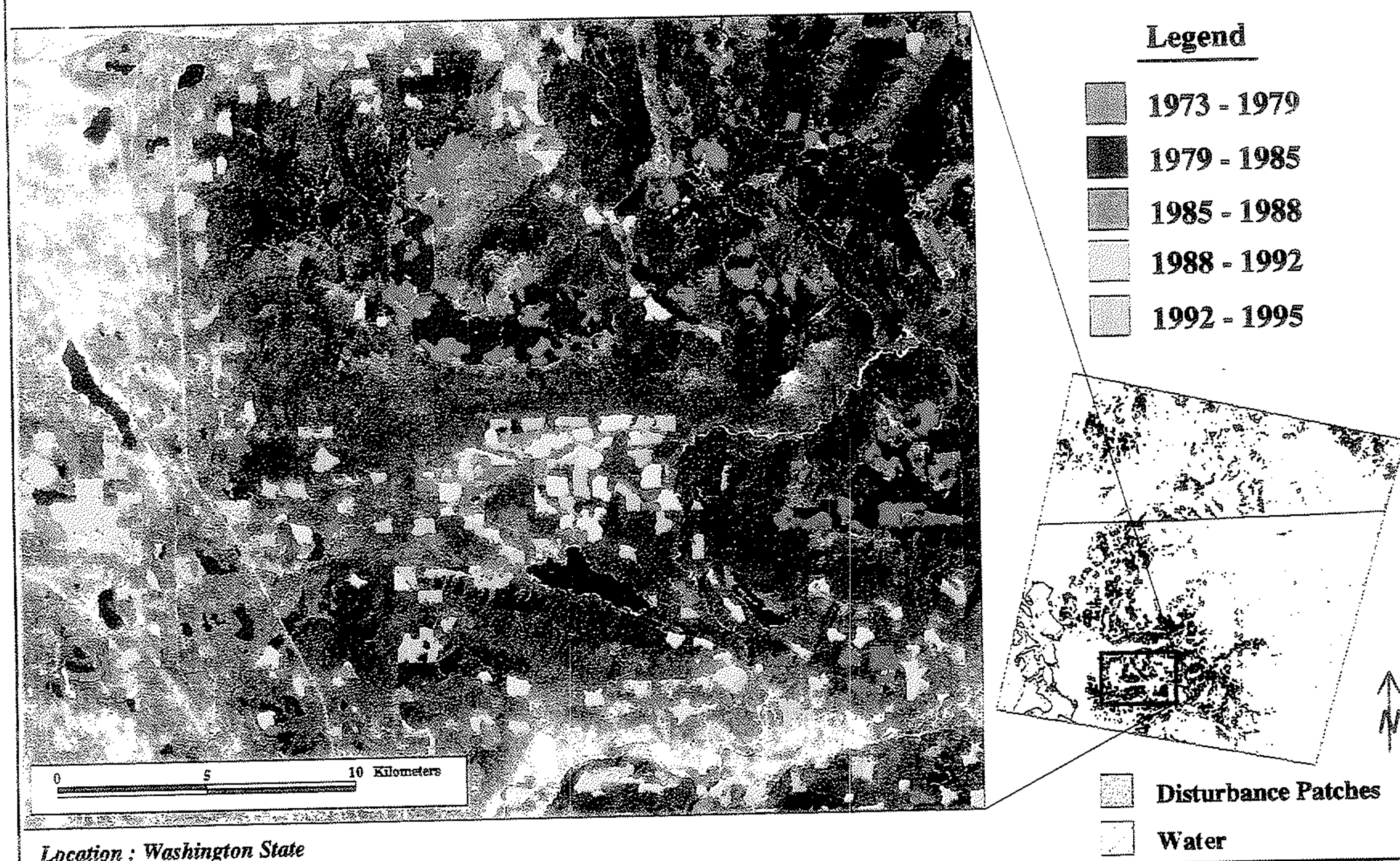
Table 4 : Total Area Disturbed, Percent Forest Disturbed, and Average Rate of Disturbance by Land Ownership from 1973 to 1995

	Total Area (ha)	% of Forest Disturbed	Rate (% forest / year)
Total	89,252	100	0.28
Washington	59,777	6.25	0.28
British Columbia	29,475	5.83	0.26
Protected	716	0.15	0.007
Unprotected	88,536	8.97	0.41
B.C. Protected	410	0.36	0.016
B.C. Unprotected	29,065	7.43	0.34
Washington Protected	306	0.08	0.004
Washington Unprotected	59,471	9.99	0.45
Washington Federal	11,857	4.97	0.23
Washington State	13,814	13.39	0.61
Washington Private	33,800	13.33	0.61

Washington & British Columbia

In both Washington and B.C approximately 6% of the forest area is disturbed from 1973 - 1995. In Washington, disturbed areas cover 59,777 ha accounting for 6.25% of the original forest area

Figure 5 : Disturbance Patches by Time Period and TM 1995 Color Composite



(Table 4) reducing forest cover from 71.54% in 1973 to 67.67% in 1995 (Table 5). In B.C. 29,475 ha of forest were disturbed which was less than the amount of area disturbed in Washington but similar in regards to the proportion of the overall forest area disturbed at 5.83%. Forest cover in B.C. therefore experienced a similar decline in forest area from 73.08% in 1973 to 68.82% in 1995. Examining the rates of disturbance, 0.28% of the forest area was disturbed per year in Washington and 0.26% of the forest area was disturbed per year in British Columbia (Table 4). Although values are slightly larger in Washington, similarities in the amount of disturbed forest area and the rates of disturbance between countries from 1973 - 1995 suggests that similar forces may control disturbance rates on both sides of the international border.

Protected and Unprotected Forests: Total, Washington and B.C.

Although the disturbed area and rate of disturbance vary little by country there is a considerable difference when disturbances are examined by protective status. Approximately one-third (32.10%) of the entire study area is protected within federal and provincial parks, recreation areas, and wilderness areas of Washington and British Columbia. In 1973, protected areas contained 32.54% of the total forest cover with a larger portion of Washington's forests protected (37.78%) as compared to British Columbia (22.62%) (Table 5).

From 1973 - 1995, disturbances in protected areas are minimal and only affect 0.15% of the total forest area (Table 4). The amount of disturbed area is extremely small, only 716 ha during the 22-year period. However, the percentage of the forest area disturbed in B.C. is 4.5 times greater than in Washington (0.36% and 0.08%, respectively). In contrast, unprotected forests changed considerably from 1973 - 1995. Overall, 8.97% of the unprotected forest in the study area was disturbed between 1973 - 1995, reducing forest cover on unprotected lands from 67.46% in 1973 to 65.40% in 1995. When disturbed areas are examined by country the amount of disturbance is higher in unprotected forests of Washington, impacting 9.99% of the forest area, compared to B.C. where disturbance impacts 7.43% of the forest area. Disturbed areas therefore reduce the percentage of unprotected forest cover in Washington and B.C. during the 22-year period. In the unprotected forests of Washington, forest cover is reduced from 62.22% in 1973 to 59.73% in 1995 in contrast to B.C. where forest cover only declines slightly from 77.38% in 1973 to 76.06% in 1995.

The reduction in forest cover in combination with the small amount of disturbance on protected lands actually leads to an increase in the amount of protected forest as a percentage of the total forest area in 1995. Although the amount of disturbed area in protected forests actually reduces the total forest area in hectares, protected forests now account for 34.60% of the total forest area in 1995 as compared to 32.54% of the total forest area in 1973 (Table 5). Similarly, in Washington the percentage of protected forest cover increases from 37.78% in 1973 to 40.27% in 1995. In B.C., there was a smaller increase from 22.62% in 1973 to 23.94% in 1995.

The rate of disturbance in protected forests is extremely low. The overall rate of disturbance on protected lands is 0.007% per year and although higher in B.C. as compared to Washington (0.016% per year in B.C. versus 0.004% per year in Washington) the rates are still only a fraction of those found in unprotected forests (Table 4). From 1973 - 1995 the annual rate of disturbance in unprotected forests is 0.41% per year. In Washington the rate is higher, 0.45% per year, as compared to B.C where the rate is 0.34% per year.

Washington Ownership: Federal, State, & Private

In Washington, the unprotected forest area is divided such that forests in private ownership covered the largest amount of the original forest area (42.59%) as compared to federal (40.08%) and state ownership (17.33%) (Table 5). Federal forests, administered almost entirely by the Mount Baker-Snoqualmie National Forest, cover a sizable portion of Washington's unprotected forests but disturbances during the 22-year period only impact 4.97% of the forest cover (Table 4). On state and private forest lands the difference in the amount of hectares disturbed is large (13,814 ha on state forests versus 33,800 ha on private forests) but when normalized by area the amount of disturbance is similar for both ownership classes (13.39% on state and 13.33% on private). Therefore, for both the state and private forests normalized disturbance areas are approximately 2.7 times larger than on federal lands. Annual disturbance rates from 1973 - 1995 are far lower on federally owned forests (0.23% per year) when compared to state and private owned forests which are both disturbed at a rate of 0.61% of the forest area per year.

The Rate of Disturbance by Time Period

Study Area

Annual disturbance rates in forests differ according to the five time intervals (1973 - 1979, 1979 - 1985, 1985 - 1988, 1988 - 1992, 1992 - 1995) during the 22-year period (Figure 6); (Tables 6 - 10). The annual rate of disturbance averages 0.28% on all forests in the region. However, annual rates range from 0.21% in the initial time period from 1973 - 1979 to 0.37% from 1985 - 1988.

Washington & British Columbia

Average rates of disturbance over the 22-year period for forests in Washington and B.C. are similar (0.28% in Washington and 0.26% in B.C.), yet annual rates of disturbance vary by time interval. In general annual disturbance rates display an increasing trend through the first time periods followed by a gradual decrease in disturbance rates. Annual rates in Washington range from 0.18% in 1973 - 1979 to 0.42% in 1988 - 1992 (Figure 6) and are more variable than in British Columbia. In B.C., the minimum rate of disturbance occurs in the time period from 1992 - 1995 at 0.21% per year while the maximum rate of disturbance is 0.37% from 1985 - 1988, one time period earlier than in Washington.

Protected and Unprotected Forests: Total, Washington and B.C.

The extremely low rates of disturbance on protected lands vary only slightly in Washington ranging from no disturbance in 1985 - 1988 to a rate of 0.006% in the time intervals from 1979 - 1985 and 1988 - 1992 (Figure 7). In B.C. annual rates are always larger and more varied in

Figure 6 :
Rates of Disturbance in Forests of Washington and British Columbia from 1973 to 1995

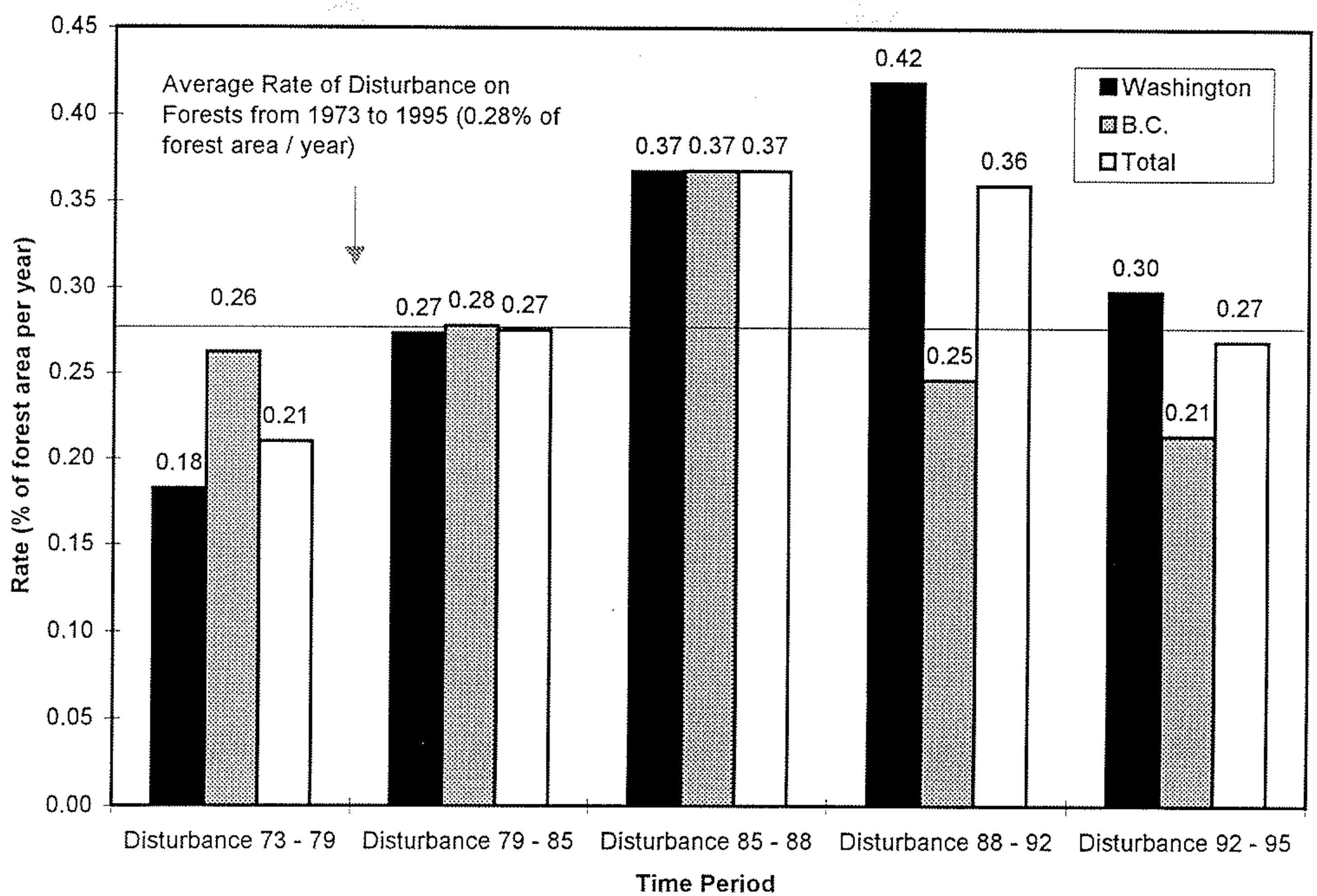


Figure 7 :
Rates of Disturbance in Protected Forests of Washington and British Columbia from 1973 to 1995

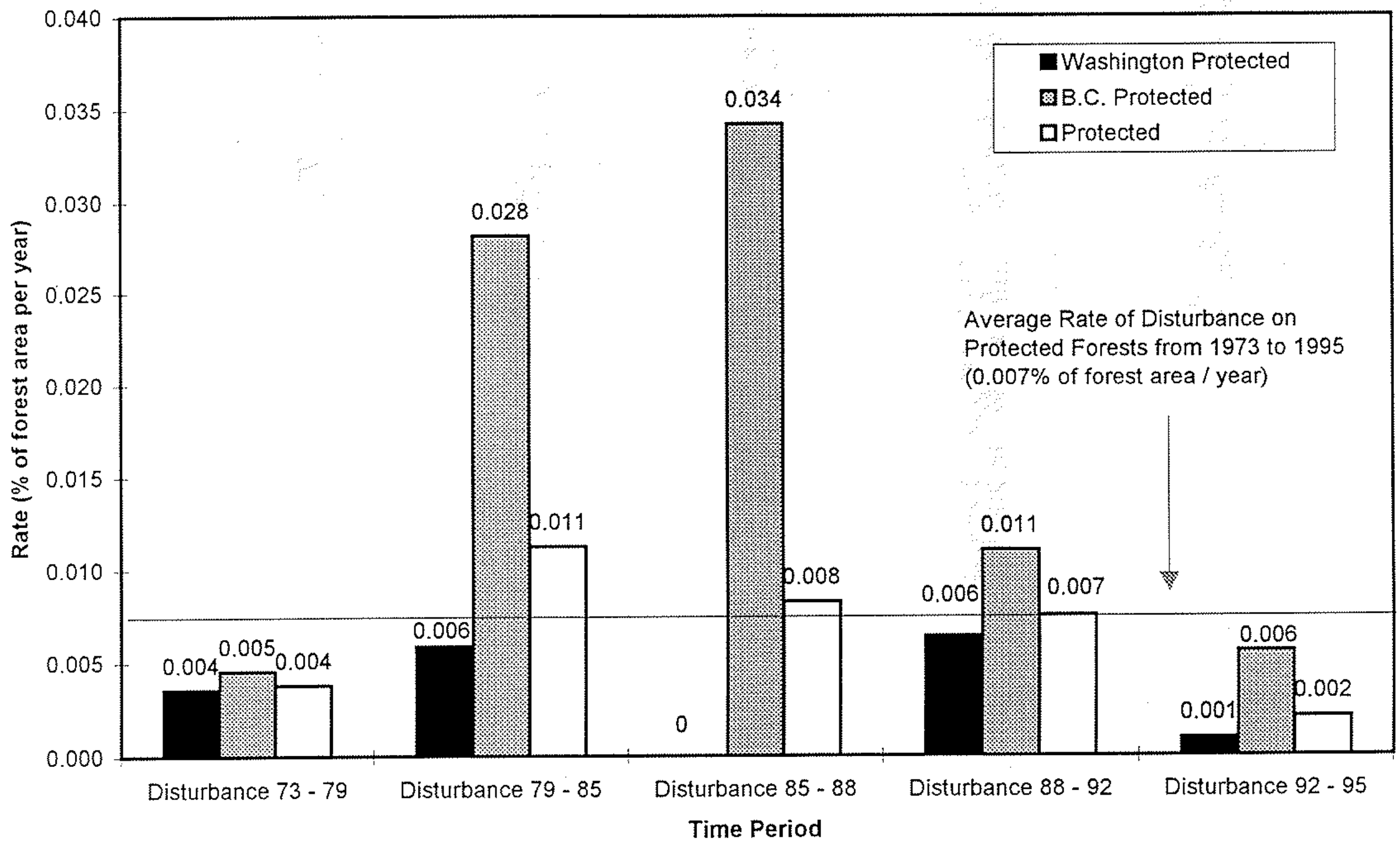


Table 6 : Total Area Disturbed and Average Rate of Disturbance by Land Ownership from 1973 to 1979

	Total Area (ha)	Rate (% forest / year)
Total	18,420	0.21
Washington	10,470	0.18
British Columbia	7,950	0.26
Protected	108	0.004
Unprotected	18,312	0.31
B.C. Protected	31	0.005
B.C. Unprotected	7,919	0.34
Washington Protected	77	0.004
Washington Unprotected	10,393	0.29
Washington Federal	3,309	0.23
Washington State	2,441	0.39
Washington Private	4,643	0.31

Table 7 : Total Area Disturbed and Average Rate of Disturbance by Land Ownership from 1979 to 1985

	Total Area (ha)	Rate (% forest / year)
Total	23,815	0.27
Washington	15,523	0.27
British Columbia	8,291	0.28
Protected	320	0.004
Unprotected	23,494	0.31
B.C. Protected	193	0.028
B.C. Unprotected	8,098	0.35
Washington Protected	127	0.006
Washington Unprotected	15,396	0.44
Washington Federal	4,633	0.33
Washington State	3,115	0.52
Washington Private	7,648	0.51

Table 8 : Total Area Disturbed and Average Rate of Disturbance by Land Ownership from 1985 to 1988

	Total Area (ha)	Rate (% forest / year)
Total	15,660	0.37
Washington	10,263	0.37
British Columbia	5,397	0.37
Protected	117	0.008
Unprotected	15,543	0.55
B.C. Protected	117	0.034
B.C. Unprotected	5,280	0.47
Washington Protected	0	0.0
Washington Unprotected	10,263	0.60
Washington Federal	2,022	0.29
Washington State	2,821	0.96
Washington Private	5,420	0.75

Table 9 : Total Area Disturbed and Average Rate of Disturbance by Land Ownership from 1988 to 1992

	Total Area (ha)	Rate (% forest / year)
Total	20,198	0.36
Washington	15,433	0.42
British Columbia	4,765	0.25
Protected	142	0.007
Unprotected	20,056	0.54
B.C. Protected	50	0.011
B.C. Unprotected	4,715	0.32
Washington Protected	92	0.006
Washington Unprotected	15,341	0.69
Washington Federal	1,620	0.18
Washington State	3,583	0.95
Washington Private	10,138	1.07

Table 10 : Total Area Disturbed and Average Rate of Disturbance by Land Ownership from 1992 to 1995

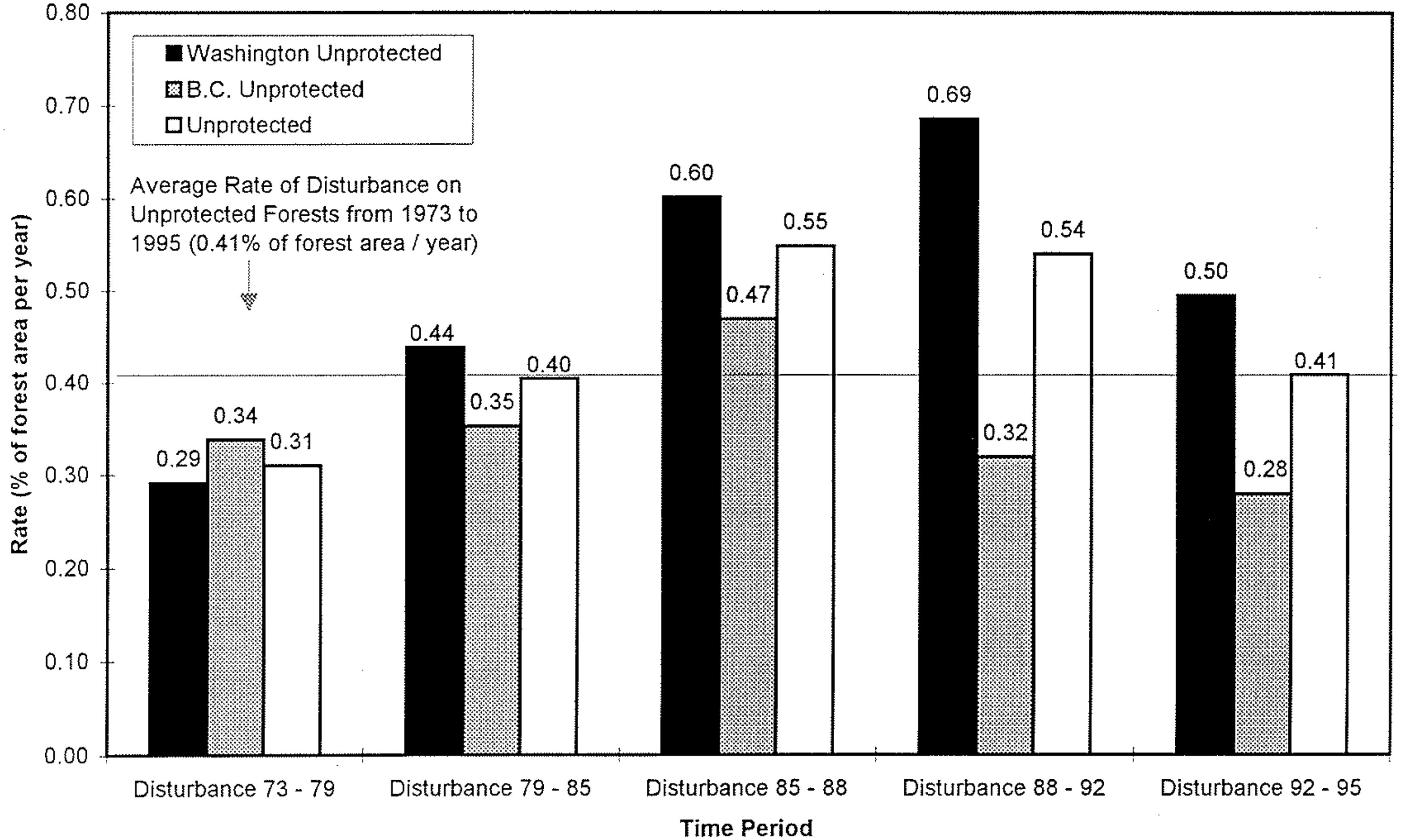
	Total Area (ha)	Rate (% forest / year)
Total	11,159	0.27
Washington	8,088	0.30
British Columbia	3,072	0.21
Protected	29	0.002
Unprotected	11,131	0.41
B.C. Protected	19	0.006
B.C. Unprotected	3,053	0.28
Washington Protected	10	0.001
Washington Unprotected	8,078	0.50
Washington Federal	273	0.04
Washington State	1,854	0.68
Washington Private	5,951	0.88

comparison to Washington where the annual rate is lowest from 1973 - 1979 at 0.005% but then rises substantially in 1979 - 1985 to 0.028% and again in 1985 - 1988 at 0.034%.

In general, disturbance rates increase through the mid 1980's before declining in the mid 1990's. However, important differences exist between rates and temporal patterns, *i.e.* the timing of minimum and maximum annual rates in forests of Washington and British Columbia. The annual disturbance rates in unprotected B.C. forests are more stable through time and only vary from 0.28% in the period from 1992 - 1995 to 0.47% in the period from 1985 - 1988 (Figure 8). In Washington, annual rates of disturbance in unprotected forests are more varied and differ in regards to the timing of maximum and minimum rates. Annual rates of disturbance range from 0.29% in 1973 - 1979 to 0.69% from 1988 - 1992. The minimum rate of disturbance occurs during the first time interval rather than the last interval as in B.C. while the maximum rate in Washington occurs prior to that of British Columbia.

As disturbance rates vary by the amount and timing between Washington and B.C., so do the differences between rates within each time interval. For example, in the interval from 1973 - 1979, the annual rates of disturbance for Washington and B.C are only different by 0.05%. Initially, the rate of disturbance is slightly higher in British Columbia. However, over time the annual disturbance rates in Washington surpass those in B.C. and increase to a greater degree than rates found in British Columbia (Figure 8). In the interval from 1988 - 1992 the maximum difference between rates in Washington and B.C. is reached in which the disturbance rate in Washington exceed the rate in B.C. by 0.37% per year, 7.4 times higher than the difference in the initial time period. From 1988 - 1992 the disturbance rate in Washington reached its maximum value while the disturbance rate in B.C. peaks one time period earlier and is at a rate lower than found in the first time period.

Figure 8 :
Rates of Disturbance in Unprotected Forest of Washington and British Columbia from 1973 to 1995



Washington Ownership: Federal, State, & Private

In unprotected forests of Washington the rates of disturbance also vary according to ownership class, *i.e.* federal, state, or private and time interval. Disturbance rates on federal lands peak during the period from 1979 - 1985 at 0.33% per year before decreasing to only 0.04% per year in the period from 1992 - 1995 (Figure 9). The annual rates of disturbance on federal forests are lower in comparison to state and private forests for all time intervals. In addition, as federal rates decline the rates on state and private forests increase and grow rapidly across time intervals. On state lands the rate of disturbance increases dramatically from 0.39% in the period from 1973 - 1979 to 0.96% from 1985 - 1988. After 1988 rates at first remain stable, at 0.95% in 1988 - 1992, and then decrease to 0.68% from 1992 - 1995. Annual rates on private forests experience a similarly large increase over time but at a more gradual rate in contrast to the rate on state lands that jump 0.44% from the 1979 - 1985 period to the 1985 - 1988 period. In 1973 - 1979 the rate of disturbance is 0.31% per year but increases by approximately 1.5 times during each interval to reach a maximum rate of 1.07% from 1992 - 1995 before decreasing to 0.88% in 1992 - 1995.

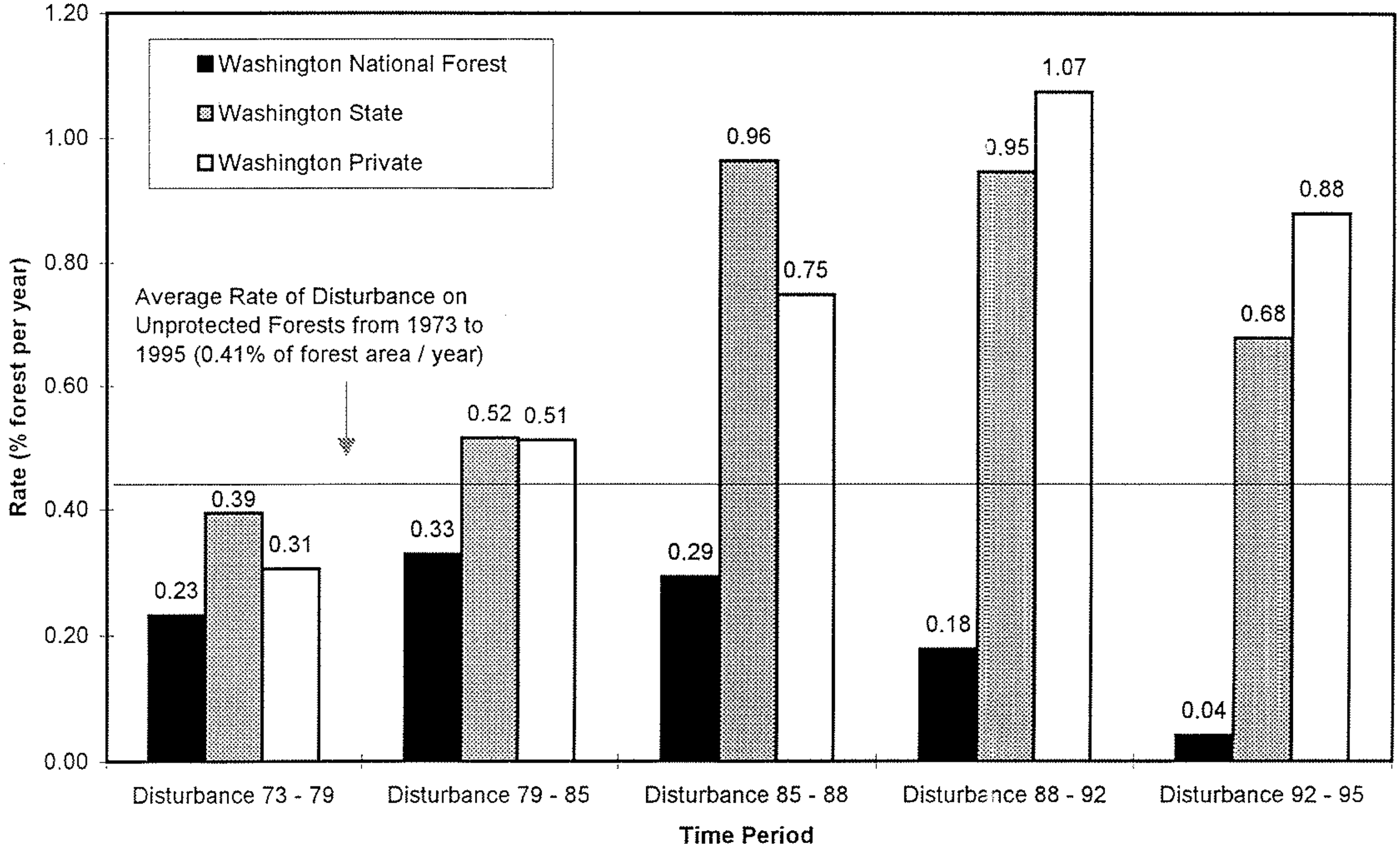
The differences between the rates of disturbance on federal, state and private lands is small from 1973 - 1979. During this time interval the rate on state forests is greatest (0.39% per year) but only exceeds rates on federal forests by 0.16% per year and private forests by 0.08% per year. By the 1988 - 1992 time period the rates on state and private lands (0.95% and 1.08% respectively) are substantially higher, over 5.28 times as high, as compared to the rates on federal forests (0.18%). The time period from 1988 - 1992 is also important because it represents the first time when rates on private forests exceed the rates on state forests.

Disturbance Patterns: 1973 to 1995

Study Area / Washington & British Columbia

The spatial characteristics and patterns of disturbance patches, measured as mean patch size (MPS) and the area-weighted mean shape index (AWMSI), are similar for disturbances in

Figure 9 :
Rates of Disturbance in Unprotected Forests of Washington from 1973 to 1995



Washington and B.C. from 1973-1995 (Table 11). For the entire study area MPS is 16.41 ha while AWMSI is 2.08. In B.C. the MPS is 17.27 ha and slightly larger than the MPS found in Washington which is 15.95 ha. Values for AWMSI are essentially the same for both Washington and B.C. where values are 2.09 for Washington and 2.05 in British Columbia.

Table 11 : Mean Patch Size (MPS) and Area-Weighted Mean Shape Index (AWMSI) by Land Ownership from 1973 to 1995

	MPS (ha)	AWMSI
Total	16.41	2.08
Washington	15.95	2.09
British Columbia	17.27	2.05
Protected	6.56	1.87
Unprotected	16.59	2.09
B.C. Protected	7.51	1.93
B.C. Unprotected	17.47	2.05
Washington Protected	3.47	1.43
Washington Unprotected	16.14	2.10
Washington Federal	9.96	1.84
Washington State	10.70	1.93
Washington Private	15.56	2.16

Protected and Unprotected Forests: Total, Washington and B.C.

In protected versus unprotected forests MPS and AWMSI values from 1973 - 1995 are different. Disturbance patches within protected forests are smaller and less complex in comparison to disturbances found in unprotected forests. The MPS in protected forests is larger in B.C., 7.57 ha, as compared to Washington, 3.47 ha, with the overall MPS on all protected forests equal to 6.56 ha (Table 11). The AWMSI for all protected lands is 1.87 while the value is higher for B.C. at 1.93 but much lower for Washington at 1.43. Thus, on protected lands the disturbance patches in Washington are smaller and more simple in shape as compared to British Columbia. Although differences exist it is important to note that disturbance in protected forests is low and values for MPS and AWMSI are not normalized by the number of polygons. Therefore, in protected areas

MPS and AWMSI represent only a small number of disturbance patches and must therefore be compared with care to the patterns of disturbances from unprotected forests.

In unprotected forests average values for MPS and AWMSI are considerably larger than those found on protected areas which indicates both larger patch sizes and more complex patch shapes. The MPS for all disturbances on unprotected lands is 16.59 ha, a value 2.53 times larger than the MPS found on protected lands, while the AWMSI is 2.09. Values for Washington and B.C. are similar during this 22-year period. The MPS is 16.14 ha in Washington and 17.47 ha in B.C. while AWMSI in Washington is 2.10 as compared to a AWMSI of 2.05 for British Columbia.

Washington Ownership: Federal, State, & Private

For unprotected forests of Washington, average values for MPS and AWMSI from 1973 - 1995 are different depending upon ownership class (Table 11). In general, disturbance patches became larger and displayed more patch shape complexity following the order from federal to state to private ownership. On federal forests disturbance patches have a MPS of 9.96 and a AWMSI of 1.84. Values on state lands are slightly higher with a MPS of 10.70 ha and AWMSI of 1.93. Values for private lands are greatest with a MPS of 15.56 ha and a AWMSI of 2.16.

Disturbance Patterns by Time Period

Study Area / Washington & British Columbia

Values for MPS and AWMSI not only vary by country, protective status and ownership from 1973 - 1995 but also display variability when examined by time period (Figure 10); (Tables 12 - 16). For all forests the average MPS values vary only slightly across time intervals with a maximum variation of 7.02 ha. The MPS between Washington and B.C., within individual time periods only varies by 3.03 ha during 1985 - 1988. For AWMSI, values are similar between countries within time intervals where the maximum variation of 0.27 between Washington and B.C. occurs in the period from 1979 - 1985 (Figure 11). Total AWMSI values display a decreasing trend through

Figure 10 :
Mean Patch Size (MPS) of Disturbances on Forests of Washington and British Columbia from 1973 to 1995

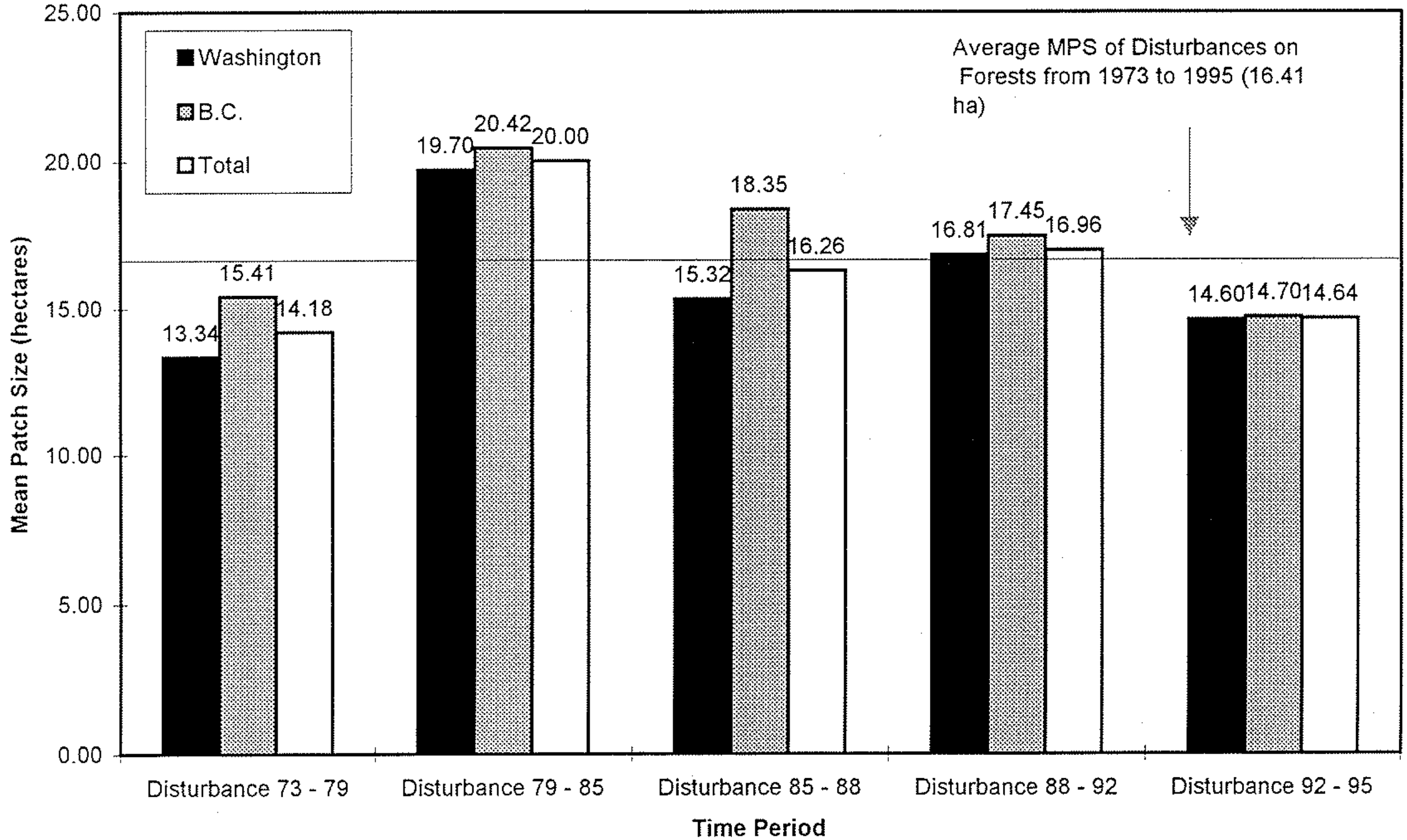


Figure 11 :
Area Weighted Mean Shape Index (AWMSI) for Disturbances in Forests of Washington and British Columbia from 1973 to 1995

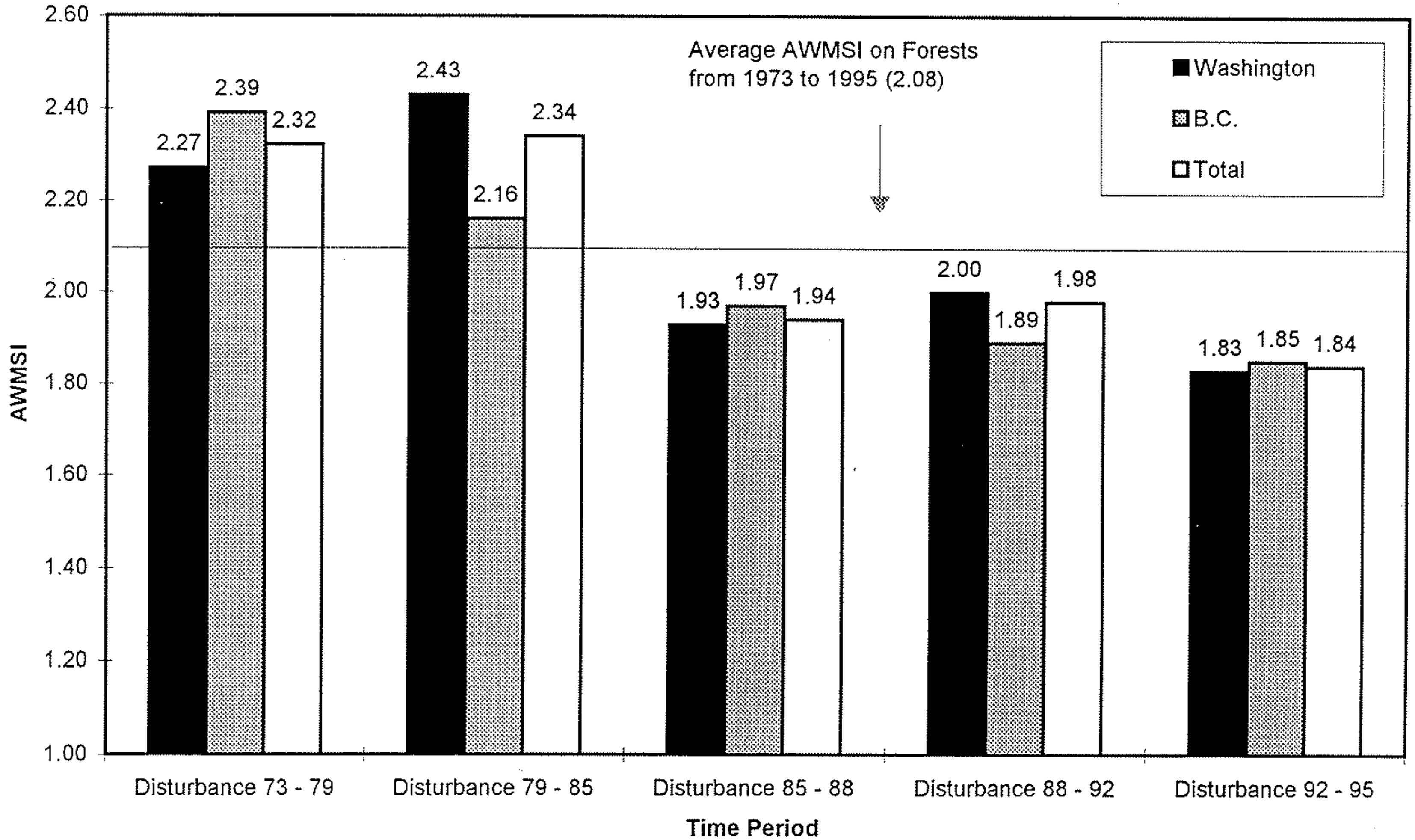


Table 12 : Mean Patch Size (MPS) and Area-Weighted Mean Shape Index (AWMSI) by Land Ownership from 1973 to 1979

	MPS (ha)	AWMSI
Total	14.18	2.32
Washington	13.34	2.27
British Columbia	15.41	2.39
Protected	3.08	1.79
Unprotected	14.43	2.33
B.C. Protected	2.77	1.86
B.C. Unprotected	15.62	2.39
Washington Protected	3.10	1.77
Washington Unprotected	13.62	2.28
Washington Federal	9.79	1.95
Washington State	12.45	2.29
Washington Private	13.04	2.32

Table 13 : Mean Patch Size (MPS) and Area-Weighted Mean Shape Index (AWMSI) by Land Ownership from 1979 to 1985

	MPS (ha)	AWMSI
Total	20.00	2.34
Washington	19.70	2.43
British Columbia	20.42	2.16
Protected	7.44	2.52
Unprotected	20.38	2.33
B.C. Protected	9.62	2.82
B.C. Unprotected	20.93	2.14
Washington Protected	5.54	2.05
Washington Unprotected	20.05	2.43
Washington Federal	11.76	1.94
Washington State	12.66	2.12
Washington Private	23.46	2.51

Table 14 : Mean Patch Size (MPS) and Area-Weighted Mean Shape Index (AWMSI) by Land Ownership from 1985 to 1988

	MPS (ha)	AWMSI
Total	16.26	1.94
Washington	15.32	1.93
British Columbia	18.35	1.97
Protected	11.66	1.83
Unprotected	16.19	1.95
B.C. Protected	11.66	1.83
B.C. Unprotected	18.14	1.98
Washington Protected	0	0
Washington Unprotected	15.32	1.93
Washington Federal	8.79	1.62
Washington State	11.71	1.82
Washington Private	14.19	2.03

Table 15 : Mean Patch Size (MPS) and Area-Weighted Mean Shape Index (AWMSI) by Land Ownership from 1988 to 1992

	MPS (ha)	AWMSI
Total	16.96	1.98
Washington	16.81	2.00
British Columbia	17.45	1.89
Protected	4.90	1.61
Unprotected	17.23	1.98
B.C. Protected	4.20	1.57
B.C. Unprotected	17.93	1.90
Washington Protected	5.40	1.63
Washington Unprotected	17.03	2.01
Washington Federal	10.06	1.69
Washington State	8.89	1.74
Washington Private	14.84	2.09

Table 16 : Mean Patch Size (MPS) and Area-Weighted Mean Shape Index (AWMSI) by Land Ownership from 1992 to 1995

	MPS (ha)	AWMSI
Total	14.64	1.84
Washington	14.60	1.83
British Columbia	14.70	1.85
Protected	5.70	1.62
Unprotected	14.70	1.84
B.C. Protected	9.28	1.59
B.C. Unprotected	14.75	1.85
Washington Protected	3.31	1.68
Washington Unprotected	14.66	1.83
Washington Federal	9.41	1.98
Washington State	7.79	1.70
Washington Private	12.27	1.85

time, indicating a decrease in patch shape complexity, so that AWMSI in the period from 1992 - 1995 is at its lowest value.

Protected and Unprotected Forests: Total, Washington and B.C.

On protected lands in Washington and B.C. values for MPS tend to vary widely across time intervals and between Washington and British Columbia (Figure 12). This is especially true in the period from 1985 - 1988 when the absence of disturbance area, and therefore MPS, in Washington is in contrast to a MPS of 11.66 ha in British Columbia. Values for AWMSI are highest in Washington and B.C. in the period from 1979 - 1985 and then decline over time while values between countries remain relatively similar (Figure 13). Because disturbances in protected forests only amount to 0.08% of the total amount of disturbance in the study area MPS and AWMSI are viewed as having far less of an impact on the overall landscape as compared to disturbances on unprotected areas.

In unprotected forests MPS and AWMSI vary only slightly between countries (Figures 14 - 15). In unprotected forests MPS for Washington and B.C. are similar both across time intervals and between countries. After an initial increase in the second time interval from 1979 - 1985, MPS values for Washington and B.C. gradually decline but never vary by more than the 3 ha found in the first time interval (Figure 14). Although there is little variation between countries, MPS in B.C. is always greater than the MPS found in unprotected forests of Washington. The values for AWMSI are also similar between countries with a maximum difference between values occurring in the period from 1979 - 1985 at 0.29 (Figure 15). Over time AWMSI again follows a decreasing trend reaching minimum values for Washington and B.C. in the last time interval from 1992 - 1995. The time period from 1992 - 1995 not only displays low MPS and AWMSI values for both Washington and B.C. but also represents the period when the differences between Washington and B.C. are the smallest with only a 0.09 ha difference in MPS and a difference of 0.02 in AWMSI.

Figure 14 :
Mean Patch Size (MPS) of Disturbances in Unprotected Forests of Washington and British Columbia from 1973 to 1995

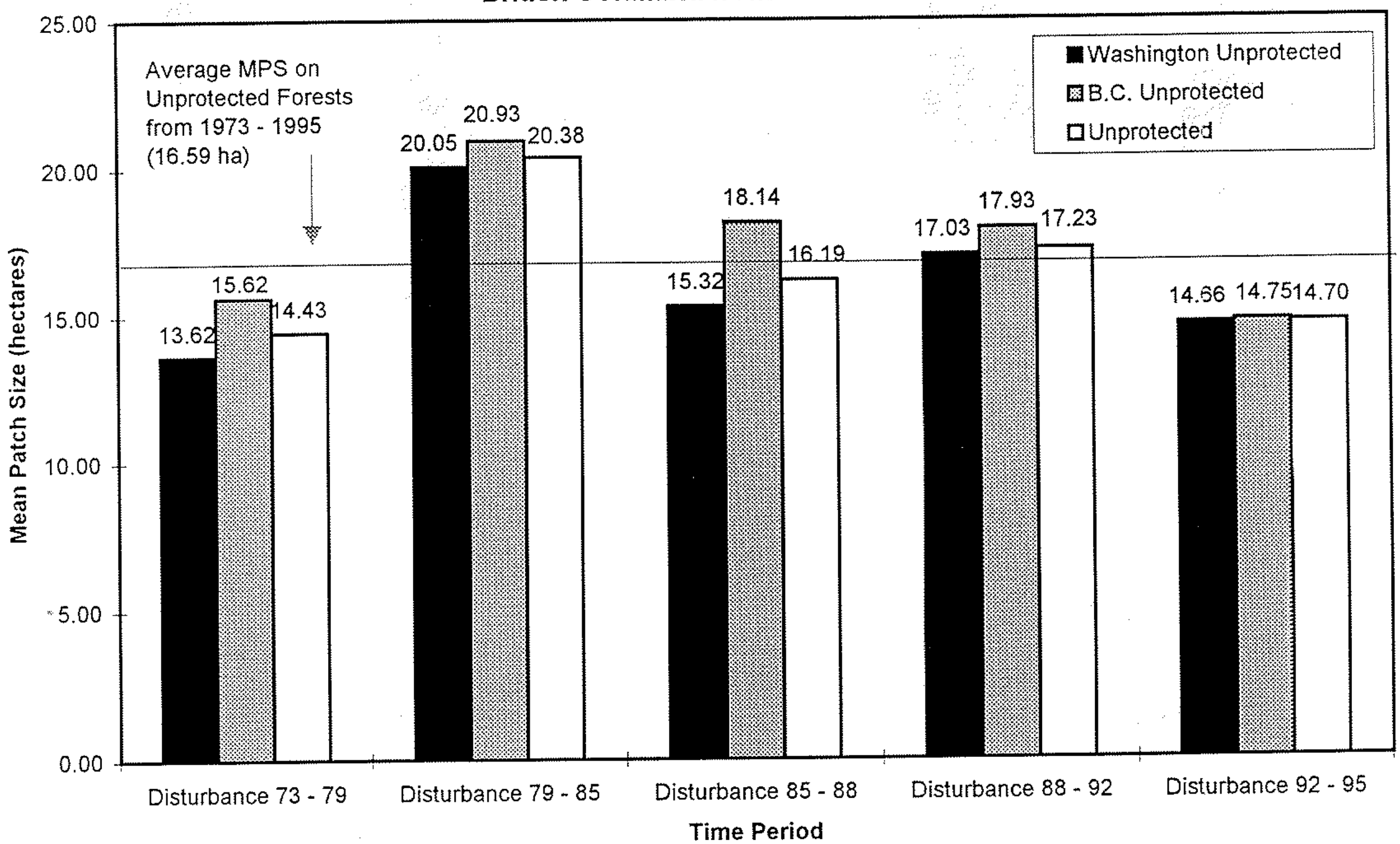
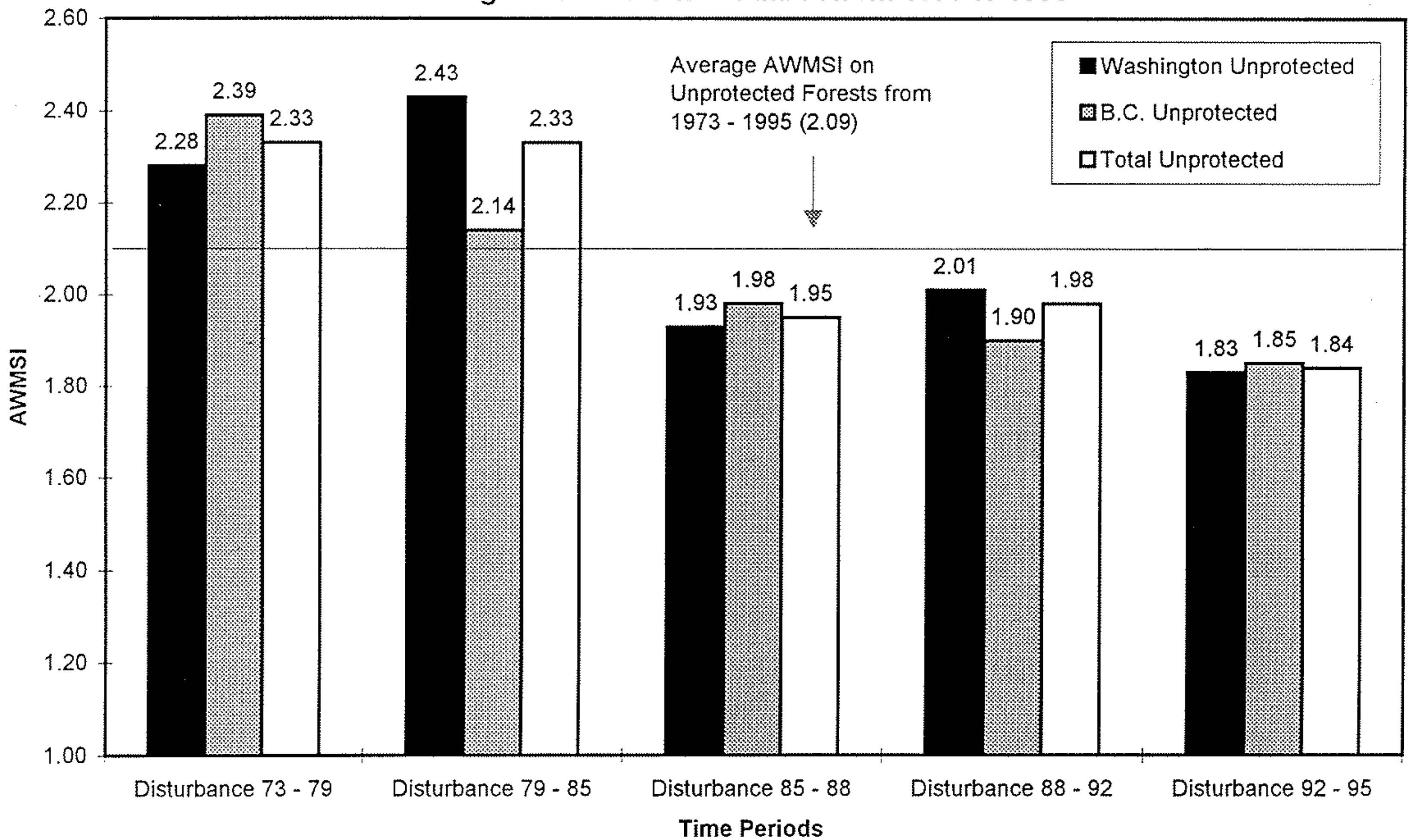


Figure 15 :
Area Weighted Mean Shape Index (AWMSI) for Disturbances in Unprotected Forests of Washington and British Columbia from 1973 to 1995



Washington Ownership: Federal, State, & Private

The spatial patterns of disturbance patches within unprotected forests of Washington display variability within time periods based upon federal, state, and private ownership and have similar trends when examined by ownership class across time intervals. For example, except for the MPS on private forests in the period from 1979 - 1985, which is almost twice as high as all other private MPS values, variability in both MPS (Figure 16) and AWMSI (Figure 17) is relatively small between ownership classes. Although values are similar between ownership classes, important relationships exist. Values for MPS and AWMSI are always larger on private forests as compared to state and federal forests. In addition, MPS and AWMSI display decreasing trends over time so that by the 1992 - 1995 time interval values on private and state forests are at their lowest values. Values for MPS and AWMSI on federal forests are not at their lowest values during the last period; in fact from 1992 - 1995 AWMSI is actually the largest across time intervals for federal forests. However, the annual rate of disturbance on federal lands during the final time interval is only 0.04% of the federal forest area; therefore, MPS and AWMSI are describing only a small number of disturbance patches that cover a small area.

Accuracy Assessment

Pixel Level Assessment

Accuracy is greater than 95% for both the disturbed and undisturbed classes. All 100 of the randomly selected undisturbed pixels were correctly classified based upon a visual examination of the raw satellite imagery. Of the 100 randomly selected disturbed pixels 95% (95 / 100) are correctly classified as disturbed during the correct time period. The five incorrectly classified pixels are accurately identified as disturbed but within a different time interval and were located along the edge of a disturbance patch that is adjacent to another area of disturbance. In

Figure 16 :
Mean Patch Size (MPS) for Disturbances in Unprotected Forests of Washington from 1973 to 1995

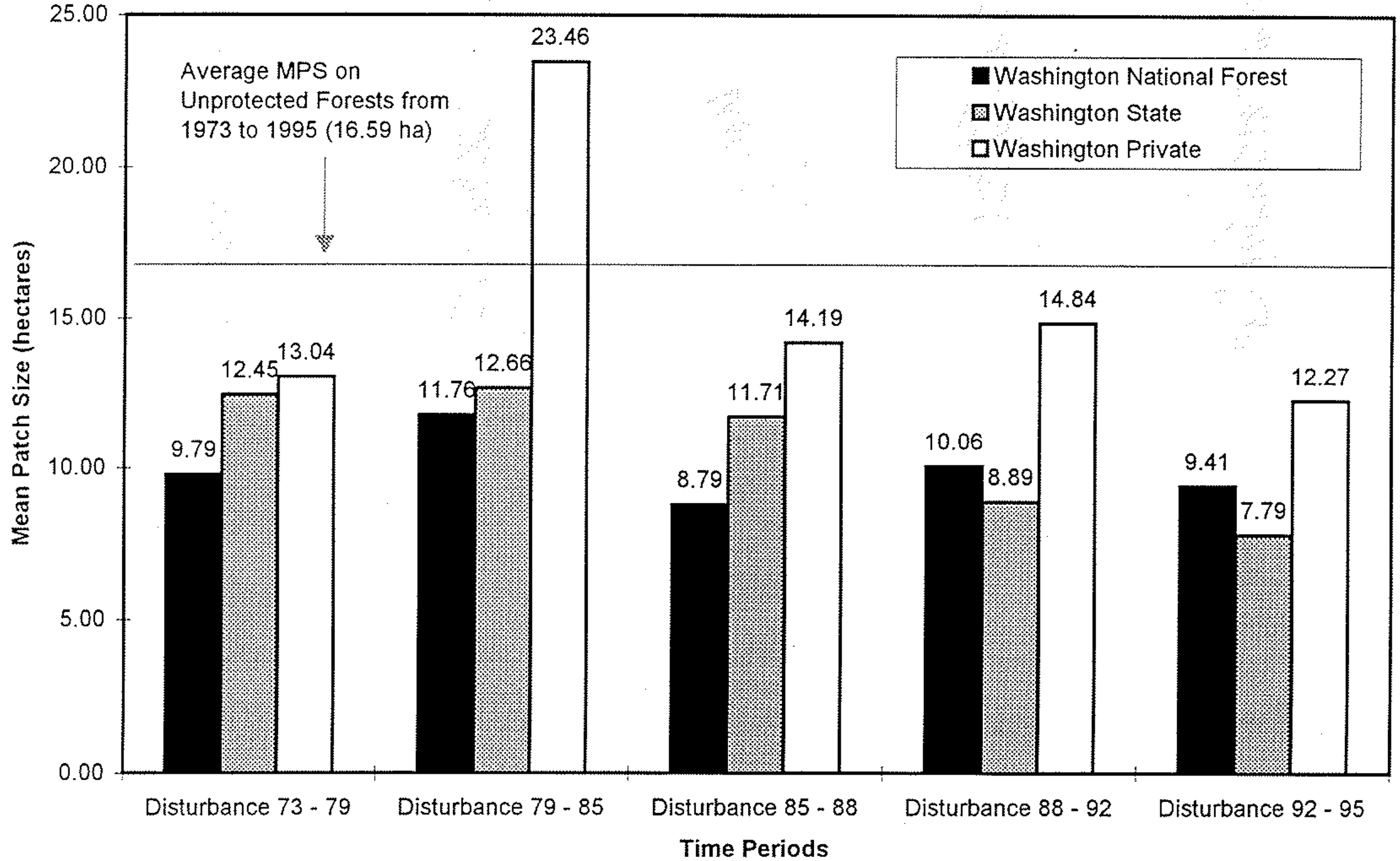
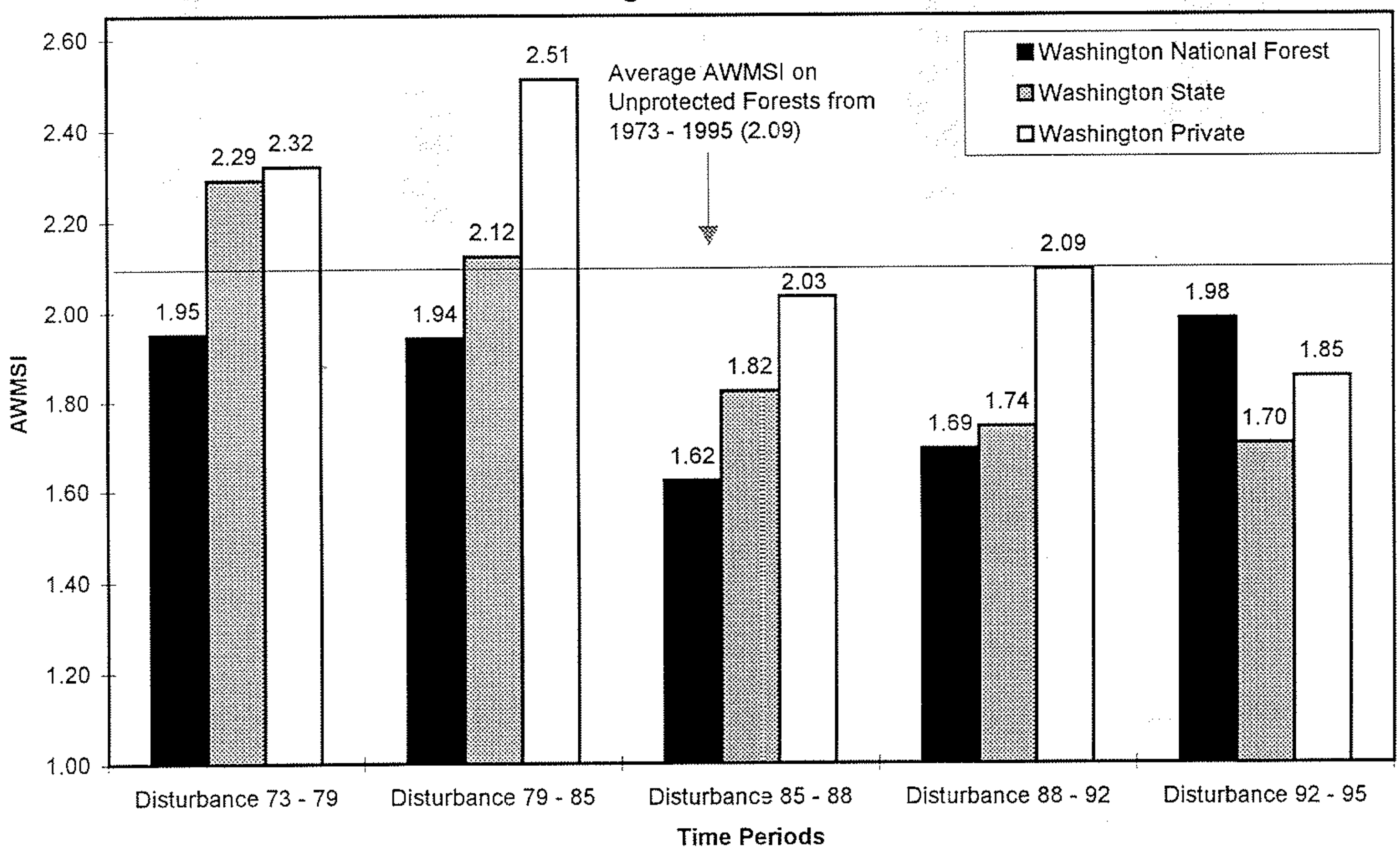


Figure 17 :
Area Weighted Mean Shape Index (AWMSI) of Disturbances in Unprotected Forests of Washington from 1973 to 1995



each instance the majority filter applied to the change detection results led to misclassification along patch borders where the filtered results are compared to the unfiltered raw satellite imagery.

Independent GIS Disturbance Data

Within B.C. 86% (382 / 451) of the harvest polygons from the LULC data had a portion of their area in common with the change detection results. As discussed previously, an accuracy assessment examining the date and the amount of disturbance could not be conducted because the LULC data does not include the date of harvest and has a different minimum mapping unit. Accuracy for fire polygons located in B.C. and within the Mount Baker-Snoqualmie National Forest in Washington was much lower as compared to the harvest data. Of the 94 total observed fire polygons only 45% (42 / 94) had a portion of their area in common with the change detection results. Accuracy within B.C. was only 40% (33 / 82) while in Washington accuracy was higher at 75% (9 / 12) but based on a small number of polygons. The Mount Baker-Snoqualmie National Forest fire history data did contain information on the date of disturbance and when this was included accuracy was reduced to 58% (7 / 12).

Independent Harvest Data

The change detection results and the DNR harvest data are compared for private, state and federal lands on an area basis for Whatcom and Skagit counties in Washington. Based upon this analysis the total area disturbed between 1988 - 1992 is 14,850 hectares (Table 17). The amount of disturbance detected is less than the reported harvest area from the DNR data during the period from 1988 - 1993. This makes sense since the DNR data include areas that were harvested or disturbed after 1992. However, the amount of area disturbed according to the change detection results is also less when compared to the DNR harvest data reported from 1988 - 1991 even though this period of record is one year shorter. When comparing data by ownership the DNR harvest area was higher on private and state lands yet lower on federal lands for both time periods. There are a number of issues and problems to be considered when comparing results. First, both studies used USGS LULC to mask non-forest areas. However, the DNR studies did not utilize elevation data as part of the post-classification masking procedure (Collins 1996). The change detection results for this analysis may have therefore eliminated forest harvest polygons on private and state lands at elevations lower than 100 meters. In addition, the DNR studies are designed to detect and map only harvest activity on commercial forest lands. Lower DNR harvest amounts on federal lands may therefore reflect the absence of areas disturbed by fire within higher elevations of Whatcom and Skagit counties that were not examined in the DNR analysis. The total area of disturbance found in this analysis for state and private lands within Whatcom county is also lower than the area recorded in the Forest Practice Applications for harvest from 1988 - 1992 (Table 18). The amount of disturbed area on private lands is much lower than indicated within the Forest Practice Applications while the disturbed area on state lands is over twice as high. These differences may be the result of discrepancies between the application date and proposed harvest area recorded in the Forest Practice Applications and the actual date and size of harvest.

Table 17 : Comparison of Change Detection Results to DNR Harvest Data for Whatcom and Skagit Counties, Washington

	Change Detection Results 1988-1992	DNR 1988-1991	DNR 1988-1993
	Area (ha)	Area (ha)	Area (ha)
Private	10,937	11,373	13,934
State	3,012	3,120	3,800
Federal	901	715	749
Total	14,850	15,208	18,483

Table 18 : Comparison of Change Detection Results to Forest Practice Applications for Whatcom County, Washington 1988 - 1992

	Forest Practice Applications. 1988-1992	Change Detection Results 1988-1992	Difference
	Area (ha)	Area (ha)	Area (ha)
Private	5,839	4,169	1,670
State	597	1,321	-724
Total	6,436	5,490	856

Discussion

Disturbance Area and Rates: 1973 to 1995

Study Area

The amount of disturbed area accounts for only 4.40% of the total area and 6.10% of the original forest area from 1973 - 1995. Because forest cover is determined using small scale Land-Use, Land-Cover (LULC) data, the actual amount of forest cover is overestimated while the amount of disturbed area is underestimated. The percentage of the disturbed area is therefore a conservative estimate of the actual amount of disturbed area for this region. This may explain why the rate of forest disturbance is reasonable yet low given other remote-sensing based change detection studies from temperate regions including the Pacific Northwest (Ripple *et al* 1991, Spies *et al* 1994, Turner *et al* 1996). Comparisons between studies are limited and problematic because of differences in location, time periods, and size of the study area. Nevertheless, the disturbance rate for this region of Washington and B.C. is comparable to studies which have examined areas greater that 1 million hectares in size. For example, in a 4.2 million ha study area of interior B.C. the amount of disturbed area was 4.5% of the total area and 6.6% of the forest area from 1975 - 1992 (Sachs *et al.* 1998).

When compared to other remote-sensing based estimates it is evident that the overall rate of forest disturbance for this study area is low. However, rates tend to vary depending upon the study region and the time period observed. In tropical forest areas the annual rate of deforestation has been estimated to be 1.42% per year in the 1980's (WRI 1990). In the Mato Grosso area of Brazil the annual rate of deforestation was 0.25% from 1981-1984 (Nelson *et al.* 1987). In the Brazilian Amazon Basin Skole and Tucker (1993) estimated the rate of deforestation to be 1.91% per year in 1978 and as high as 5.6% per year in 1988. The same variation in annual disturbance rates can be found in temperate forest regions including portions of the Pacific Northwest and British Columbia. In south central B.C., Sachs *et al.* (1998) reported an annual disturbance rate of 0.39% per year in a 4.2 million ha study area. In a 1.2 million ha study area in western Oregon, Cohen *et al.* (1998) reported an annual disturbance rate of 0.70% per year on forest lands.

Washington & British Columbia

There have been only a limited number of change detection studies that have quantified differences between the amount and rate of disturbance across international borders. In an example from a temperate forest region, Zheng *et al.* (1997) found different rates of forest cover change between areas in China and North Korea between 1972 - 1988. The annual rate of disturbance in unprotected forests of China was 2.7 times higher when compared to rates in North Korea (0.84% as compared to 0.31%, respectively). In China, harvest activity at lower elevations occurred more recently in comparison to North Korea with the difference in timing attributed to alternative land-use histories and forest management practices which eventually influenced the amount of disturbed area and the annual rate of disturbance between countries.

For the 22-year period, similarities between the amount of disturbance area and rates of disturbance between Washington and B.C. suggest that economic factors and environmental regulations have apparently had a similar influence on the rate of forest change. In Washington, disturbances covered 6.25% of the original forest area (Table 4) and occurred at an annual rate of 0.28% from 1973 - 1995. In B.C., values were slightly lower with 5.83% of the original forest area disturbed at an annual rate of 0.26%. Because the amount of area disturbed and the disturbance rates describe change across the total forest area (forests within and outside of protected areas) and are based upon a 22-year average, additional levels of analysis are required. For instance, forests in the study area can be divided by protected status to examine differences that would potentially be associated with natural disturbance regimes in protected forests as opposed to harvest activity in unprotected, commercial forests that cover a substantial portion of the landscape.

Protected and Unprotected Forests: Total, Washington and B.C.

The amount of disturbed area and rates of disturbance vary considerably by protected status in forests of Washington and British Columbia. The amount of disturbed area in protected forests from 1973 - 1995 is just 0.8% of the total amount of disturbance (716 ha of 89,252 ha) and only covers 0.15% of the total forest area. In unprotected forests the area disturbed is dramatically larger. Of the 89,252 ha of total disturbance in the study area virtually all of this area, 99.2%, occurred in unprotected forests. The amount of area disturbed in unprotected forests also varies between Washington and British Columbia. In Washington, a greater amount of the unprotected forest area, 9.99%, is disturbed during the 22-year period as compared to B.C. where only 7.43% of the forest area is disturbed (Table 4).

The disparity between the amount of disturbed area in unprotected versus protected forests and the spatial arrangement of disturbance patches provides evidence as to the origins of forest change. Protected areas in Washington and B.C. cover a large portion of the forest area (32.54%) where the majority of the land cover is rugged, mountainous, and roadless. However, a visual examination of the change detection map reveals that disturbance patches in both countries lie along unprotected forest boundaries but rarely cross into protected areas (Figure 18). Disturbance patches in unprotected forests are also closely associated with roads unlike patches found in protected areas (Figure 19). This evidence, in addition to the results of the accuracy assessment where in B.C. 86% of the harvest polygons from the LULC data had area in common with the change detection patches, indicates that disturbances in unprotected forests are largely anthropogenic in origin, constrained in location by administrative bounds, and are the result of harvest activity. Areas of disturbance in protected forests are therefore likely the result of natural disturbances, primarily fire, which have occurred with an intensity sufficient to cause a gross vegetation change and a spectral response which is similar to a forest clearcut.

Across large landscapes it is not unusual to have disturbances occurring as a result of both fires and harvest activity. In central B.C., Delong and Tanner (1996) found that from 1970 - 1990, 12%

Figure 18 : Disturbance Patches and Protective Lands

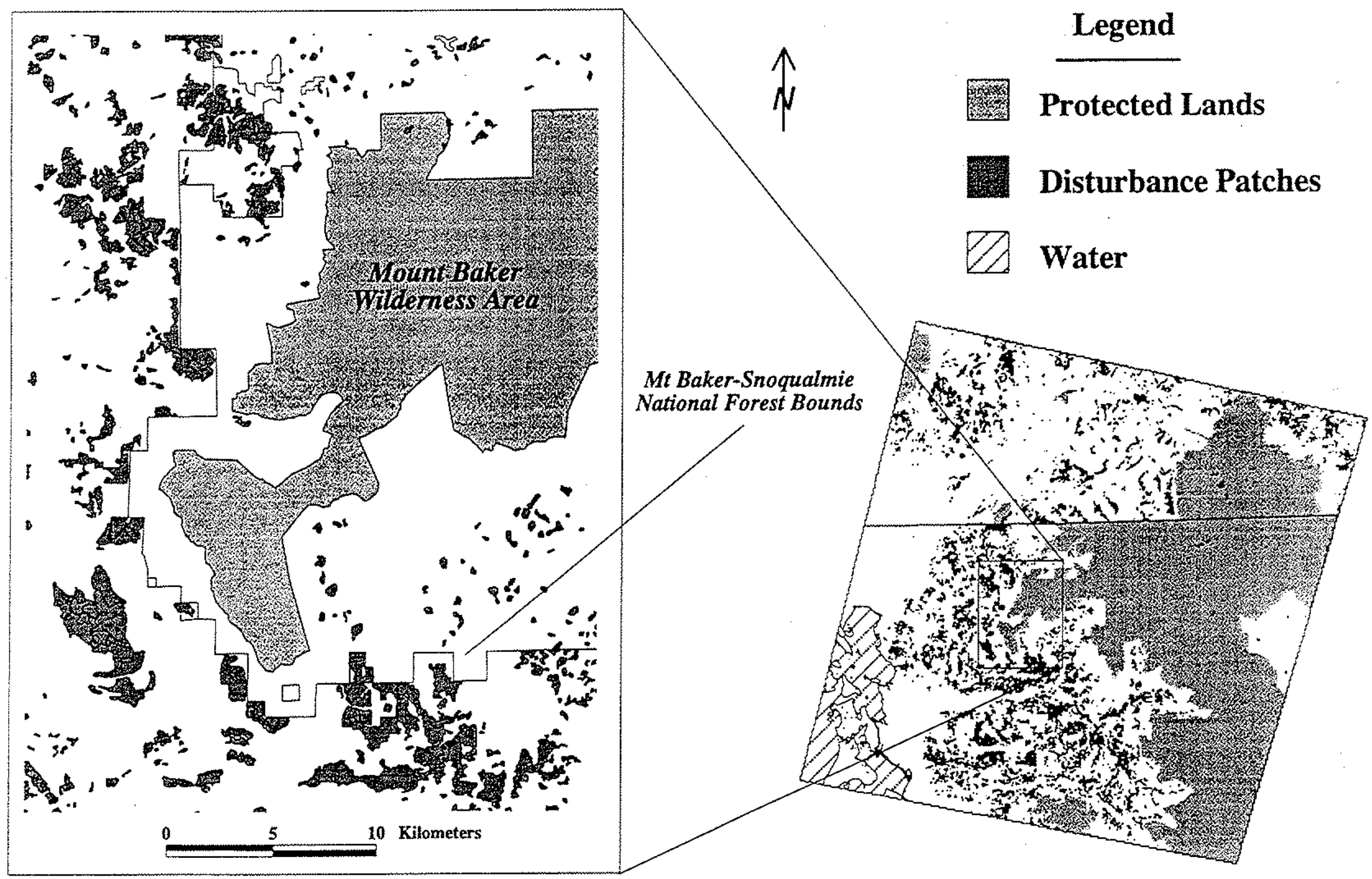
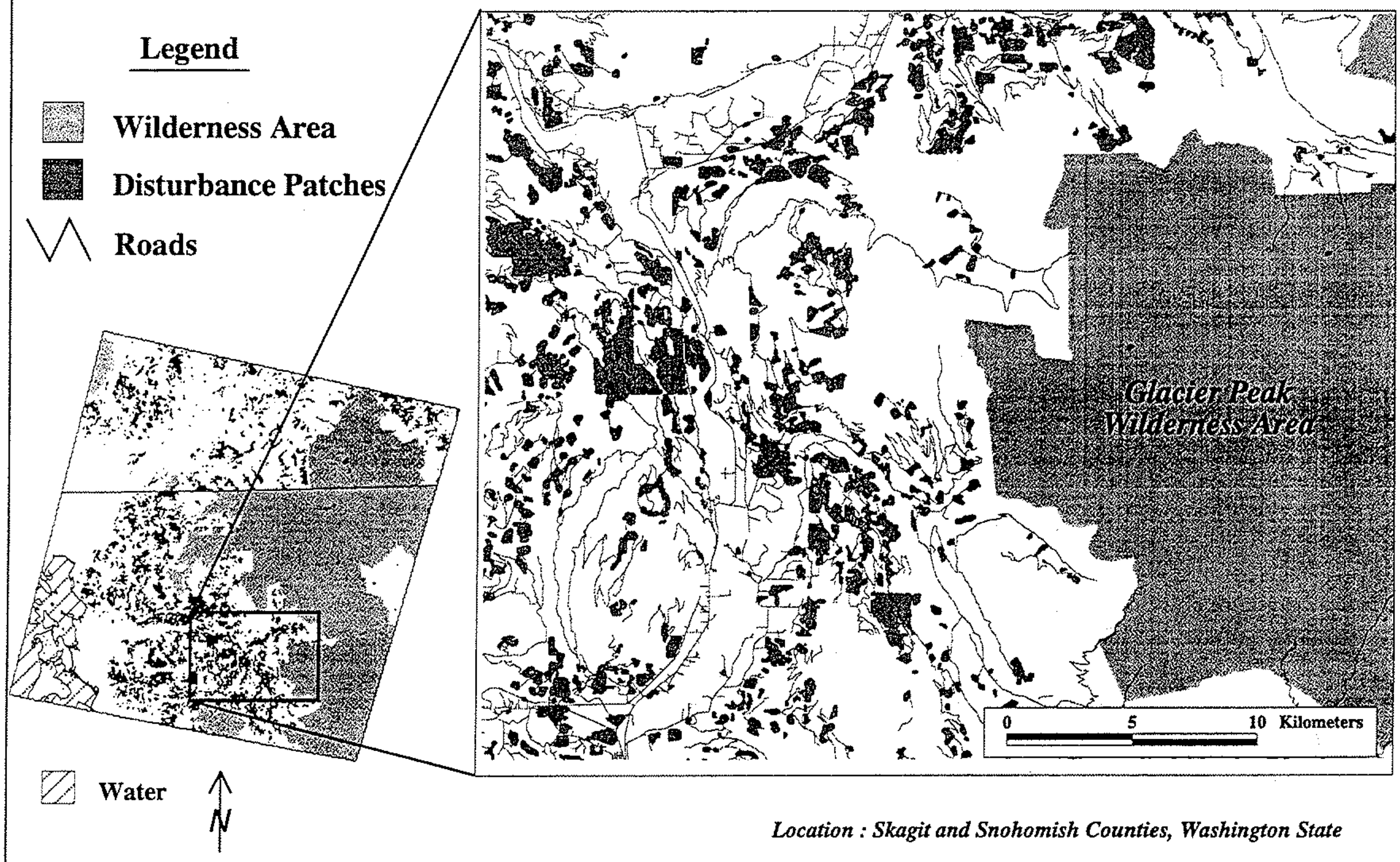


Figure 19 : Disturbance Patches in Proximity to Roads



of the forest lands were disturbed by clearcuts while only 0.15% of the forest area was disturbed by fire. These results are very similar to the results from Washington and B.C. where from 1973 - 1995, 8.97% of the unprotected forest and 0.15% of the protected forest was disturbed. The introduction of timber harvesting and fire suppression within the landscape caused a shift in the disturbance regimes of central B.C. from one characterized by fire to a system characterized by harvest activity (Delong and Tanner 1996). When landscape patterns are outside of those found in a pre-disturbed landscape a variety of ecosystem functions and processes may be affected (Wallin *et al.* 1996b). Therefore, the differences between rates of disturbance in protected versus unprotected forests in Washington and B.C. have important ecological and forest management implications especially due to the fact that harvest activity, not natural disturbance, is the most significant element of forest change within the landscape.

The annual rates of disturbance in protected forests are low but not unrealistic as compared to results from other studies especially those that examined large study areas. Annual disturbance rates ranged from 0.004% per year in Washington to 0.016% per year in B.C with an annual rate of 0.007% per year for all protected forest lands (Table 4). For an area located in south central B.C. the annual disturbance rate within provincial parks from 1975 - 1992 was 0.02% per year (Sachs *et al.* 1998). In the Changbia Mountain International Biosphere Reserve in northeast China the annual rate of disturbance was slightly larger but still only 0.04% per year from 1972-1988 (Zheng *et al.* 1997).

For unprotected forests the annual rates were 0.34% per year in B.C., 0.45% per year in Washington, and 0.41% on all unprotected lands from 1973 - 1995 (Table 4). Annual rates for unprotected forests have been estimated at 0.49% per year for interior B.C. (Sachs *et al.* 1998), 1.0% per year for watersheds of western Washington from 1991 - 1993 (Collins 1997), and 1.12% per year in China and North Korea from 1972 - 1988 (Zheng *et al.* 1997). There are a number of factors that influence natural disturbance regimes (climate, elevation) and forest management practices (economics) throughout the world which make comparisons between landscapes and regions difficult. However, the annual rates observed within this study area are low yet similar to rates estimated using remote-sensing based studies from other temperate forest regions.

Washington Ownership: Federal, State, & Private

On Washington's unprotected forest lands the amount of area disturbed and the rate of disturbance is the same for state and private lands but substantially lower for forests under federal ownership (Table 4). From 1973 - 1995 the area disturbed on federal forest land is 4.97% and occurred at a rate of 0.23% per year. In contrast, 13.39% of the original state forest and 13.33% of the private forest was disturbed during this 22-year period at an annual rate of disturbance of 0.61% suggesting that forest management has on average been the same during the 22-year period. When the annual rates of disturbance are compared to other studies from the Pacific Northwest, including Washington, results are lower across ownership groups as compared to those found in most other studies. For a 259,000 ha study area of western Oregon, Spies *et al.* (1994) reported disturbance rates of 1.2% per year on public, non-wilderness forest lands and 3.9% per year on private forest lands over a 16-year period. In Washington, Turner *et al.* (1996) focused on two watersheds on the Olympic Peninsula and reported annual disturbance rates of 0.28% on public lands and 1.41% / year on private lands from 1975 - 1991.

The Rate of Disturbance by Time Period

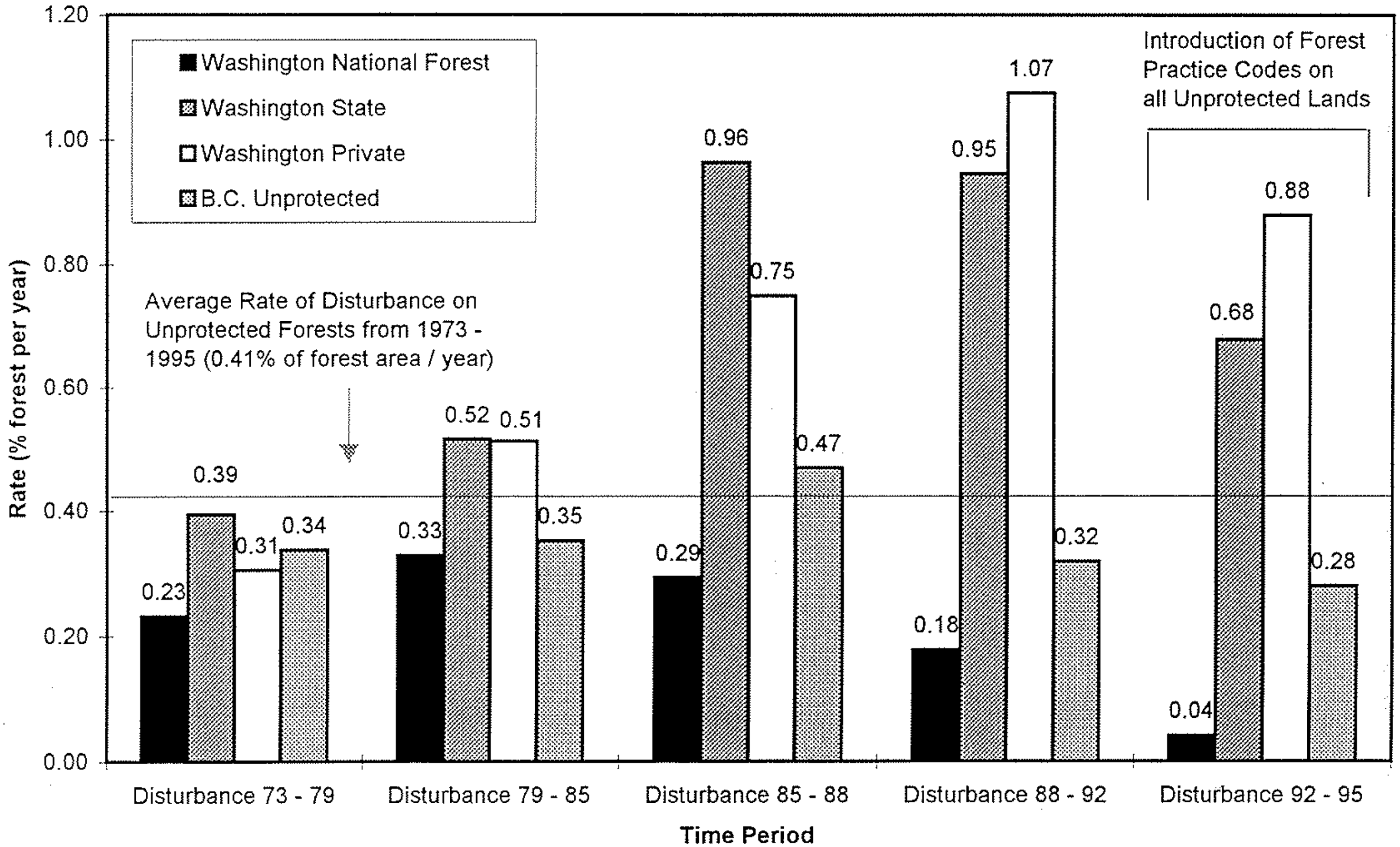
Unprotected Forests: Total, Washington and B.C.

Differences in disturbance rates in unprotected forests vary due to a number of social and economic factors that influence landscape change within a forested region. In unprotected, commercial forests management practices and policies typically focus on timber production where economic conditions drive harvest activity and determine the rates of disturbance. At smaller spatial scales, site specific factors (slope, elevation, proximity to roads, and distance to markets and population centers) can be important factors influencing rates of harvest and disturbance (Turner *et al.* 1996). When disturbance is examined regionally and especially across the international border, site specific factors, or local physical conditions, may be less of an issue when large land owners have the ability to shift harvest locations or vary harvest rates (Turner *et al* 1996). For this reason it is assumed that economic forces, influenced largely by timber markets, are essentially the same in Washington and B.C. unprotected forests from 1973 - 1995. This helps explain some of the similar harvest rates in unprotected forests between countries as they respond to international economic conditions. For example, in the period from 1985 - 1988 annual disturbance rates for Washington and B.C. experience the largest increase of any period, an increase of 0.16% in Washington and 0.12% in British Columbia (Figure 20), which corresponds to historically high rates of harvest on federal lands in the Pacific Northwest and strong foreign timber markets (Warren 1992). However, trends in disturbance rates between countries diverge over time reaching a maximum difference during the 1988 - 1992 time period when the annual rate of disturbance in Washington (0.69%) is 2.2 times higher than the rate in British Columbia (0.32%). Therefore, economic factors alone apparently fail to explain the changing disturbance rates between countries over time. This would indicate the presence of additional forces that influence harvest activity which may be evident when disturbances are influenced by different forest management practices and policies.

British Columbia and Washington Ownership: Federal, State, & Private

Annual rates of disturbance in unprotected forests of Washington vary considerably when examined by ownership class through time as compared to the moderate variability in rates found in unprotected forests of British Columbia (Figure 20). On federal forests, after reaching a peak in the annual rate during 1979 - 1985 (0.33%), rates dramatically decline during the remaining time periods. The substantially smaller areas and lower rates of disturbance indicate the presence of factors which have transformed the management of federal forests including the shift to an ecosystem management approach (FEMAT 1993). Ecological studies on late-successional

Figure 20 :
Rates of Disturbance in Unprotected Forests of Washington (by Land Ownership) and British Columbia from 1973 to 1995



forests in the 1970's and 1980's revealed that forest management required a broader focus and management at a larger spatial scales. An increased awareness and emphasis on biodiversity led to management practices and policies which have reduced harvest rates in federal forests in the Pacific Northwest since 1973 as economic benefits are weighed with ecological considerations at the ecosystem or landscape scale (FEMAT 1993). The dramatic reduction in disturbance rates in federal forests eventually led to a rate similar to that found in protected forest areas, *i.e.* 0.04% in the period from 1992 - 1995 (Figure 20).

As the disturbance rates on federal forests decline, rates of disturbance on state and private forests increase at dramatic rates especially in the period from 1985 - 1988 (Figure 20). The increase in state and private forests coincides with the largest increase in disturbances in B.C. and with the decline in rates of disturbance in federal forests. In addition, the increase in the disturbance rate from 1979 - 1985 to 1985 - 1988 for state forests is greater than on private lands. Although both state and private forests are managed according to similar management practices and policies, the larger increase on state lands may indicate the presence of increased short-term economic pressures on state forests which provide revenue as part of the state trust. Declining harvest rates on federal forests reduce federal receipts to local counties which may stimulate harvest activity on state forests to offset federal reductions.

From 1992 - 1995, timber harvest activity on all unprotected forests, including B.C., decrease in response to new forest policies, regulations, and practices which came into effect by 1995. The Washington Forest Practices Act (1992) was introduced to regulate activities including timber harvesting, road construction, chemical application, and reforestation on state and private lands in Washington (Washington State Forest Practices Boards 1992). The Washington Forest Practices Act led to a decline in harvest rates from 1992 - 1995 but may have also influenced rates during the previous period (Figure 20). From 1988 - 1992 the rate on state lands was higher than average but relatively unchanged from the previous period. However, the annual rate of disturbance increases on private lands surpassing the rate on state forests perhaps in anticipation of the Forest Practices Act. In this case private owners may have been stimulated to increase harvest rates to maximize timber harvests before the introduction of regulations and codes which would limit future harvests and increase costs (Miles pers. comm.).

The Northwest Forest Plan was introduced in 1994 to set standards and guidelines that govern activities on federal forest lands (Anderson 1994). Even though harvest rates had been declining in federal forests since the 1979 - 1985 period, the introduction of the Northwest Forest Plan continued to reduce the annual rate of disturbance (Figure 20). Similarly, in 1995 the B.C. Forest Practices Code was introduced to set provincial and regional forest management practices and guidelines and enforce environmentally sound forest practices (COFI 1998). Although the rates of disturbance were generally declining prior to the introduction of the Forest Practices Code, as they were on federal lands in Washington, the introduction of new timber harvest regulations further reduced rates of disturbance in unprotected forests of British Columbia.

Disturbance Patterns: 1973 to 1995 & By Time Period

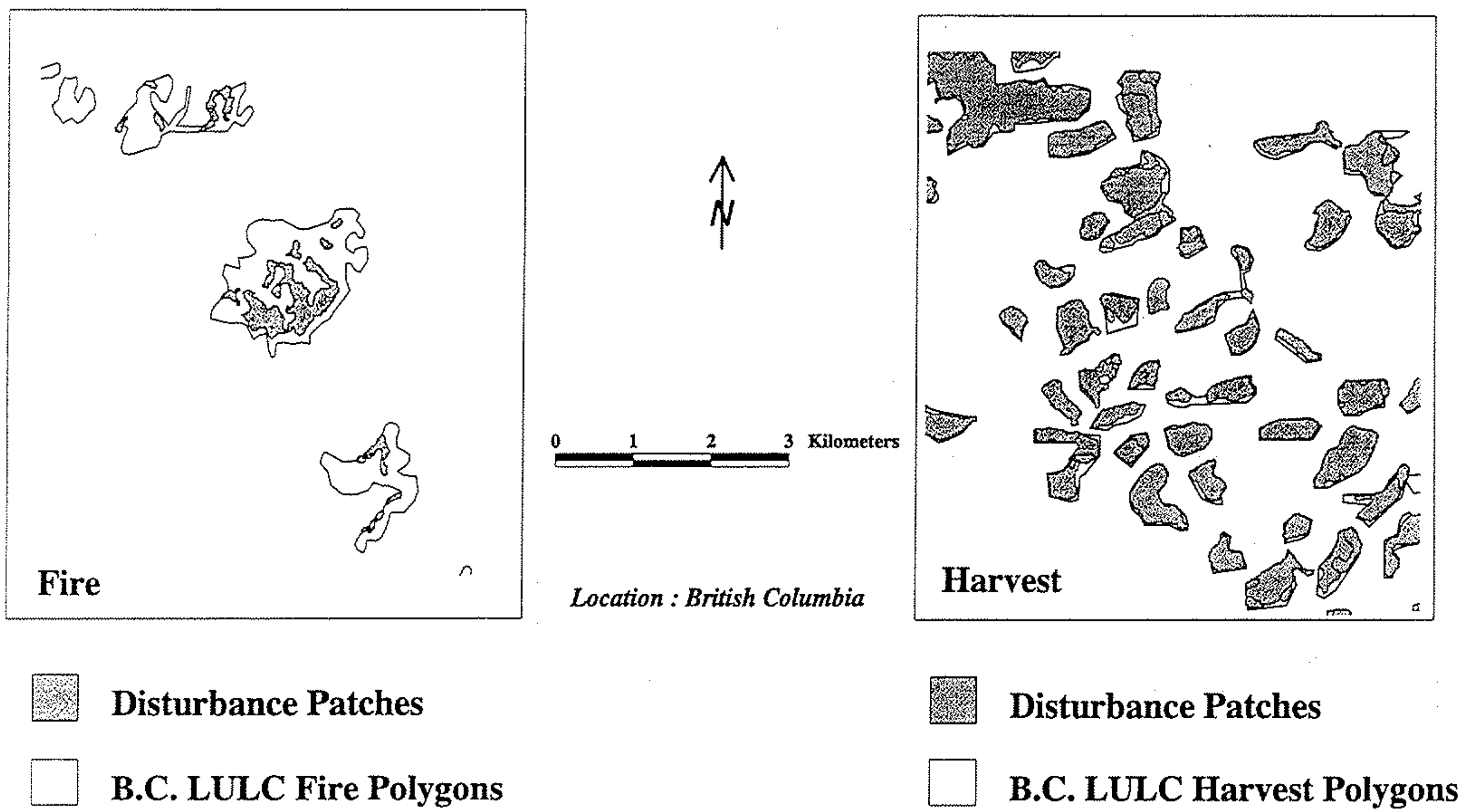
Study Area / Washington & British Columbia / Protected and Unprotected Forests: Total, Washington and B.C.

The differences between spatial patterns in protected versus unprotected forests from 1973 - 1995 are large and different than expected. Disturbances on protected lands are primarily the result of fire and should therefore display characteristics typical of natural disturbance regimes. Disturbances in unprotected forests, which are thought to be the result of harvest activity, are instead smaller in size and have less patch shape complexity (are more simple in shape) when compared to disturbance patches in protected forests. Spatial patterns that result from fire compared to harvest activity will vary by region depending on natural conditions and forest management practices which control fire suppression yet, in general natural disturbance patches would be expected to have a larger values for both MPS and AWMSI. For example, Delong and Tanner (1996) found that wildfires, even during times of fire suppression, had more complex shapes as compared to disturbances caused by clearcut harvest activity for a region in central British Columbia. In addition, for patch sizes below 10 ha, which would exceed the MPS in protected forests in this study, wildfires created a larger percentage of the total amount of disturbed area and are therefore assumed to have a larger MPS. The spatial patterns and complexity caused by fires make an identification of the entire disturbed area difficult especially when using satellite imagery to detect gross vegetation change. Therefore, disturbance patches caused by fire have probably not been adequately mapped in regard to their actual size and shape since the entire area affected does not share the same spectral characteristics as a forest clearcut (Figure 21).

From 1973 - 1995, MPS and AWMSI values for disturbances in unprotected forests are very similar for Washington and B.C. indicating that the spatial patterns of disturbance are similar between countries over time even though rates of disturbance are higher in Washington's unprotected forests. A slight downward trend in both MPS and AWMSI eventually results in equal values in the period from 1992 - 1995 for both countries. New forest management practices were introduced on all unprotected forests in the period from 1992 - 1995 and may explain similarities in Washington and B.C. but would fail to explain the downward trend to smaller, more regularly shaped disturbance patches. One possible explanation may have to do with a decrease, over time, in the amount of forest available for harvest which is unknown because there is no information on the disturbance activity prior to 1973 or current forest cover. Visual evidence in Washington's unprotected forests indicates that harvest activity may be filling in the gaps left by harvest activity that occurred prior to 1973. As a result, spatial patterns for these disturbances may display smaller values for both MPS and AWMSI even as disturbance rates vary by country and new forest management practices are introduced to address the issues surrounding landscape fragmentation as caused by the staggered-setting of harvest activity.

Figure 21 : Disturbance Patches caused by Fire and Harvest Activity

Example images of fire and harvest disturbance patches in association with LULC data for areas located in British Columbia.

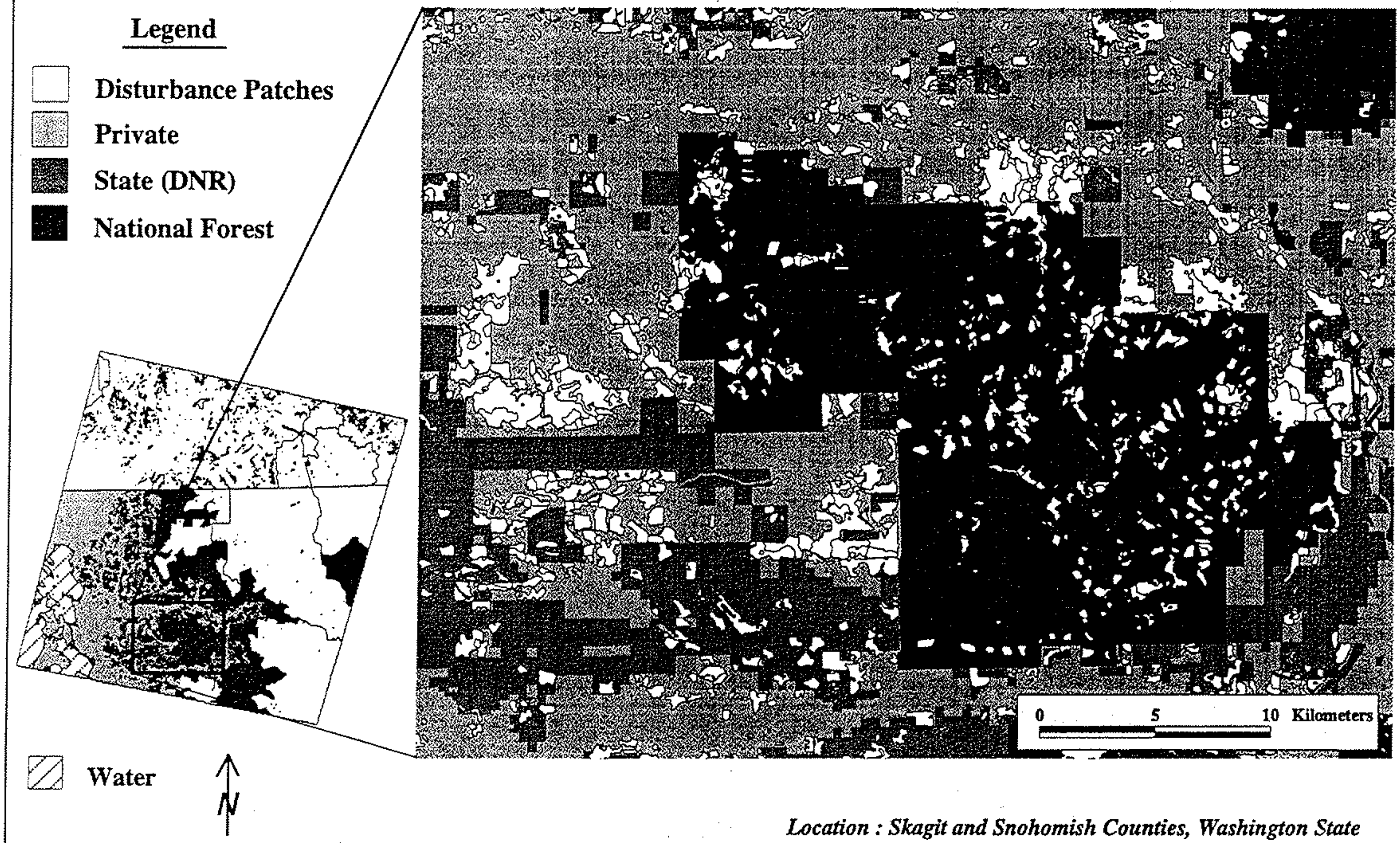


Washington Ownership: Federal, State, & Private

In unprotected forests of Washington, MSP and AWMSI values from 1973 - 1995, including individual time periods, reflect the different factors which influence timber harvest activity and the way in which they vary by ownership especially between federal and private lands. On federal forests disturbances are smaller and have less patch shape complexity as compared to disturbances on private lands. Despite a slight downward trend in MPS and AWMSI over time, values found on private forest lands are always larger (Figures 16 - 17) with the exception of AWMSI during 1992 - 1995. This relationship between disturbance patterns on federal and private lands is in agreement with the typical conditions found on commercial forests throughout the Pacific Northwest over the past 50 years (Spies *et al* 1994). During this time period the staggered-setting system of harvest on National Forest lands has used smaller (*i.e.* 10 - 20 ha) dispersed clearcuts as opposed to harvests on private lands which are typically much larger (Spies *et al* 1994). It is also visually evident from the 1973 - 1995 disturbance map and AWMSI values that the staggered-setting system on federal forests also has created disturbance patches with more simple shapes compared to disturbance patches on private forests (Figure 22).

The spatial patterns of disturbance patches therefore show some variation and trends from 1973 - 1995 by protected status and ownership, yet comparisons to the studies from other regions are difficult because few studies have examined the spatial patterns of disturbance patches across administrative boundaries. For interior B.C., Sachs *et al.* (1998) reported that MPS and AWMSI did not vary across natural biogeoclimatic zones from 1975 - 1992. In addition, MPS for disturbed patches were smaller (in the range of 20 - 50 ha) and less complex as compared to forest patches. Because most studies have examined spatial patterns of the entire landscape, including disturbances and non-forest areas, they have reported that harvest activity has increased mean size, edge, and shape complexity of non-forest patches (Zheng *et al.* 1997). This study on the other hand only examines the spatial patterns of disturbances and how they vary both through time and by administrative and political bounds.

Figure 22 : Disturbance Patch Size and Shape in Unprotected Forests



Conclusions

In comparison to other remote sensing based studies in temperate forest regions the average annual rates of disturbance across the study area are relatively low. Annual disturbance rates for the period from 1973 - 1995 on protected and unprotected forest lands are similar to those found in a large region of central B.C. (Sachs *et al.* 1998), yet are far below estimates from areas such as western Oregon (Cohen *et al.* 1998, Spies *et al.* 1994). In unprotected forests of Washington and B.C. the annual disturbance rate of 0.41% translates into a 227-year rotation period which implies that forest management during this 22-year period has maintained harvest rates at sustainable levels. However, the annual disturbance rates on unprotected lands, even for Washington (0.45%) and B.C. (0.34%), fail to describe the variations in disturbance rates that were found between the five time periods and by ownership groups in Washington. For example, annual rates of disturbance in unprotected forests range from 0.04% on federal lands from 1992 - 1995 to 1.07% on private lands from 1988 - 1992.

Change detection results have the ability to monitor the impacts of new forest practices on disturbance activity and also assess the success or failure of new forest management plans over time. This is especially important in areas such as Washington and B.C. where numerous agencies have implemented forest management at larger spatial scales even though political and administrative boundaries divide forests and the extant management practices. In these circumstances disturbances that occur at different rates and with different spatial patterns according to new forest management policies, practices and objectives may in fact inadvertently create forest fragmentation based upon administrative bounds and have unforeseen impacts on such ecological functions as biodiversity. For example, if disturbance continues at higher rates in unprotected forests, as compared to protected forests, then the majority of the remaining forest in the landscape will be contained in protected areas. Having a larger amount of protected forest area may initially be considered beneficial to biodiversity, especially in Washington where protected areas are more contiguous than in British Columbia. However, this view fails to consider impacts across the entire forested landscape and minimizes the importance of the lowland forest ecosystem which continues to support a number of federally protected species and provides a critical function in the support of biodiversity within the region.

The resulting disturbance map provides critical information on disturbance activity over a very large region which is useful for a variety of research projects. Therefore, every effort should be made to obtain future satellite images to include in the change detection analysis to provide additional information on disturbance rates and patterns within the region and to continue the baseline of data on forest change throughout the landscape.

This study focused only on disturbances within the landscape whereas most other studies have examined the patterns of disturbance in conjunction with forest patches to analyze landscape patterns and assess landscape fragmentation over time (Ripple *et al.* 1991, Sachs *et al.* 1998, Spies *et al.* 1994, Zheng *et al.* 1997). Therefore, one avenue for future research would be to examine disturbances as part of the entire landscape using a forest cover classification derived from the satellite imagery. This would allow for a analysis of the entire landscape and an interpretation of forest disturbance prior to 1973. In addition, a classification of forest cover would permit a more accurate estimate of disturbance impacts on forest cover. Currently, differences in the disturbance amounts and rates are examined as function of the total forest cover which is defined by coarse scale land-use / land-cover data which does not identify the age or structure of forest. Because all forest area is viewed in the context of the 1973 forest coverage there is no way to address issues related to the actual amount of forest available for harvest by ownership groups through time.

There are also spatial patterns evident within the landscape that are not adequately described by MPS or AWMSI but are important in terms of their role in forest change. Disturbance activity varies by ownership group through time but the influence of administrative and political boundaries on the arrangement of disturbances has not been quantified. A visual inspection of the change detection map indicates that the administrative borders limit the extent and determines shape of disturbance patches, primarily harvest units, in the landscape. In almost each instance disturbance polygons did not cross the border between political or administrative groups and the border instead behaves as a physical barrier. Satellite imagery from throughout the world has visually depicted the impacts of forest conversion and land use practices as they differ between neighboring countries. For example, Sader (1995) detected differences in forest change for a study site along the border between Mexico and Guatemala from 1986 to 1990 where the majority of forest clearing occurred on the Mexican side of the border. However, the impacts of borders on the spatial patterns and characteristics of disturbance requires more work.

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