*Discussion Paper*

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# Disturbance regimes in coastal British Columbia

**Lori D. Daniels[1] and Robert W. Gray[2]**

## Abstract

What is the dominant disturbance regime in coastal British Columbia? In this literature review, we discuss the relative importance of fire versus canopy gaps as agents of disturbance affecting the structure and dynamics of unmanaged coastal forests in British Columbia. Our analyses focus on the province's wet coastal temperate rain forests, specifically the Hypermaritime and Very Wet Maritime Coastal Western Hemlock (CWHvh and CWHvm) subzones, and the Wet Hypermaritime and Moist Maritime Mountain Hemlock (MHwh and MHmm) subzones. After reviewing the relationships between disturbance events, disturbance regimes, and stand dynamics, we critically assess the traditional classification of fire regimes in the wet coastal temperate rain forests, in part by differentiating between fire occurrence and mean return intervals. We provide four lines of evidence to reject the traditional view that stand-initiating fire at intervals of 250–350 years was the dominant disturbance regime in the wet coastal temperate rain forests of British Columbia. According to recent field research, historical fires were very infrequent in wet coastal temperate rain forests and were more likely low- and mixed-severity events, rather than stand-initiating fires. As an alternative to fire, we propose that fine-scale gap dynamics is the dominant process explaining the structure and dynamics of most unmanaged stands in the province's wet coastal temperate rain forests. Improved understanding of the spatial and temporal attributes of disturbance regimes in coastal forests has important implications for sustainable forest management and conservation of biodiversity.

**KEYWORDS:** *canopy gap dynamics, Coastal Western Hemlock zone, disturbance regime, ecosystem management, fire return intervals, Mountain Hemlock zone, wet coastal temperate rain forest.*

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## Introduction

Natural disturbance of coastal temperate rain forests in British Columbia includes fire, stand-level blowdown, windthrow of individual trees, pathogens, insects, mass movements, avalanches, and floods (Dorner and Wong 2003; Wong *et al.* 2003). At recent workshops on variable retention and partial cutting in coastal British Columbia, Lori Daniels raised the question, "What is the dominant disturbance regime in coastal British Columbia?" and presented two opposing answers: stand-initiating fires versus fine-scale canopy gaps caused by the combined effects of pathogens, insects, wind and (or) tree age (Turner 2003; Daniels and Gray 2004).

In this literature review, we discuss the relative importance of fire versus canopy gaps as agents of disturbance affecting the structure and dynamics of wet coastal forests in British Columbia. We do not consider stand-level blowdown, insect outbreaks, and geomorphic disturbances to be "dominant" disturbance regimes because they are restricted to specific topographic positions and have limited impact at landscape to regional scales (Wong *et al.* 2003). It is also important to recognize that the relative importance of fire versus canopy gaps varies regionally and locally due to climate, topography, and site effects (Agee 1993; Wong *et al.* 2003).

The steep environmental gradients that characterize coastal British Columbia result in a range of disturbance regimes within and between the Coastal Douglas-fir (CDF), Coastal Western Hemlock (CWH), and Mountain Hemlock (MH) biogeoclimatic zones. Our analysis focusses on the wettest forests in coastal British Columbia, specifically the Very Wet Hypermaritime CWH (CWHvh), Very Wet Maritime CWH (CWHvm), Wet Hypermaritime MH (MHwh), and Moist Maritime MH (MHmm) subzones (hereafter "wet coastal temperate rain forests," Figure 1). These forests dominate the north and central coasts, the western Haida Gwaii (Queen Charlotte Islands), much of northern and western Vancouver Island, and the mountain valleys of the south coast, including the north shore of the Lower Mainland (Figure 1). They are generally dominated by western redcedar, western hemlock, and amabilis fir at submontane elevations, with increased abundance of yellow-cedar and mountain hemlock with increased elevation. Douglas-fir dominates some stands, but it is a minor component at the regional scale, differentiating the forests in this study from the forests that dominate the east side of Vancouver Island (wet to xeric subzones of the CWH zone and the CDF zone), and the majority of forests in the Pacific Northwest of the United States.

*We discuss the relative importance of fire versus canopy gaps as agents of disturbance affecting the structure and dynamics of wet coastal forests in British Columbia.*

The objectives of this paper are:

1. to review the relationships between disturbance, disturbance regimes, and stand dynamics;
2. to critically assess traditional classifications of fire return intervals and magnitude in the wet coastal temperate rain forests, in part by differentiating between fire occurrence and mean return intervals; and
3. to justify our interpretation that gap dynamics explains the dominant structures observed at stand, landscape, and regional scales in wet coastal temperate rain forests of British Columbia.

### Disturbance and Stand Dynamics

A *disturbance* is any temporally discrete event that alters ecosystem, community, or population structure, and changes resources or substrate availability or the physical environment (White and Pickett 1985). The following six factors describe an individual disturbance event (see page 56 for definitions of terms used):

1. causal agent(s),
2. location,
3. extent or size,
4. shape,
5. timing, and
6. magnitude.

A *disturbance regime* is the spatial and temporal characterization of the disturbances affecting a defined landscape through time (White and Pickett 1985). A disturbance regime cannot be determined from an individual disturbance event; rather, many disturbance events are required to describe spatial and temporal patterns. *Frequency* and *return interval* are often used to describe disturbance regimes. Other important descriptors include *spatial distribution, predictability,*

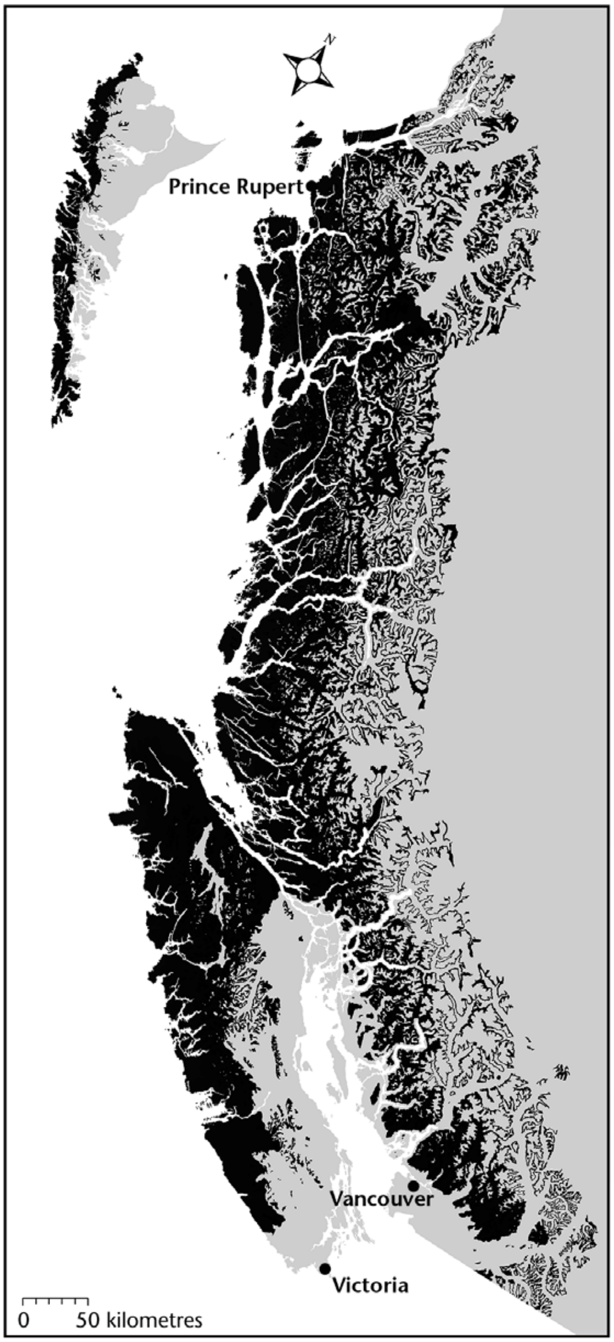


**FIGURE 1.** Distribution of wet coastal temperate rain forests in British Columbia. The shaded region includes forests in four biogeoclimatic subzones as follows: Very Wet Hypermaritime Coastal Western Hemlock (CWHvh), Very Wet Maritime Coastal Western Hemlock (CWHvh), Wet Hypermaritime Mountain Hemlock (MHwh) and Moist Maritime Mountain Hemlock (MHmm). (Source: B.C. Ministry of Forests 2003a)

*rotation period*, *disturbance cycle,* and *turnover time*. Different *agents* or *types of disturbance* will have different spatial and temporal attributes and impacts on the forest. Moreover, disturbance agents may interact, often with additive effects (Sousa 1984; Glenn-Lewin and van der Maarel 1992).

In closed-canopy forests, four stages of *stand development* generally follow a severe, stand-initiating disturbance (Figure 2; Oliver 1981; Oliver and Larson 1997):

1. stand initiation,
2. stem exclusion,
3. understorey re-initiation, and
4. the old-growth stage.

During the first three stages, the forest canopy is dominated by an even-aged cohort of trees (Oliver and Larson 1997). Site colonization and establishment occur during stand initiation. Initial tree growth is rapid until resources become limiting. During the stem exclusion stage, the canopy closes, inter-tree competition is intense, and tree regeneration and the shrub and herb strata are limited. Together, the stand initiation and stem exclusion stages generally last 80–100 years in coastal temperate rain forests (Franklin *et al.* 2002). During the understorey re-initiation stage, mortality of some overstorey trees opens the canopy and provides opportunities for regeneration of herbs, shrubs, and trees. The transition from the understorey re-initiation to the old-growth stage of development involves several processes, including increased biomass and diversity in the understorey, accumulation of coarse woody debris, and horizontal and vertical diversification of the canopy (Franklin *et al.* 2002). This transition occurs over several decades to centuries. In general, wet coastal temperate rain forests classified as "old forest" or "old growth" in forest inventories are assumed to be at least 250 years old (B.C. Ministry of Forests 1997). The old-growth stage is distinguished by fine-scale disturbance resulting from the mortality of small groups of trees creating canopy gaps (Lertzman and Krebs 1991; Lertzman *et al.* 1996;

*Knowledge of stand development after stand-initiating disturbance allows us to interpret forest structure and make inferences about disturbance regimes.*

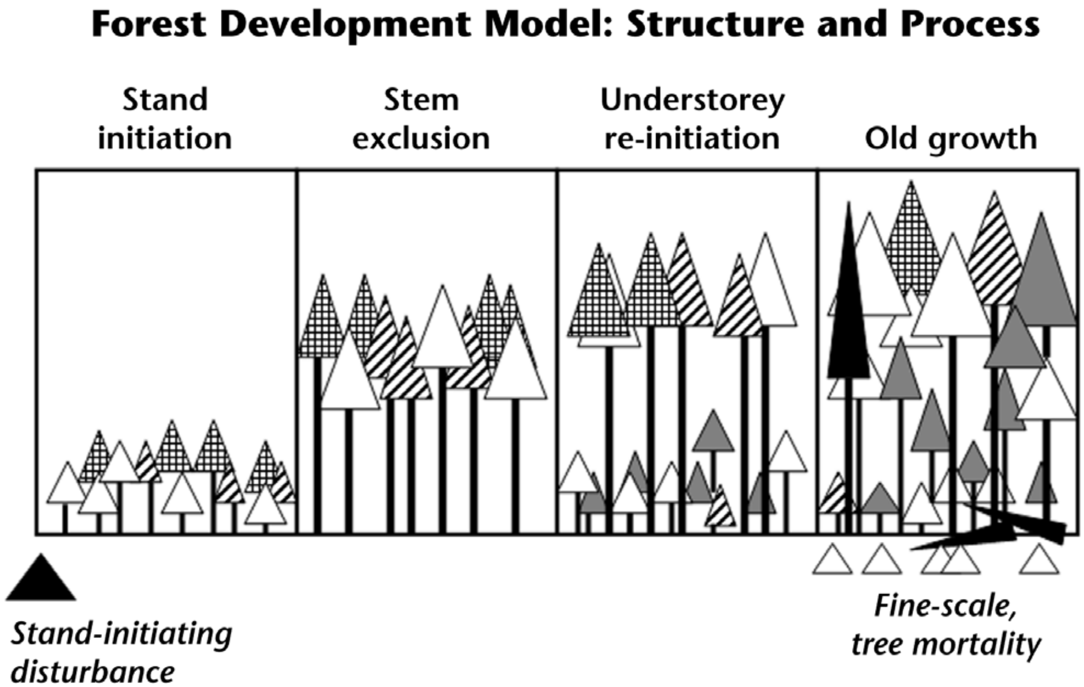


**FIGURE 2.** A general four-stage model of stand development for closed-canopy temperate forests. Tree species are represented by different colours or patterns; snags and logs are black. After Oliver 1981; Oliver and Larson 1997.

Wells *et al.* 1998). One to a few trees are killed, generating coarse woody debris and creating small openings in the canopy. The patchy mortality of canopy dominants facilitates tree regeneration and recruitment in gaps. Thus, driven by gap dynamics, the forest canopy is continuously renewing itself and maintaining complex canopy structure and stand-level biomass.

Knowledge of stand development after stand-initiating disturbance allows us to interpret forest structure and make inferences about disturbance regimes. Consider the following disturbance scenarios and their impacts on forest structure at the landscape and regional spatial scales. Where the disturbance regime is characterized by high-severity, stand-initiating disturbances that occur with a mean return interval less than the lifespan of the dominant trees, even-aged stands will dominate the landscape. For example, in a landscape with a mean return interval of 100 years, about 63% of the stands will be less than 100 years old (van Wagner 1978; Fall 1999, Figure 3). If the lifespan of the dominant trees is greater than 100 years, then most stands will be in the stand initiation, stem exclusion, and understorey re-initiation stages of development. Since stand-initiating disturbance replaces many stands before canopy trees die of old age, small canopy gaps rarely form and only 8% of the landscape is in the old-growth stage of development (Table 1). The fire regimes of lodgepole pine forests of the interior of British Columbia and many boreal forests historically followed this model of relatively frequent, stand-initiating disturbance.

In forests where high-severity, stand-initiating disturbances are infrequent relative to tree lifespan, stands commonly advance to the old-growth stage of development. During the long interval between stand-initiating disturbances, individual trees will reach old age and die, or they will be affected by fine-scale disturbances, forming small gaps in the canopy. In old-growth stands, small gap-forming disturbances dominate, resulting in complex, uneven size and age structures. In landscapes with mean return intervals of 250 or 350 years between stand-initiating disturbances, 63% or 51% of the forests, respectively, will be in the stand initiation, stem exclusion, and understorey re-initiation stages of development; old-growth stands will account for 37% or 49% of the forest cover, respectively (Van Wagner 1978; Fall 1999, Figure 3). According to disturbance regime theory, landscapes in which old-growth stands dominate greater than 70% of the area have mean return intervals approaching 1000 years for stand-initiating disturbances (Table 1).

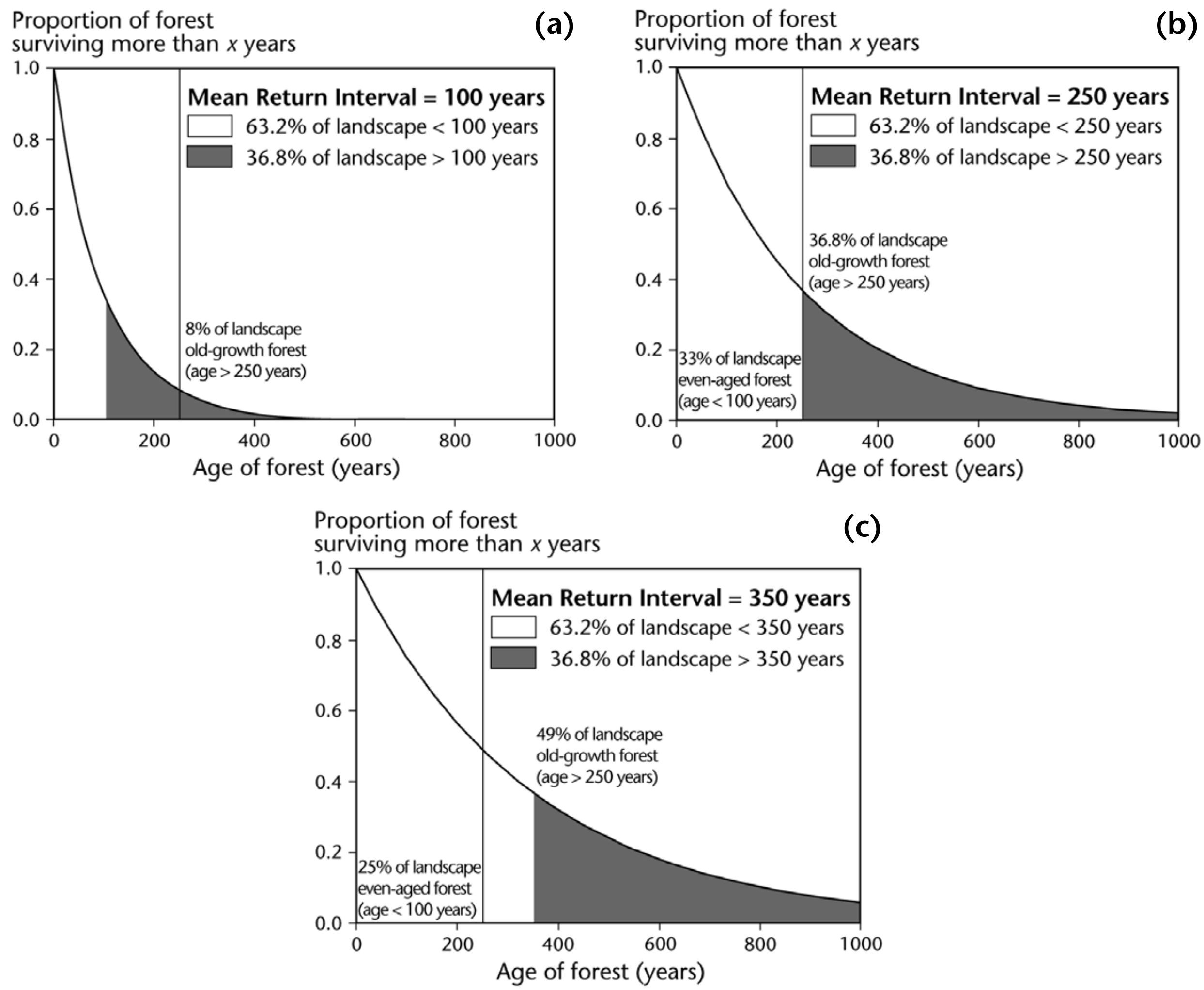


**FIGURE 3.** Stand survivorship curves for landscapes with mean disturbance return intervals ranging from 100 years (a) to 350 years (c). The mean return intervals from 100 to 350 are based on the *Biodiversity Guidebook*'s (B.C. Ministry of Forests and B.C. Ministry of Environment, Lands and Parks 1995) estimates of stand-initiating blowdown and fire in coastal British Columbia forests. Survivorship curves indicate the proportion of the landscape surviving longer than the age indicated on the *x*-axis. The vertical lines at 250 years differentiate forests in early stages of development (left) from old-growth forests (right).

These examples illustrate a range of possible mean return intervals along a broad continuum of possible disturbance frequencies. In general, the majority of any landscape is younger than the mean return interval, over one-third of the landscape is older than the mean return interval, and the oldest stands are several decades to centuries older than the mean return interval (Figure 3). As the mean return interval increases, a larger proportion of the landscape is old-growth forest (age greater than 250 years) and the maximum stand ages will exceed the lifespan of the canopy dominant trees. In the oldest stands, the age of the oldest trees may be less than stand age. Survivorship curves and age distributions derived from actual landscape data will differ from the theoretical models, as the models represent average landscapes that develop under the influence of a constant disturbance regime (Van Wagner 1978). Nevertheless, if estimated return intervals approximate the actual disturbance regimes of coastal landscapes, then observed landscape structures (e.g., percentages of even-aged and old-growth forests) should be similar to those predicted by the theoretical models (Table 1).

**TABLE 1.** Landscape age structures based on the negative exponential model for mean disturbance return intervals from 100 to 1000 years. To allow direct comparison between theoretical models and empirical data in Table 2, young forests included stands with ages ≤ 100 and ≤ 140 years, old forests included stands > 140 years old, and old-growth forests included stands > 250 years old. Mean return intervals from 100 to 350 years are based on the *Biodiversity Guidebook*'s estimates of stand-initiating blowdown and fire in coastal British Columbia forests (B.C. Ministry of Forests and B.C. Ministry of Environment, Lands and Parks 1995); return intervals of 500–1000 years provided for comparison.

| | Percentage of landscape | | | | |
|---|---|---|---|---|---|
| Mean disturbance return interval (years) | Young forest (≤ 100 years) | Young forest (≤ 140 years) | Old forest (> 100 years) | Old forest (> 140 years) | Old forest (> 250 years) |
| 100 | 63.2 | 75.3 | 36.8 | 24.7 | 8.2 |
| 200 | 39.3 | 50.3 | 60.7 | 49.7 | 28.7 |
| 250 | 33.0 | 42.9 | 67.0 | 57.1 | 36.8 |
| 350 | 24.9 | 33.0 | 75.1 | 67.0 | 49.0 |
| 500 | 18.1 | 24.4 | 81.9 | 75.6 | 60.7 |
| 750 | 12.5 | 17.0 | 87.5 | 83.0 | 71.7 |
| 1000 | 9.5 | 13.1 | 90.5 | 86.9 | 77.9 |

## Fire in Wet Coastal Temperate Rain Forests of British Columbia

### Estimated Mean Fire Return Intervals

According to the *Biodiversity Guidebook*'s classification of natural disturbance types, the dominant disturbance in coastal British Columbia is stand-initiating fire at mean return intervals of 250 or 350 years, depending on biogeoclimatic zone and subzone (B.C. Ministry of Forests and B.C. Ministry of Environment, Lands and Parks 1995). All fires are assumed to be stand-initiating events that result in even-aged forests, which would follow Oliver and Larson's (1997) model of stand development (Figure 2). If stand-initiating fires burned every 250–350 years in coastal British Columbia, as indicated in the *Guidebook*, then a large proportion of unmanaged forests should be even-aged stands (Figure 3, Table 1). These forests would be in the stand initiation (stage 1) through understorey re-initiation (stage 3) stages of development (Figure 2), because the interval between disturbances is much less than the lifespan of the dominant trees (lifespans of most coastal species exceed 350 years). However, in contrast to *Guidebook* intervals, old-growth forests dominate the unmanaged forests of coastal British Columbia (Table 2). Interpretation of aerial photographs of watersheds in the Lower Mainland, Clayoquot Sound, and the central coast consistently shows that less than 10% of unlogged forests are even-aged stands less than 100–140 years old, and old-growth forests are ubiquitous, accounting for more than 90% of unlogged forests at watershed to regional scales (Clayoquot Sound Scientific Panel 1995; Acres International 1999; Pojar *et al.* 1999; Pearson 2000, 2003). According to disturbance regime theory, mean fire return intervals would have to exceed 750–1000 years to explain the natural landscapes observed in coastal British Columbia (Table 1).

Tree ages are another source of data that provide evidence of historic fires, but age data must be considered at the appropriate spatial scale to differentiate between fire events and the fire regime (see definitions, page 56). In the coastal temperate rain forests of British Columbia, Douglas-fir is shade-intolerant and establishes after relatively large, stand-initiating disturbances (Klinka *et al.* 1990; Carter and Klinka 1992). Even-aged, open-grown cohorts of Douglas-fir are generally interpreted as evidence of past fires (Green *et al.* 1999), although other agents of disturbance (e.g., mass movements or large canopy gaps) also result in conditions suitable for establishment. Eis (1962) and Schmidt (1970) reported Douglas-fir cohorts that originated each century over the past 500–1000 years in the Lower Mainland and northern Vancouver Island. Although these cohorts provide evidence of historic stand-level disturbances at least once per century within the region, they do not represent the mean fire return intervals or the fire cycle for the region. Rather, the observations by Eis (1962) and Schmidt (1970) quantify fire occurrence—the number of years between fires somewhere in the region, but not necessarily in the same stand. In contrast, the interval between successive fires in a single stand (e.g., fire return interval; see page 56) or number of

**TABLE 2.** Landscape age structures determined from aerial photographs combined with timber inventory data for coastal temperate rain forests of British Columbia. Values are for forested areas that have not been logged. Young forests include even-aged stands with age ≤100 or 140 years; the criterion for young versus old stands varied between studies as indicated. Old forests include uneven-aged mature and old-growth stands.

| Location | Criterion for young forest (years) | % young forest in landscape | % old forest in landscape | Source |
|---|---|---|---|---|
| Ursus and Sydney watersheds, Clayoquot Sound | 100 | 1 | 99 | Pearson 2000 |
| Megan and Clayoquot watersheds, Clayoquot Sound | 100 | 3 | 97 | Pearson 2000 |
| Capilano watershed, Lower Mainland | 140 | 4 | 96 | Acres International 1999 |
| Seymour watershed, Lower Mainland | 140 | 3 | 97 | Acres International 1999 |
| Coquitlam watershed, Lower Mainland | 140 | 1 | 99 | Acres International 1999 |
| Four islands, Central Coast Region | 140 | 1 | 99 | Pearson 2003 |
| 13 watersheds, Central Coast Region | 140 | 3 | 97 | Pearson 2003 |

years required to burn an area equal to study area (e.g., fire cycle for the region; see page 56) are much longer than the interval representing fire occurrence within the region. To determine mean fire return intervals or the fire cycle requires high-quality age data representing the time since last fire for each stand in the study area (e.g., time-since-fire map, Johnson and Gutsell 1994). Age data from a small number of post-fire stands do not represent the fire regime at stand, watershed, or regional spatial scales.

Similarly, a recent study of fire occurrence in Douglas-fir stands of the Capilano River watershed in the Lower Mainland reported evidence of pre-settlement mean fire return intervals of close to 350 years in some stands (Green *et al*. 1999). Green *et al*. (1999) sampled 17 stands with evidence of fire such as charcoal and Douglas-fir cohorts and residual trees. According to age data from 306 trees, post-disturbance cohorts were established during the pre-settlement period between about 1690 and 800 AD. At individual sites, times since the last fire ranged from 310 to 850 years (in 1997), a conservative estimate of the interval between fires, as the stands have not re-burned. The difference in age between multiple cohorts in seven stands indicated mean fire return intervals of 200–450 years, with an average of 346 years. In this example, the reported fire return intervals represent the study sites but not the entire watershed. The study focussed on stands dominated by Douglas-fir growing predominantly on warm aspect slopes at submontane elevations (Green *et al.* 1999), topographic positions that are most likely to burn (Gavin *et al.* 2003a). Douglas-fir currently dominates less than 20% of the unmanaged forests in the Capilano River watershed; the majority of submontane and montane forests in the watershed are dominated by old-growth stands of western redcedar, western hemlock, and amabilis fir (Acres International 1999).

In contrast to the Douglas-fir cohorts, age structures of western redcedar-dominated stands in the Capilano, Seymour, and Coquitlam river watersheds in the Lower Mainland provide evidence that intervals between stand-initiating fires often greatly exceed 350 years (Arsenault 1995; Daniels *et al.* 1995; Daniels 2003). Peak age classes can indicate relatively severe disturbances that facilitate a pulse of regeneration (Veblen 1992). However, even at the sites dominated by individual cohorts of western redcedar, where stand-level disturbance most likely occurred, residual veteran trees were present (Arsenault 1995; Daniels *et al.* 1995; Daniels 2003). Western redcedar has thin, flammable bark, making it susceptible to fire (Agee 1993). The presence of residual, fire-intolerant western redcedar suggests a need to carefully reconsider the role of stand-initiating fires in these forests (Daniels 2003). Combined, the age data for multiple cohorts of Douglas-fir and western redcedar in the Capilano River watershed do not indicate stand-initiating fires historically dominated the landscape. Rather, tree age structures provide evidence of very infrequent, low- to moderate-severity fires or very infrequent, high-severity fires that were small or patchy.

There is growing evidence that using a mean interval of 350 years dramatically underestimates the period between fires in the wet coastal temperate rain forests of British Columbia. According to soil charcoal and tree age cohorts sampled in the very wet maritime forests of Clayoquot Sound (CWHvm subzone) and charcoal from lake sediments in the subalpine forests of the Lower Mainland (MHmm subzone), mean fire return intervals are typically over 1000 years, and some locations have not experienced fire for several thousand years (Gavin *et al.* 2003a, 2003b; Hallet *et al.* 2003; Lertzman *et al.* 2002). For example, over the last 1800 years, 23 fires burned in the 254-ha catchment of Clayoquot Lake on the west coast of Vancouver Island (Gavin *et al.* 2003a). Since 1100 AD, fire occurrence for the entire catchment averaged about 300 years, but burning was restricted to south-facing slopes, which were more than 25 times more likely to burn than north-facing slopes. Of 83 sample sites in the valley upstream from Clayoquot Lake, 45% of sites burned in the past 1000 years, including all south- and west-facing slopes, only 27% of north- and east-facing slopes had burned, and 20% of sites had not burned for at least 6000 years (Gavin *et al.* 2003b). Time since last fire at individual sites ranged from 64 to about 12 000 years, with a median of 4410 years on terraces and 740 years on hillslopes (Gavin *et al.* 2003b).

## Why is Fire Infrequent in Wet Coastal Temperate Rain Forests?

Historically, fire was infrequent in wet coastal temperate rain forests because of rare opportunities for ignition and low fuel flammability, which limits fire spread. Lightning frequency is low in the coastal temperate rain forest compared with other parts of British Columbia, reducing the probability of ignition (Lertzman *et al.* 2002; B.C. Ministry of Forests 2003b). When lightning does occur, fuels are required for ignition and spread (Rorig and Ferguson 1999). Fuel availability and combustibility are influenced by both "bottom-up" and "top-down" controlling factors (Lertzman *et al.* 1998). Bottom-up controls include local-scale topographic influences on fuel size class distribution, fuel moisture, and fire behaviour. Top-down controls are large-scale, long-term climate regimes such as the dry climate prior to the Little Ice Age versus the current climate regime.

Under the influence of a cool, wet climate, bottom-up controls strongly influence fire occurrence and extent (Gavin *et al.* 2003). In wet coastal temperate rain forests, fuels accumulate in fine-scale canopy gaps that are dispersed within a stand through time. Fine fuels decompose rapidly; thus, insufficient fine fuels accumulate at any specific location to be a significant pre-cursor for a stand-initiating fire. In general, the flammability ratings of the wet coastal temperate rain forest are low. Coarse woody debris accounts for the majority of persistent surface fuels. These fuels have high bulk density and remain moist beneath a mantle of moss and herbs in the shade of multiple layers of the canopy (Wetzel and Fonda 2000). Even during years of extreme drought, high moisture content in fuels retards ignition and spread of fire. The spread of fire is influenced by the flammability of fuels, which in turn varies with topography and climate (Huff 1995). Topography determines exposure of fuels to irradiance and wind, and indirectly influences fuel moisture, making certain parts of the landscape more susceptible to fire. For example, forests on steep, southwest-facing slopes are more flammable than forests on steep, northwest-facing slopes or flat ground in the bottom of valleys. Within stands, subtle differences in microtopography can limit the spread of fire and restrict fire size in the wet coastal temperate rain forest (Gavin *et al.* 2003b).

During periods of dry climate, top-down controls are more important than fuel dynamics for determining fire occurrence in the wet coastal temperate rain forests (Hemstrom and Franklin 1982; Gavin *et al.* 2003a). Historically, years of high fire activity were most likely to occur when persistent high pressure ridges formed along the west coast, blocking westerly winds, reducing precipitation, and allowing fuels to dry for extended periods (Agee 1991). Under these conditions, dry winds could spread fire, where fuels were available. This scenario depends on three essential conditions:

1. ignition by lightning, and persistence of fire during precipitation and (or) high humidity associated with lightning storms;

2. availability of fuels of appropriate size and distribution; and
3. an extended period of drought to dry surface fuels and permit the spread of fire.

Using 20th century climate data, Agee and Flewelling (1983) modelled climate-fire scenarios for the west side of the Olympic Peninsula in Washington State and concluded that fire return intervals averaged about 900 years. Evidently, the ideal combination of lightning ignition and bottom-up (fuels) and top-down (climate) controls suitable for stand-initiating fires is very rare in wet coastal temperate rain forests.

### Fire Magnitude

Stand-initiating fires since European settlement in the late 1800s have strongly influenced our perception of fire in coastal forests, but these fires do not represent the historic fire regime. For example, the Forks Fire on the Olympic Peninsula in 1951 was preceded by a cyclone in 1921 that created abundant fuel for the subsequent fire. Fires in the 1920s in the Capilano River watershed near Vancouver, B.C., resulted from escaped slash burns. Similarly, timber harvest was a precursor to the Tillamook Fire in Oregon, the Yacolt Fire in Washington, and the Seward and Chilliwack Valley fires in British Columbia in the early part of the 1900s. Logging created large fuel loads and microclimatic conditions that allowed the fuels to dry, making these sites conducive to burning. Moreover, most of these recent, large-scale fires in coastal forests were ignited by humans. Thus, stand-initiating fires have burned coastal forests in the past century, but under unusual circumstances.

Historically, low- and mixed-severity fires likely burned in wet coastal temperate rain forests, resulting in complex stands with multiple age cohorts (Agee 1993; Daniels *et al.* 1995; Daniels 2003; Green *et al.* 1999). The impacts of fire may have varied through time, influenced by climate variation (Agee 1993; Daniels *et al.* 1995). Documenting spatially and temporally mixed-severity fire regimes is fundamentally different from researching high-severity, stand-initiating fire regimes. Stand-initiating fire regimes are quantified from time-since-fire maps (Johnson and Gutsell 1994). To reconstruct fire history of mixed-severity disturbance regimes requires time-since-fire maps, combined with high-quality, spatially explicit age and fire scar data within stands and across landscapes (e.g., Heyerdahl *et al.* 2001; Swetnam *et al.* 1999). Unfortunately, these data are difficult and costly to acquire in wet coastal temperate rain forests, as tree radii often exceed the length of the longest increment borers, heartwood is decayed in many canopy trees, and fire scars are rare (Daniels 2003). Moreover, historical evidence has been lost from many forests that have been altered significantly by logging and urban development.

## Gap Dynamics in Coastal British Columbia

We reject the traditional view that stand-initiating fire at intervals of 250–350 years was the dominant disturbance regime in coastal British Columbia. Alternatively, we propose that fine-scale gap dynamics is the dominant process explaining the structure and dynamics of most unmanaged stands in the province's wet coastal temperate rain forests. We have offered four lines of evidence to support this assertion.

1. Old-growth forests dominate at landscape scales in unmanaged wet coastal temperate rain forests. According to disturbance regime theory, mean fire return intervals must be at least 350 years for old-growth forests to cover more than 50% of the landscape. For landscapes with greater than 80% cover of old-growth forests, mean fire return intervals exceed 1000 years.
2. Recent research provides evidence that fire was historically very infrequent, with mean return intervals of 350 to several thousand years in wet coastal temperate rain forests. Although fires have burned some stands in the past 1000 years, as indicated by persistent Douglas-fir age cohorts, the return intervals between fires at individual stands are so long that gap dynamics is the dominant disturbance explaining current stand structures.
3. Biophysical conditions limit fires in wet coastal temperate rain forests. Historically, fire was infrequent because of rare opportunities for ignition and low fuel flammability, which limits fire spread.
4. Old-growth stands are structurally diverse and include trees of all sizes and ages. Fine-scale gap dynamics explains these attributes as follows. One to a few trees are killed, generating coarse woody debris and creating small openings in the canopy. The patchy mortality of canopy dominants facilitates tree regeneration and recruitment in gaps. Thus, the forest canopy is continuously renewing itself and maintaining canopy structure and stand-level biomass, driven by gap dynamics.

## Implications For Ecosystem Management

A primary objective of management in British Columbia's wet coastal temperate rain forests is to achieve ecological sustainability, extracting renewable resources while maintaining key habitat characteristics and biodiversity. In one model of ecosystem-based management, harvesting is conducted on spatial and temporal scales that are consistent with natural disturbance regimes at stand to landscape spatial scales (Christensen *et al.* 1996; Landres *et al.* 1999). The goal of this approach is to maintain forest structures and processes that provide necessary habitat for native plants and animals, while extracting timber. In this context, variable retention silviculture has replaced clearcut logging of many wet coastal rain forests of British Columbia (Mitchell and Beese 2003). Clearcut logging at economic rotations of 80–120 years is clearly inconsistent with both canopy gap dynamics and the historic fire regime (Clayoquot Sound Scientific Panel 1995). However, if variable retention is intended to be consistent with natural disturbance regimes, then harvesting needs to occur in space and over time in ways that are consistent with either the natural canopy gap regime or fire regime. For example, variable retention that emulates canopy gaps would create small patches that are dispersed through a stand and would include multiple entries into the stand over many decades to centuries. Variable retention that emulates fire will create a range of patch sizes, leave remnant islands and single trees, and will have long rotations of many hundreds of years. Conceptually, these two models of management are possible in coastal British Columbia; however, they are limited in three ways. First, practical limitations may reduce the ability to design a silvicultural system that is consistent with natural disturbances while meeting other management objectives (Mitchell and Beese 2002). Second, if implemented at stand to landscape scales, both models have significant impacts on the allowable annual cut, which is unlikely to be acceptable from an economic perspective. Third, knowledge of natural disturbance regimes in the wet coastal temperate rain forests of British Columbia remains incomplete. Therefore, variable retention silviculture will emulate some, but not all, aspects of natural disturbance.

*We need to understand the spatial and temporal attributes of natural disturbance regimes, the variability of historical disturbances, and the effects of disturbance on forest development and dynamics.*

If we are to objectively determine whether forest management is ecologically sustainable over the long term, we must be able to compare the impacts of variable retention silviculture on forest composition and structure with the impacts of natural disturbance regimes over large areas and long periods of time. This goal requires a better understanding of the natural disturbance dynamics of wet coastal temperate rain forests, including canopy gaps, fire, wind, insects, pathogens, and geomorphic disturbances. Specifically, we need to understand the spatial and temporal attributes of natural disturbance regimes, the variability of historical disturbances, and the effects of disturbance on forest development and dynamics. Ultimately, more complete knowledge of natural disturbance regimes will provide a baseline for comparative analysis of the structure and dynamics of natural versus managed forests, and ecosystem-specific guidelines for ecologically based variable retention silviculture.

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## Definition of Terms Describing Disturbance Events and Regimes

Six factors—*causal agent(s)*, *location*, *extent* (size), *shape*, *timing* and *magnitude*—describe an *individual disturbance event*. Magnitude may be measured as *intensity* or *severity*. *Intensity* is the force of the disturbance agent and is measured directly during the disturbance. *Severity* measures the impact of disturbance on the vegetation or environment (e.g., stand-initiating versus stand-maintaining disturbance).

Descriptors of a *disturbance regime* characterize the events affecting a defined landscape through time. *Spatial distribution* locates individual disturbances and relates their position in the landscape to other disturbances and landscape features. *Frequency* is the number of disturbance events occurring at a given point or within a region during a defined time period. *Return interval* is the mean or median number of years between successive events and must report the variation in return intervals, such as standard deviation or range. *Predictability* is inversely related to the variation of the mean return interval. It quantifies the temporal distribution of events and describes whether they occur relatively regularly. *Rotation period*, *disturbance cycle*, and *turnover time* are summary statistics of the mean time required to disturb an area equivalent to the size of the study area.

# *Test Your Knowledge . . .*

*Disturbance regimes in coastal British Columbia*

**How well can you recall some of the main messages in the preceding discussion paper? Test your knowledge by answering the following questions. Answers are at the bottom of the page.**

1. Which of the following statements does not describe an old-growth forest?
   A) The forest is stable and maintained in absence of disturbances.
   B) One to a few trees die, generating coarse woody debris and creating canopy gaps.
   C) Trees regenerate and recruit to the upper canopy in gaps.
   D) The forest is continually changing, while maintaining complex stand structure and stand-level biomass.

2. Based on empirical evidence, including interpretation of aerial photographs and analysis of tree age structures and soil charcoal, the best descriptor of historic fire regimes in wet coastal temperate rain forests of British Columbia is:
   A) Stand-initiating fires at intervals of 100 years
   B) Stand-initiating fires at intervals of 250 years
   C) Stand-initiating fires at intervals ≥ 350 years
   D) Mixed-severity fires at intervals of ≥ 350 years

3. Evidence that gap dynamics is the dominant disturbance regime in wet coastal temperate rain forests of British Columbia includes:
   A) Old-growth forests dominate unmanaged landscapes.
   B) Fire return intervals range from 350 to several thousand years.
   C) Biophysical conditions limit fire ignitions and fuel flammability.
   D) Old-growth forests are structurally diverse due to patchy mortality of canopy trees that create coarse woody debris and facilitate regeneration.
   E) All of the above.

*ANSWERS*

*1. A 2. D 3. E*