Old-Growth Definitions for the Forests of British Columbia, Canada

Ralph W. Wells
Centre for Applied Conservation Biology
University of British Columbia
Vancouver, B.C. V6T 1Z6 Canada

Ken P. Lertzman
School of Resource and Environmental Management
Simon Fraser University
Burnaby, B.C. V5A 1S6 Canada

Sari C. Saunders
School of Forestry
Michigan Technological University
Houghton, MI 49931 USA

Natural Areas Journal 18:279–292

ABSTRACT: Increased scarcity of old forests of natural origin, and improved understanding of the ways in which they are ecologically distinct, have led to a need for standardized definitions for old-growth forests in British Columbia, Canada. Useful definitions of old growth that are simple and concise have been elusive because the old-growth stage of forest development occurs as a part of a continuum of development and varies greatly over ecological gradients at several scales. Therefore, we propose the development of ecologically based definitions in three broad categories: conceptual, quantitative, and working. We suggest that old growth be defined conceptually as a forest in which processes of gap dynamics predominate. We further propose that definitions of old growth should incorporate the distinct structural and compositional characteristics that arise from these developmental processes, because direct measures of gap dynamics are elusive and because structural attributes perform important ecological roles. Indices of forest structure that capture the inherent variability of structural characteristics of old-growth stands show promise for quantifying the qualitative features contained in conceptual definitions; minimum thresholds and demographic measures also have merit. In the interim, working definitions based on minimum age and height for different forest types have allowed the completion of province-wide inventories from existing databases. Future research should be directed toward determining the structural characteristics and variability of the different late-successional forest types in British Columbia so that conceptual definitions can be tested and type-specific ecological definitions can be developed. The paucity of basic information on characteristics of old-growth forests limits the ability of managers to determine the area and location of specific types of old-growth forest, and to develop appropriate management goals and methods.

Index terms: Old growth, old-growth forests, old-growth definitions, old-growth indices, stand dynamics

INTRODUCTION

Public interest in conserving older, unharvested forests in the Canadian province of British Columbia, as elsewhere, has increased due to the growing scarcity of old forests of natural origin and improved understanding of their ecological uniqueness. As a consequence, forest management agencies require standardized definitions of old growth to complete inventories, make land use decisions, and develop management strategies. Good definitions are also required to assist further research into the processes and functions of the old-growth stage of forest development.

Useful definitions of old-growth forests that are simple and concise have been elusive. Our conceptual understanding of what constitutes old growth has evolved over time and continues to do so with new knowledge and changing values, making earlier definitions obsolete (Juday 1988). Human values, including economic, social, and cultural as well as ecological values, influence our ideas about what constitutes old growth (Hunter 1989, Rolston 1989). Moreover, the development of definitions is not easy, even when viewed from a strictly ecological perspective. This is partly because the old-growth stage of forest development occurs as part of a continuum of development that varies in both time and space (Spies and Franklin 1988, Oliver and Larson 1996). At what point in its development a stand becomes "old growth" is often as much a matter of judgment as science. In British Columbia the issue is compounded by the presence of many forest types (Meidinger and Pojar 1991), each with its own distinct developmental characteristics. Finally, the building of good definitions for British Columbia is hindered by a lack of research describing the structural, compositional, and functional characteristics of old growth for the many different forest types of the province (Hamilton and Nicholson 1991). Various definitions of old growth reflect

Table 1. Definitions of old growth from the Old Growth Strategy Workshop (modified from B.C. Ministry of Forests 1989).

"When I think of old growth, I think of a natural progression of forest growth without evidence of man's influence."—Sydney Haskell, Carmanah Forestry Society

"The forest-state that stretches from the time of dominant stand height growth cessation, through to and including the stable forest climax, should this develop."
—Western Canada Wilderness Committee

"Forest stands well beyond the rotation age for managed forests."
—Canadian Pacific Forest Products Ltd.

"We define 'Old Growth' as those mature and over-mature forests which occupy sites which have not previously been impacted by the hand of man."
—Fletcher Challenge Ltd.

different values. Most definitions tend to fall into three broad categories: economic, aesthetic, or ecological. For example, to some, old growth might mean a forest that is beyond the age of its maximum mean annual increment, the point at which the rate of accumulation of wood volume in a stand begins to decline (DeBell and Franklin 1987), or beyond the age of its maximum economic value (Hunter 1989). These economic definitions are primarily based on wood productivity and often associated with the "over-mature" description noted in Table 1. When asked to define old growth, others refer to forests in which they have had experiences associated with "cathedral-like" surroundings. This is essentially an aesthetic or spiritual definition (Rolston 1989). Some people see individual old trees and think of them as "old growth," while most ecologists define old growth at the stand level, based on the characteristics of larger groups of trees. Definitions that focus on the ecological aspects of old-growth forests may be developmental or process oriented, such as the definition offered by Oliver and Larson (1996; Table 2), or they may focus on structure and composition as does the definition of Franklin and Spies (1991a; Table 2).

From within this somewhat confusing and subjective context, we examined the literature for various definitions of old growth and evaluated these definitions for their applicability to the forests of British Columbia. We further attempted to provide an objective basis for defining old growth: we believe that definitions of old growth need to be based on fundamental ecological and physical characteristics of old-growth forests to be useful for forest management and conservation. Even highly subjective aesthetic and spiritual senses of old growth are to some extent associated with the aggregate of tangible, ecological characteristics of the forest.

ECOLOGICALLY BASED DEFINITIONS

For the remainder of this paper we focus on definitions of old growth that are ecologically based. While this narrows the range of definitions to be examined, the task remains challenging: useful ecologically based definitions must be broad enough to incorporate the range of variation found in different types of old-growth forest. Yet they must also be detailed and precise enough to distinguish old-growth from stands of other developmental stages within the same forest type. To be implemented and widely applied in the short- to medium-term, ecologically based definitions should utilize information that is currently available or that is readily measurable. We believe these somewhat conflicting requirements can be met by developing ecologically based definitions in three broad categories: conceptual, quantitative, and working.

Conceptual definitions are abstract or generic descriptions that define old growth qualitatively. Such definitions have significant heuristic value and can play important roles as conceptual guides, even in the absence of local data for quantifying the attributes of old growth. Ideally, a conceptual definition is broad enough to cover as many forest types as possible yet specific enough to be a basis for development of good, quantitative definitions. Pojar et al. (1992) recognized the need for ecologically based, conceptual definitions of old growth and recommended that such a definition be developed for British Columbia. Quantitative definitions are designed to quantify the qualitative features of conceptual definitions. These quantitative definitions are needed to allow identification of old growth in the field and to facilitate research, planning, and management. Working definitions are interim quantitative definitions based on existing inventory data. Working definitions are necessary

Table 2. Ecologically based conceptual definitions of old growth.

"Stands in which the relic trees have died and which consist entirely of trees which grew from beneath [the canopy] *will be referred to as true old growth stands."*
—Oliver and Larson (1996)

"Old-growth forests are later stages in forest development that are often compositionally and always structurally distinct from earlier successional stages.

All climax forests . . . qualify as old-growth, although most old growth forests are not climax.

Old-growth forests could theoretically originate after either human or natural disturbance because they are defined by composition, structure, and function and not by origin or naturalness."—Franklin and Spies (1991a) to manage resources in the near to medium term, while more precise quantitative definitions are being developed. Working definitions represent the overlap between the current state of knowledge and availability of data concerning old-growth forests. The need for quantitative or working definitions for British Columbia has been recognized by Pojar et al. (1992), although they did not distinguish between the two categories. Finally, it is important to note that all definitions will evolve as our understanding of forests improves and the quality and quantity of inventory information increase. The remainder of this paper examines the development and application of conceptual, quantitative, and working definitions of old growth for the forests of British Columbia.

Conceptual Definitions

Ecologists' conceptual views of old growth typically have fallen into two different categories. One is historically organism-centered and arises from thinking about the dynamics of populations and communities, often in the context of succession. The other category is historically ecosystem-centered and has focused on the structural and compositional characteristics of forests in relation to a variety of ecosystem processes, such as patterns of productivity, nutrient cycling, and habitat attributes. Largely because of old growth's management context, forest structure has emerged from this approach as a key proxy for ecosystem function. Over the past decade we believe these different approaches have merged to the point where a general, process-based approach to the dynamics within old-growth forests may be proposed.

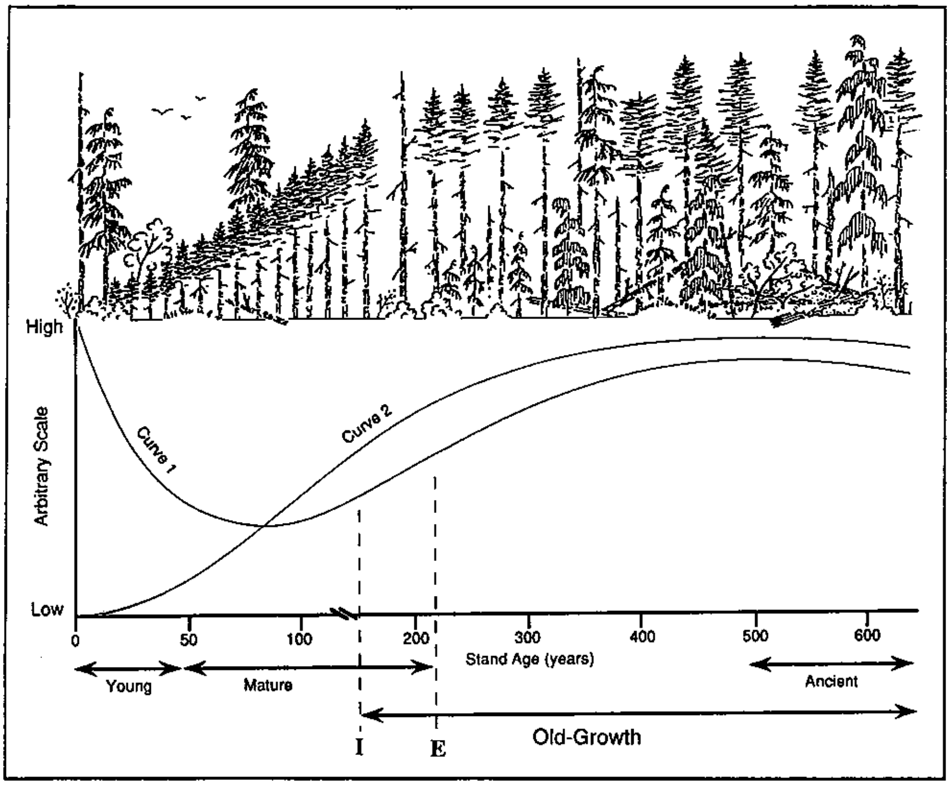

Figure 1. Schematic diagram of natural succession following a stand-destroying event such as a fire (based on Franklin and Spies 1991b). Curves 1 and 2 below the successional illustration represent generalized patterns of change in ecosystem attributes over long recovery periods (based on Spies and Franklin 1988). The curve for snags and logs follows a U-shaped pattern (Curve 1) after a stand-destroying disturbance results in a large initial input of dead trees. Decay reduces this dead material until, later in succession, mortality of individual trees produces new snags and logs. Understory development also follows an approximate U-shape. Initially, understory herbs, shrubs, and saplings grow well in an open environment following the disturbance. As the young forest develops, a dense overstory canopy forms, cutting off light from the understory and decreasing plant life there. Eventually, tree mortality leads to gaps in the canopy and allows more light to reach the understory, again allowing growth of herbs, shrubs, and trees. Tree size and tree biomass follow an approximate S-shaped curve (Curve 2), which is at its minimum directly following a major disturbance and eventually reaches a plateau. Though these are idealized trajectories, the development of structural attributes in many stands is well approximated by these patterns (see also Table 3). These curves were developed for Douglas-fir forests; the patterns are expected to apply to other forest types in British Columbia, although the age scale will vary among forests types and site conditions. See text for discussion of points I and E.

Conceptual Definitions Based on Demographic Processes

After a major disturbance (termed "stand-initiating" because it kills all or most of the pre-existing stand), forests progress through a characteristic series of developmental stages leading, in the absence of further large-scale disturbances, to an old-growth stage, (e.g., Oliver 1981, Peet and Christensen 1987, Oliver and Larson 1996, Spies and Franklin 1996; Figure 1). Some authors focus on the compositional dynamics during these stages: "A forest which has reached the climax stage of succession" is one conceptual definition of old growth that has been used in the past (Hunter 1989). However, the climax criterion is a poor indicator for old growth because even extremely old forests are often undergoing slow directional changes in composition and structure (e.g., Lertzman 1992, Tyrell and Crow 1994), and many undeniably old-growth stands contain long-lived early seral species (e.g., many of the Douglas-fir forests of the U.S. Pacific Northwest and southwestern British Columbia).

Oliver and Larson (1996) proposed an expanded definition based on demographic processes. They suggest that stands that consist entirely of trees originating beneath a forest canopy are old-growth stands. Pioneer tree species that colonize disturbed areas following a major disturbance are often unable to grow under the shade of a forest canopy and are eventually replaced by more shade-tolerant species. Only these shade-tolerant species are able to maintain themselves after the canopy has developed and, thus, should exclusively make up the old-growth forest of the Oliver and Larson (1996) definition. This definition does not require a stable, climax species composition, and thus avoids the problems associated with the steady-state assumption of a climax-based definition. Elsewhere in this issue, Kneeshaw and Burton (1998) present a definition similar to that proposed by Oliver and Larsen (1996) for spruce forests in the interior of British Columbia. They defined old growth based on the dominance of the cohort that established after a disturbance relative to the cohort(s) that replace(s) it. One nice aspect of this approach is that it does not require that these cohorts belong to different tree species.

However, the Oliver and Larson (1996) definition seems unreasonably narrow in its application. Many stands that researchers and others would consider old growth would still be excluded by it, such as the relatively old stands of Sitka spruce and Douglas-fir in coastal British Columbia. The dominant species in these forest types are pioneer species that would, in the absence of major disturbance, eventually be replaced by other species of shade-tolerant trees such as western hemlock.

Demographically based definitions have embodied a simplistic model of the disturbance-response process wherein forest dynamics are driven primarily by infrequent major disturbances. We know, however, that disturbances in forests can occur on gradients of size, frequency, and severity (Lertzman and Fall 1998) and vary substantially in the kinds of roles they play in forests. For instance, intervening partial disturbances may accelerate the development of old-growth structural characteristics in relatively dry Douglas-fir forests (Agee 1991). In the wetter forests of coastal British Columbia, large-scale fires may only occur every few millennia (Gavin et al. 1996, 1997), and the intervening dynamics are driven by small patchy disturbances within the context of persisting, extensive old-growth forest (Lertzman et al. 1996). In many forests outside western North America, early successional tree species can recruit in such a context, persisting over time this way in the old-growth mosaic (e.g., Runkle 1981). The paradigm of major structural and compositional changes following a single catastrophic disturbance misses the most interesting dynamics in such systems. The range of forest types to which a demographic approach to old growth could reasonably be applied will depend critically on the match between the distribution of opening sizes within old-growth stands and the regeneration requirements of the species growing there. If most (in space and time) disturbance patches create large openings with a high rate of mortality in them, and many tree species require those large openings to establish, then a demographic model may be appropriate. Simple demographically based models are less likely to be useful where frequent partial disturbances induce uneven age structure in younger stands, where openings are smaller and many species can recruit in them, where the time between major disturbances is very long, or where the species that require larger openings are long-lived. More complex demographic models incorporating detailed analysis of multi- or all-aged stand structure may be useful for such forests (see Kneeshaw and Burton 1998), but will likely be difficult to implement in a management context.

Conceptual Definitions Based on Structure and Composition

Extensive research in old-growth forests of the Pacific coast of the U.S. Pacific Northwest has shown that these coastal old-growth forests are structurally, compositionally, and functionally distinct from earlier seral stages (Franklin et al. 1981, Alaback 1984, Franklin and Spies 1991b; Table 3). Few studies have compared old-growth forest to younger stages in British Columbia; those that did found similar results (Arsenault and Bradfield 1995, Wells 1996, Kneeshaw and Burton 1998). Franklin and Spies (1991a) suggested that old growth can be defined using characteristics from these three categories, although a practical definition would focus on structural and compositional features rather than functional characteristics, which are more difficult to measure.

Conceptual definitions based on structural attributes of old growth are appealing. These definitions focus on biologically important features that can be readily measured and assessed. The structural attributes they address tie directly to various kinds of management concerns, and are relatively easily made the target of management actions. Attributes such as large snags, canopy gaps, and productive understory are important to ecosystem function and provide habitat for plants and animals. The old-growth characteristics presented in Table 3 can be used to form an ecologically based conceptual definition of old growth that includes a number of specific attributes, and yet is broad enough to apply to most temperate and subalpine forests of the U.S. Pacific Northwest (Franklin and Spies 1991a).

The British Columbia government's Forest Land Use Liaison Committee (FLULC) de-

Table 3. Ecological characteristics of old-growth forests (Franklin and Spies 1991b).

Structural
- wide range of tree sizes and spacing
- large trees for species and site conditions
- decadence in large older trees
- presence of large snags and down logs of varying decay classes
- canopy gaps
- understory patchiness
- high organic matter accumulations
- multiple canopy layers

Compositional
- high diversity of plant, vertebrate, and invertebrate communities
- increased richness and productivity of arboreal and understory plant communities
- high habitat diversity

Functional
- distinctive nutrient and hydrological cycles
- slow growth of dominant trees
- stable biomass accumulation

Table 4. Conceptual definition of old growth for British Columbia (Forest Land Use Liaison Committee 1989).

"Old growth is a forest that contains live and dead trees of various sizes, species composition and age class structure that are part of a slowly changing but dynamic ecosystem. Old growth forests include climax forests, but do not exclude sub-climax or even mid-seral forests. The age and structure of old growth varies significantly by forest type and from one biogeoclimatic zone to another."

"The age at which old growth develops the specific structural attributes that characterize old growth will vary widely according to forest type, climate, site characteristics and disturbance régime. However, old growth is typically distinguished from younger stands by several of the following attributes:

- *large trees for species and site*
- *wide variation in tree size and spacing*
- *accumulations of large size dead standing and fallen trees*
- *multiple canopy layers*
- *canopy gaps and understory patchiness*
- *decadence in the form of broken or deformed tops or boles and root decay"*

veloped an ecologically based conceptual definition of old growth for British Columbia (Forest Land Use Liaison Committee 1989), which was adopted for use with the Old-Growth Strategy (B.C. Ministry of Forests 1992; Table 4). The FLULC definition emphasizes the structural characteristics of old growth. It avoids the problems associated with terms like climax by explicitly recognizing that a mid-successional forest may qualify as old growth as long as it has the appropriate structural characteristics. This definition also acknowledges the wide variation in old-growth structure expected among forest types in different regions of the province. Finally, it recognizes that the age at which a stand may attain old-growth structural characteristics is variable.

Conceptual Definitions Based on Gap Dynamics

Essentially all the structural characteristics associated with old growth (Tables 3 and 4) result from the mortality of individual canopy dominants or small groups of canopy trees. The primary developmental process through which mature stands are transformed into old growth, by either structural or demographic criteria, is this patchy mortality of canopy trees and the chain of consequences arising from it (Figure 2). These mortality events create gaps in the forest canopy, which influence understory microclimates in a variety of ways, notably increasing light availability for growth of understory trees, shrubs, and herbs. In mature stands, this is associated with the transition to an understory reinitiation phase (Oliver 1981, Oliver and Larson 1996). Trees whose death created the canopy gaps will remain as snags and logs, decomposing over time. A wide range of tree sizes and ages develops as trees in successive gaps recruit to the canopy, leading first to multicohort stands and eventually to all-aged stands. In the absence of large-scale disturbances, older forests cycle through these patchy disturbance and recovery processes and thus continue to develop in structure, composition, and function as they age. We expect "old" (or "ancient") old growth to differ from

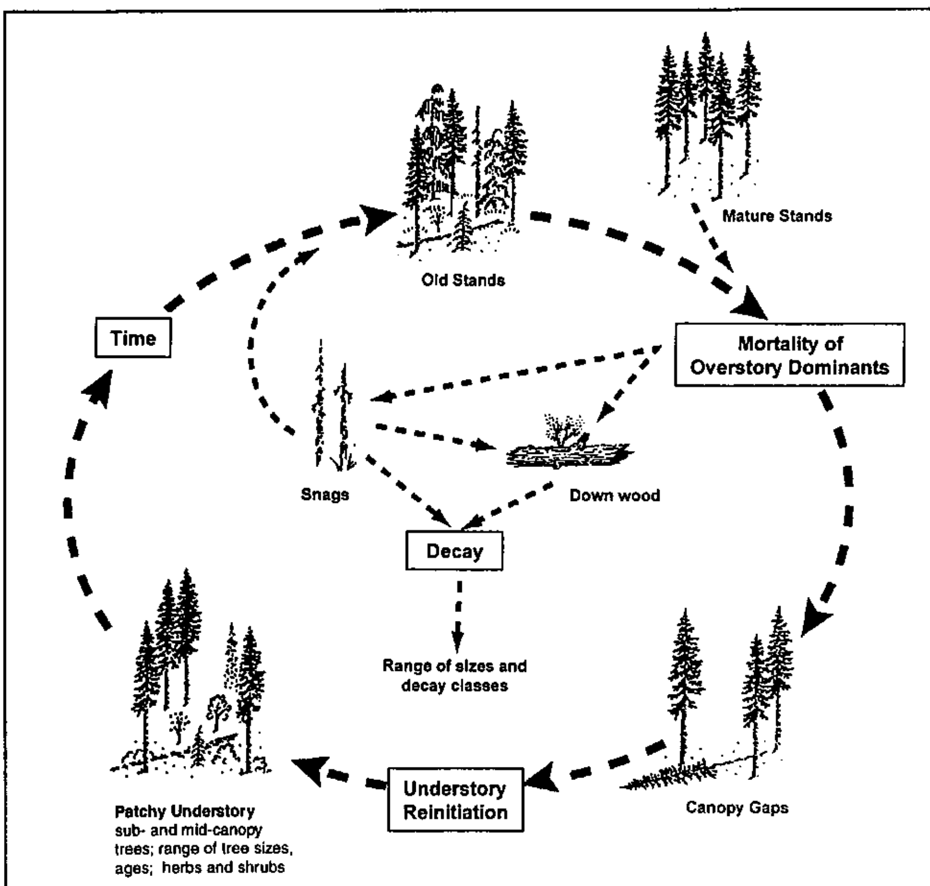

Figure 2. Processes and structures associated with old-growth forests. Old-growth forests have distinct structural and compositional characteristics including a range of tree sizes and species, large snags, large logs, and openings of various sizes in the canopy. In forest types where large-scale disturbances are rare, processes of gap formation are a major source of forest heterogeneity (Spies et al. 1990, Lertzman and Krebs 1991).

"young" old growth (see Appendix 1).

Gap dynamics provide a process-based conceptual definition of old growth in which the important aspects of the demographic approaches and structural approach can be combined. We propose that the transition from mature stands to old growth be defined as the phase in development where the mortality of canopy dominants begins to influence forest structure and understory microclimate. The old-growth stage is characterized by the accumulated results of this process over time, for example, canopy gaps, large dead trees in various states of decay, a productive understory layer, and so on. During the old-growth stage, forests that have been subject to these processes for longer will display more of these consequences. The gap dynamics approach to a conceptual definition is consistent with definitions endorsed by the U.S. Forest Service (Old-Growth Definition Task Group 1986) and the FLULC. It doesn't replace them or make them less useful, but rather provides a process-based rationale for them.

In British Columbia many forests easily fit this conceptual definition. The best documented examples are the coastal forests of the Coastal Western Hemlock (wetter subzones) and Mountain Hemlock (forested subzone) biogeoclimatic zones. Long intervals between major disturbances and shade tolerance of most species can lead to forests that are largely shaped by their histories of gap dynamics (Lertzman and Krebs 1991, Lertzman 1992, Ar-

Table 5. Applicability of old-growth criteria to mature forests in different biogeoclimatic zones of British Columbia (from Pojar et al. 1992); y = yes, n = no, s = somewhat or sometimes, ? = unknown. Applicability of the criteria was determined through discussions with research ecologists from the B.C. Ministry of Forests Research Branch.

	Biogeoclimatic Zones[a]										
Criteria	PP	IDF	MS	SBPS	SBS	ICH	ESSF	BWBS	CDF	CWH	MH
Mensurational											
Age 150–200 yr or older[b]	y	y	?	n	n	y	y	n	y	y	y
Beyond culmination of MAI	y	y	y	y	y	y	y	y	y	y	y
150 yr old and ≥ 30 m tall[c]	s	s	s	?	s	s	s	?	s	y	s
Structural											
Wide range of tree sizes & ages[d]	y	y	y	n	y	y	y	y	y	y	y
Deep multilayered canopy[d]	n	y	y	n	s	y	y	s	y	y	s
Large average tree diameter[b]	y	y	s	s	s	y	y	s	y	y	y
Individual large (≥1 m dbh) old trees (25 ha^{-1})[d]	?	?	?	?	?	?	?	?	?	?	?
Much variation in tree diameter[b]	y	y	y	n	y	y	y	y	y	y	y
37 stems ha^{-1}, ≥ 50 cm dbh[d]	?	?	?	?	?	?	?	?	?	?	?
Large average tree-spacing[b]	y	y	s	n	s	y	y	s	y	y	y
2 or more tree species[d]	n	n	s	n	s	s	s	y	y	s	s
Abundant coarse woody debris[d]	n	s	s	s	s	y	y	s	y	y	y
Decadent features present[e]	y	y	y	y	y	y	y	y	y	y	y
Snags present[d,e]	y	y	y	y	y	y	y	y	y	y	y
Many snags (25 ha^{-1})[d]	?	?	?	?	?	?	?	?	?	?	?
Down woody material ≥ 37 tons ha^{-1} [e]	?	?	?	?	?	?	?	?	?	?	?
Functional											
High understory productivity[d,e]	?	?	?	n	s	s	?	?	s	s	s
Conceptual (ecologically based)											
Relatively old[f]	y	y	y	y	y	y	y	y	y	y	y
Relatively undisturbed by human activity[f]	n	n	y	y	y	y	y	y	s	y	y
Climax or shifting steady state	y	y	y	y	y	y	y	y	y	y	y
Older than average disturbance interval	y	y	y	y	y	y	y	y	y	y	y
Average trees having reached life expectancy for species	y	y	y	y	y	y	y	y	y	y	y
More diverse than younger stages[g]	y	y?	y	y	y	y	y	y	y	y	y
Natural mature stand, not significantly affected by humans, may contain varying size and age trees of different species[h]	s	s	y	y	y	y	y	y	y	y	y

[a] Forested biogeoclimatic zones (from Meidinger and Pojar 1991): PP = Ponderosa Pine, IDF = Interior Douglas-fir, MS = Montane Spruce, SBPS = Sub-Boreal Pine–Spruce, SBS = Sub-Boreal Spruce, ICH = Interior Cedar-Hemlock, ESSF = Engelmann Spruce–Subalpine Fir, BWBS = Boreal White and Black Spruce, CDF = Coastal Douglas-fir, CWH = Coastal Western Hemlock, MH = Mountain Hemlock.
[b] Alaback 1984
[c] Roemer et al. 1988
[d] Spies and Franklin 1988
[e] Habeck 1988
[f] Hunter 1989
[g] Thomas et al. 1988
[h] Forest Land Use Liaison Committee of British Columbia 1989

senault 1995, Lertzman et al. 1996). Gap dynamics have also been documented in the drier, more fire-driven Douglas-fir forests of the nearby Washington and Oregon Cascades (Spies et al. 1990). This approach should fit a variety of forest types that have not been generally thought of as gap-driven systems. For instance, to declare a lodgepole pine forest to be old-growth, using demographically based or structuraly based definitions of old growth, it must have survived long enough for the initial cohort of trees to be broken up by patchy mortality. Its life expectancy in this state may not be long, but we would expect old-growth lodgepole pine to be an exceptional case, although not nonexistent (e.g., Mehl 1992).

There are in all 12 different major forested biogeoclimatic zones in British Columbia, representing a wide variety of forest types (Meidinger and Pojar 1991; Appendix 2). Old-growth forests in these other zones display very different characteristics from the old growth of British Columbia's coastal forests. For instance, low-intensity ground fires are historically common in unmanaged forests of the Ponderosa Pine zone and Douglas-fir stands of the Interior Douglas-fir zone. Because of these fires, there are fewer logs and relatively less understory development than in coastal old growth, and tree canopies are generally not as deep and multilayered as in coastal forests (Pojar et al. 1992). In the Montane Spruce, Sub-Boreal Pine–Spruce, and Boreal White and Black Spruce zones, the relatively high frequency of extensive fires results in fewer older forests than in other zones. Old-growth forests of these zones have abundant down woody material (due to mortality by wildfire) but usually lack the large, widely spaced trees and deep, multilayered canopy of coastal old growth (Pojar et al. 1992). Nonetheless, even these forests exhibit an abundance of down wood and snags and presence of a wide range of tree ages and sizes for all but Sub-Boreal Pine–Spruce zone forests (Table 5). These characteristics are indicative of forests in a gap-dynamics stage of development, providing further evidence of the wide applicability of a gap-dynamics-based conceptual definition of old growth. However, the abundance of question marks in Table 5 indicates the paucity of available data and the need for caution about this interpretation, and underscores the need for further research on old growth in most of the forest types of British Columbia.

Quantitative Definitions

Quantitative definitions quantify the attributes that are more generally presented in conceptual definitions of old growth. They facilitate accurate inventories and further research into the characteristics of different types of old growth. Quantitative, ecological criteria for defining old growth can be derived from any given biologically based conceptual definition. For example, to develop a quantitative definition based on functional criteria researchers might use information on rates of processes such as primary production, tree mortality, and decay. However, because these functional features are difficult to measure, current quantitative definitions tend to focus on structural and compositional attributes.

The development of quantitative definitions requires researchers and managers to establish categories of forest development along a continuum of successional development. Threshold values of old-growth attributes, such as the number of snags per hectare, must be chosen from within this continuum to divide one forest stage from another. However, different attributes develop old-growth-like characteristics at different rates. Thus, when lines are drawn at specific points along this continuum, there are inevitable regions of overlap among stages of forest development that have been previously defined conceptually (Figure 1).

Because of these overlapping characteristics among stages of forest development, quantitative definitions of old growth can be designed to be either inclusive or exclusive. Minimum values of selected attributes can be used, for example, to draw a threshold between mature and old-growth forest at point I of Figure 1. This results in an inclusive definition that encompasses all stands that are perceived as old-growth stands based on structure and composition, and includes some forests that would not have been conceptually defined as old growth. Alternatively, average values for the same attributes can be used to choose a threshold point between "mature" and "old-growth" at point E of Figure 1. This results in an exclusive definition that only identifies stands that have well-developed

Table 6. Interim minimum standards for old-growth Douglas-fir forests on western hemlock sites (western hemlock, Pacific silver fir) in western Washington and Oregon and in California (modified from Old-Growth Definition Task Force 1986).

Stand Characteristic	Criteria
Live trees	Two or more species with a wide range of ages and sizes
	Douglas-fir: ≥ 20 ha^{-1} of trees > 81 cm dbh or > 200 yr old
	Shade-tolerant associates (western hemlock, western redcedar, Pacific silver fir, grand fir, or bigleaf maple) ≥ 30 ha^{-1} or trees > 41 cm dbh
Canopy	Deep, multilayered canopy
Snags	Conifer snags: ≥ 10 ha^{-1} of snags > 51 cm dbh and > 4.6 m tall
Logs	≥ 34 Mg ha^{-1} including 10 pieces ha^{-1} ≥ 61 cm dbh and > 15 m long

old-growth characteristics, and probably excludes some stands that might be defined conceptually as old growth. The same difficulties arise when determining the thresholds in attribute values that separate old-growth from "ancient" forests (Appendix 2). There is overlap in structural characteristics of stands that ecologists characterize as old growth and stands that are sometimes termed "ancient" (Figure 1). These "ancient" forests fall at the extreme end of the distributions of age and attribute development for their forest type.

Quantitative Definitions Relevant to British Columbia

To date, the development of quantitative definitions of old growth in British Columbia has been very limited. The U.S. Forest Service has undertaken the most substantive work for forest types similar to British Columbia. The Old Growth Definition Task Group of the U.S. Forest Service based their quantitative definitions on structural and compositional attributes. They developed interim, minimum criteria for old-growth Douglas-fir and mixed conifer forests of western Washington, Oregon, and California (Old-Growth Definition Task Group 1986). Their definitions for Douglas-fir stands on western hemlock sites cited expected minimum values for the size and number of live trees, snags, and down wood. The definitions incorporated the presence of a multilayered canopy and a wide range of tree ages and sizes (Table 6) and included many of the structural characteristics presented in Table 3.

The interim definition of the U.S. Forest Service did not identify old growth as well as expected. Depending on the geographic region, only 52% to 70% of stands that would be considered old growth based on an age criterion of > 200 years were distinguished by criteria used in the interim definition (Franklin and Spies 1991a). This was surprising because the definition was intended to be inclusive, using minimum standards that were well below typical attribute values for these stands. For example, the standards called for 34 Mg ha^{-1} of logs, whereas studies had shown average levels of 66 Mg ha^{-1} (Spies et al. 1988). Two factors were primarily responsible for this poor performance. First, while almost all stands met some of the structural criteria, many stands did not meet all of them. Second, median values for attributes were much lower than average ones, because the average values were strongly influenced by a few stands with extremely high levels of a given attribute. For example, a few stands had significantly more large snags than most of the other stands (Franklin and Spies 1991a).

Researchers next developed criteria that could better accommodate the inherent variability of these old-growth stands. Using data from mature (80–199 years) and old (> 200 years) plots, successive iterations of criteria were tested for their ability to distinguish among these stands (Franklin and Spies 1991a). New minimum standards were developed for a smaller number of attributes: large trees, shade-tolerant associates, snags, and log biomass (Table 7). The revised criteria successfully identified over 80% of stands older than 200 yr. The U.S. Forest Service has since developed quantitative definitions for four forest regions, covering the Pacific Northwest, the Rocky Mountains, and Alaska (e.g., Capp et al. 1992; Fierst et al. 1992, Green et al. 1992, Mehl 1992).

The B.C. Ministry of Forests Research Branch examined the applicability of old-growth criteria used by the U.S. Forest Service. They compared data from different Coastal Western Hemlock (CWH) and Interior Douglas-fir (IDF) site associations to US criteria developed for similar sites. Few old stands (stands >150 years for IDF and > 200 years for CWH) in British Columbia met the U.S. criteria (Hamilton and Nicholson 1991). The authors con-cluded that site-specific, quantitative criteria for this province would have to be developed.

Unfortunately, since Hamilton and Nicholson (1991) released their report, very little work has been undertaken. In one exception, Quesnel (1996) investigated 26 old stands in southeast British Columbia. He examined density of three size classes of large live trees, tree height, and basal area. Quesnel (1996) found that only 6 of the 26 stands were within one standard deviation of the mean value (his criterion for comparing among stands) for all attributes. However, since Quesnel did not sample mature stands, there is no way to evaluate whether his criteria are effective for distinguishing old-growth from mature stands. More recently, Gulyas et al. (1998) compiled structural data from forest cruise plots located across the province, but no attempt was made to use these data to develop structural definitions for old growth. These data include limited information on snags and no information on coarse woody debris, canopy gaps, or understory vegetation. Nonetheless, they would allow preliminary evaluation of quantitative definitions, similar to those of Quesnel (1996), over a much broader range of forest types.

Elsewhere in this issue of *Natural Areas Journal*, Kneeshaw and Burton (1998) propose and evaluate quantitative definitions for some Sub-Boreal Spruce zone forests of central British Columbia, based on demographics and stand structure. They were successful in defining old-growth stands and distinguishing old-growth from mature stands, although their results were sensitive to the method used.

Old-Growth Indices

Although old-growth definitions based on minimum criteria have been demonstrated to effectively identify old-growth stands,

Table 7. Best-performing revision of the interim definition of old growth for Western Hemlock Series stands (modified from Franklin and Spies 1991a).

Stand Characteristic	Criteria
Live trees	All species >100 cm dbh (≥ 10 ha^{-1})
Shade-tolerant associates	> 40 cm dbh (≥ 10 ha^{-1})
Snags	>50 cm dbh and >5 m tall (≥ 4 ha^{-1})
Log biomass	30 Mg ha^{-1}

these definitions nonetheless have serious limitations. To represent natural variation among old-growth stands of a given forest type while excluding younger forest stages, definitions based on minimum criteria necessarily use a small subset of the possible old-growth attributes. Some features of old growth that are important for habitat or forest ecosystem function probably are excluded from such definitions. The dichotomous distinction between "old growth" and "not old growth" drawn by these definitions is somewhat arbitrary.

Shortcomings of definitions based on minimum criteria led Spies and Franklin (1988) to propose an "index of old-growthness" or structural diversity that incorporates many different attributes of old growth. This structural diversity index is based on the developmental trajectories of stand attributes, such as snags, large trees, and down logs, during stand development (Figure 1). These structural attributes are given scores based on their abundance, density, or biomass. The scores are summed across attributes to produce an index that can be used to compare stands. Relatively old stands with many old-growth characteristics receive high scores for each attribute and thus produce high index values. Younger stands with few old-growth characteristics produce low index values; stands that fail to reach some minimum index score are not considered old growth. While this approach still implies a threshold, it more effectively represents the variability among old-growth stands than do minimum criteria definitions because the threshold could be met by various means. A given index score can be achieved by different combinations of attributes, as opposed to the fixed standards of minimum criteria definitions. By incorporating appropriate traits, indices also make it possible to distinguish among younger old-growth stands and the ancient forests described in Appendix 1 (see also Figure 1). It may be important to distinguish among degrees of "old-growthness" to achieve particular management goals, because particular components of old-growth communities continue to develop even after stands have entered the old-growth stage. For example, in the Interior Cedar Hemlock zone of B.C., higher numbers of arboreal lichen species occur in older old-growth stands than in younger old-growth stands (Goward 1993).

Franklin and Spies (1991a) tested their indexing approach by developing a specific index for Douglas-fir stands from sites in western Washington and Oregon, and tested it over a range of stand ages to determine the utility of this system for defining old growth. The index incorporated five structural attributes: crown decadence, density of large trees, density of shade-tolerant trees, density of snags, and log biomass. A plot of the results (Figure 3) demonstrates both a threshold at approximately 300 years and the general variability of structural characteristics among even very old stands; the general pattern is what one would expect from the combination of curves 1 and 2 of Figure 1. Franklin and Spies (1991a) found this combination of attributes to be very effective in distinguishing relative old-growthness even when applied to a large number of stands from the Washington and Oregon Cascade Range and Oregon Coast Range.

Another index developed through the U.S. Forest Service demonstrated the utility of an index in assessing unmanaged forests of all ages for habitat quality. Forest Service researchers evaluated forest stands in Medicine Bow National Forest using a scoring system. They found that successional stages determined by these index scores correlated well with presence of small mammal species that are known to be associated with those stages (Raphael et al. 1989).

Kneeshaw and Burton (1998) also propose an index for Sub-Boreal Spruce zone forests in central British Columbia. Except for this case, indices of old-growth attributes have not been evaluated for British Columbian forests; however, we believe they are a potentially useful tool for comparing forest structure among managed and unmanaged forests of all ages. An index of this type could also provide managers with a tool for incorporating into forest management conservation objectives based on structural criteria. Target scores for an attribute (e.g., density of snags) could be set by reference to a sample of old-growth stands in an area. Managers could then assess the potential for younger stands to provide some old-growth habitat by comparing the scores of these younger forests to the scores of the old-growth stands.

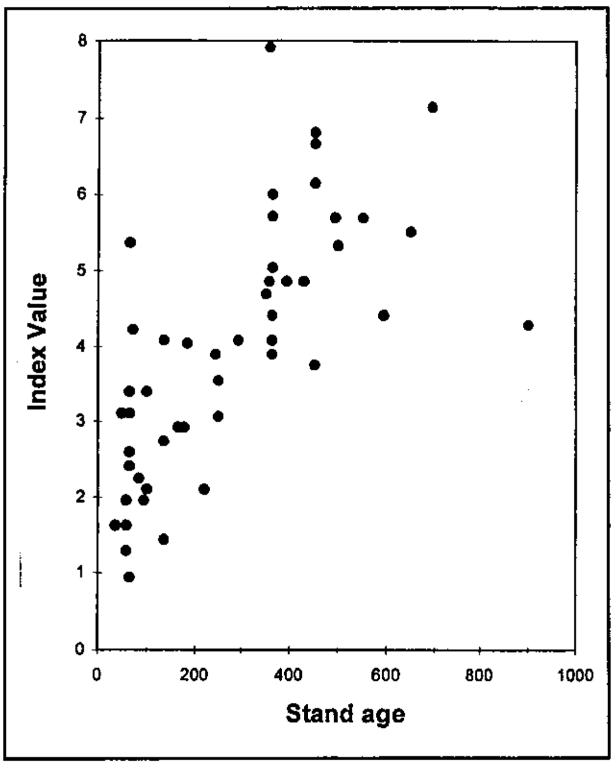

Figure 3. Test of a forest structure index for degree of old-growth development. Using data from natural forest stands in the Cascade Range of southern Washington, this index incorporates Douglas-fir crown decadence, density of all trees > 80 cm dbh., density of shade-tolerant trees > 40 cm dbh., density of large snags, and log biomass (from Franklin and Spies 1991a). Note that the index values form a shape that approximates the pattern expected from a combination of curves 1 and 2 in Figure 1.

Minimum-Criteria versus Index Based Approaches

Quantitative definitions based on minimum criteria are probably most useful as a tool for managers undertaking inventories of old growth. A relatively small number of field measurements is required to determine if a stand meets the minimum standards for a particular category of habitat or forest development. Because these criteria are unambiguous, results of field surveys are easy to interpret.

The indexing approach, however, has a number of advantages over definitions based on minimum criteria. Indices can incorporate the spatial and temporal variation that forests exhibit and can allow for different degrees of old-growth character rather than discretely categorizing a stand as either old growth or not old growth. Indices summarize a wide range of information about a stand's attributes. The database from which indices are calculated can be used in other management activities, such as evaluation of wildlife habitat.

Working Definitions

Working definitions are required as interim measures for identifying old growth in the absence of comprehensive quantitative definitions. Although, as we have noted, preliminary quantitative definitions are being developed for some forest regions in British Columbia, in most cases, current inventory data are insufficient for development of these definitions.

The Old-Growth Strategy process resulted in minimum age criteria for the different forest types in British Columbia (Table 8). These age criteria were developed by experts and intended to be inclusive definitions (i.e., identifying all forests of a given type that could have developed old-growth characteristics as well as some stands that have not yet developed these characteristics). Using age criteria also has the advantage of including only forests that have not been affected by wide-scale human disturbance. This idea of "original forest," in and of itself, fits some peoples' concept of old growth, and naturally disturbed and regenerated forests of various ages merit special attention in conservation and management. Inventories developed by inclusive criteria should be treated cautiously because they may provide inflated impressions of the amount of old growth within an area.

The purpose of an old-growth inventory and the goals of those undertaking it will determine which criteria are appropriate for use in defining old growth. Inventories undertaken using different criteria (e.g., different classes of age, height, or forest productivity) will necessarily yield different or conflicting results. When the Sierra Club of Western Canada (1991) presented its inventory of old growth for Vancouver Island, the results differed from those estimates of remaining old growth calculated by the B.C. Ministry of Forests. The Sierra Club estimated that 0.83 million ha of "ancient and mature forests" remained on Vancouver Island (Sierra Club of Western Canada 1991). This calculation was based on exclusive criteria for delineating old growth. The inventory excluded higher elevation mountain hemlock forests and "bog or marginal forests" (i.e., low-elevation, wetland forests) and focused on the forests that the Sierra Club considered to be under the greatest threat from logging (i.e., those on lower elevation, higher productivity sites). Thus, the inventory did exclude some very old forests. In contrast, the Ministry of Forests calculated that 1.48 million ha of "mature forest" remained on Vancouver Island (B.C. Ministry of Forests 1991). The B.C. Ministry of Forests inventory was based on inclusive criteria in order to incorporate all "original" forest, much of which was likely well over the 200-year minimum age criterion of the Old-Growth Strategy (A. MacKinnon, manager of forest ecology research, B.C. Ministry of Forests Research Branch, Victoria). Thus, the difference between the estimates made by these two groups resulted from the different criteria used. There are good arguments for using either an inclusive (such as the B.C. Ministry of Forests old-growth inventory) or exclusive (such as the Sierra Club inventory) approach, depending on what one wishes to learn from an inventory. However, care must be taken when comparing estimates from different inventories, and the results must be interpreted in the context of the assumptions built into the analysis.

More recently, MacKinnon and Vold (1998) were able to develop a provincial inventory of old-growth forests in British Columbia using age criteria as a working definition for old growth. While they were also able to examine the influence of tree height within some regions, working definitions appropriate for use with provincial databases remain primarily limited to age. The authors point out that even very basic information such as elevation or ecosystem classification cannot currently be incorporated into working definitions because, even when available, they are not compiled in a manner that allows province-wide statistics to be determined.

BEYOND THE STAND LEVEL

Typically old growth is considered to be stand level in nature, and the old-growth definitions discussed so far are based on stand-level attributes or characteristics. A few researchers have proposed age-based definitions based upon the natural disturbance interval of a landscape (Achuff 1989, Hunter 1989, Johnson 1995), but these landscape-based definitions are limited by difficulties in accurately determining natural disturbance intervals. More significantly, this approach is very relative: that is, the threshold age for old-growth status will be highly sensitive to the specific area for which the natural disturbance interval has been determined. Nonetheless, old growth does exist within the context of a landscape mosaic of different developmental stages, shaped by natural disturbance regimes and by management activities. This mosaic should be considered when evaluating the old-growth status of a landscape.

The degree of fragmentation of old growth is one landscape-level characteristic that we may wish to consider when undertaking old-growth inventories. Fragmentation results in edge effects, which can influence stand structure to the point that affected areas may not be considered old growth. Biotic and microclimatic edge effects can penetrate to the center of small forest fragments resulting in increased rates of nest predation, increased blowdown, and greater variation in temperature and moisture (Saunders et al. 1991). Chen et al. (1992) detected environmental changes leading to significant vegetation responses from 16 m to 137 m from the forest edge in old-growth Douglas-fir forests. If areas influenced by such edge effects are excluded from inventories of old-growth forest, estimates of the total amount of old growth can be substantially reduced in comparison with estimates based solely on stand-level criteria. For example, Morrison (1988) excluded strips of forest within 120 m of a road or clearcut, and stands smaller than 30 ha, from an inventory of old-growth forests in Oregon and Washington. This reduced the estimation of interior old growth by 38% compared to the total area identified using minimum stand-level criteria of the Old Growth Definition Task Group (Morrison 1988).

Quantitative measures of landscape-level structure such as the size, distribution, and contiguity of old-growth stands are available (e.g., Turner 1989), and studies have used these tools to analyze the structure of some forested landscapes. For example, Rogers (1993) analyzed the structure of forested landscapes in and near the Kamloops Forest Region of British Columbia, and others have analyzed forested landscapes in the U.S. Pacific Northwest (e.g., Young et al. 1993, Spies et al. 1994).

Landscape-level management activities such as fire suppression also can result in stand-level changes to forest structure and composition to the point where standard quantitative definitions developed for a stand may no longer usefully describe that stand. For example, old-growth ponderosa pine forests of the southern interior of British Columbia were historically dominated by frequent low-intensity ground fires resulting in an understory that was relatively depauperate in vegetation and dead wood. With reductions in fire frequency, fewer fire-tolerant species invade the forest understory, changing forest structure and, eventually, the species composition of the canopy layer (Habeck 1990). In cases such as these, quantitative definitions can form a baseline from which change in old-growth structure can be detected and monitored, if appropriate attributes are included in the definitions.

Table 8. Working definitions of old growth (using minimum age criteria) for broad forest-cover types in Britsh Columbia. Forests younger than this age are unlikely to be considered old growth (from B.C. Ministry of Forests 1992).

Tree Species	Common Name	Major Forested Biogeoclimatic Zone[a]	Minimum Age (yr)
Coastal Coniferous Types			
Abies amabilis	amabilis fir	CWH, MH	200
Abies lasiocarpa	subalpine fir	MH	200
Chamaecyparis nootkatensis	yellow-cedar	CWH, MH	200
Picea sitchensis	Sitka spruce	CWH	150
Pseudotsuga menziesii	Douglas-fir	CDF, CWH	150
Thuja plicata	western redcedar	CDF, CWH	150
Tsuga heterophylla	western hemlock	CWH, MH	150
Tsuga mertensiana	mountain hemlock	MH	200
Interior Coniferous Types			
Abies lasiocarpa	subalpine fir	all but IDF, PP	200
Larix lyallii	alpine larch	ESSF	200
Larix occidentalis	western larch	ICH, IDF, MS	150
Picea engelmannii	Engelmann spruce	ESSF, MS	150
Picea engelmannii x *glauca*	hybrid white spruce	ICH, IDF, SBS	150
Picea glauca	white spruce	BWBS, SWB	150
Pinus albicaulis	whitebark pine	ESSF, PP	200
Pinus contorta	lodgepole pine	all	120
Pinus monticola	western white pine	CWH, ICH	150
Pinus ponderosa	ponderosa pine	IDF, PP	150
Pseudotsuga menziesii	Douglas-fir	ICH, IDF, MS, PP, SBS	150
Thuja plicata	western redcedar	ICH, IDF	150
Tsuga heterophylla	western hemlock	ICH	150

[a]Forested biogeoclimatic zones (Meidinger and Pojar 1991); see Table 5 for full names, except SWB = Spruce Willow Birch zone.

CONCLUSIONS

One important conclusion we draw from this discussion of old-growth definitions is the idea that a single, precise definition of old growth applicable to all forest types is neither possible nor desirable. Old-growth forests display significant variability within and among forest types and are composed of many different components that develop along a continuum over time, with considerable overlap between stages of stand development. Further, a single definition of old growth is undesirable because the usefulness of a given definition depends on the purpose for which it is designed. For example, broad, inclusive definitions such as age-class-based working definitions are required to allow short-term province-wide inventories, but are of limited use beyond that. Conversely, detailed, forest-type-specific definitions are required to design appropriate management and conservation activities for old growth of specific forest types.

Although it is not possible to present a single definition of old growth that is both precise and accurate, we propose that forests in which gap processes predominate have attained functional old-growth status. However, direct measures do not currently exist that indicate whether or not gap processes predominate in an individual stand. Therefore, we suggest that definitions of old growth should incorporate the distinct structural character of these forests. Currently, structural definitions are the ones most likely to define the broadest range of forests that are consistent with our gap-dynamics-based definition of old growth. For some forest types, such as some non-coastal spruce forests of British Columbia, population-based definitions may also be good indicators that gap processes predominate in these stands.

We have presented the conceptual definition of old growth for British Columbia proposed by the Forest Land Use Liaison Committee. This definition is based on the distinctive structural characteristics that derive from the gap processes of old forests. Although we feel that this definition would be strengthened by the addition of an explicit reference to gap dynamics, we believe the FLULC definition remains the best conceptual definition proposed for British Columbian forests.

Quantitative definitions have yet to be developed for most forest types in British Columbia. This lack of progress is unfortunate and is hampering current management initiatives for old growth in the province. Minimum structural criteria have been shown elsewhere to be useful in distinguishing old growth of different types from earlier stages of forest development. Alternatively, indices of forest structure and composition that indicate the degree of development of old-growth characteristics have been developed. We find the use of indices compelling because they capture the inherent variability of structural characteristics among old-growth stands, differences between forest types, and differences among developmental stages of old growth. Indices also have the advantage of not only identifying old-growth stands, but also identifying stands that may not yet qualify as old growth but that have many old-growth attributes that are important for other management objectives.

Definitions using criteria based on minimum age and height are currently the only ones available for calculating a British Columbian inventory from existing forest data. The province has chosen inclusive age and height criteria for inventory purposes such that stands younger than those identified by these criteria are unlikely to contain old growth. While such inclusive criteria are useful for identifying the area of older forests in this province, these criteria will undoubtedly produce inventory estimates that are higher than those derived by more stringent quantitative criteria.

Future research should be directed toward improving the understanding of the gap-dynamic processes of old-growth forests so that better indicators of the gap-phase status of forests can be developed. Further, quantitative descriptions of the structural characteristics of the different late-successional forest types in British Columbia would allow the testing of conceptual definitions and development of type-specific quantitative definitions. The continuing paucity of basic information on characteristics of old-growth forests in British Columbia limits the ability of managers to determine the total area and the locations of specific types of old-growth forest, and to develop appropriate management goals and methods for them.

ACKNOWLEDGMENTS

We thank two anonymous reviewers for helpful commonts on an earlier draft of this paper and Andy MacKinnon, Gerry Still, Linda Hannah, and Risa Smith for their reviews of a report upon which this paper is based. We are especially grateful to Andy MacKinnon for his continuing support, ideas, and thoughtfulness throughout this project. The artwork of Water Wells used in drafting Figures 1 and 2 is gratefully acknowledged. We thank the Research Branch of the B.C. Ministry of Forests for financial support. Some of the ideas presented in this paper arose from work in Ken Lertzman's research lab, supported by the Natural Sciences and Engineering Research Council of Canada and Forest Renewal B.C. This paper represents research report number R-26 of the Centre for Applied Conservation Biology, University of British Columbia.

Ralph W. Wells is research scientist with the Centre for Applied Conservation Biology (CACB), University of British Columbia. He studied the dynamics of stand development in coastal temporate forests of British Columia as part of his Masters research at Simon Fraser University. Currently, he is studying species-habitat relationships for cavity-nesting birds, with emphasis on evaluating the effects of forest havesting on these species.

Ken Lertzman is associate professor in the School of Resource and Environmental Management, Simon Fraser University. He studies natural disturbance regimes and how they shape forest dynamics at various scales. His current research focuses on analyzing fire history in a landscape context and applying the results to forest conservation and management.

Sari Saunders recently completed her Ph.D. at Michigan Technological University, where she studied landscape ecology, focusing on a cross-scale analysis of microclimate in boreal forest landscape.

LITERATURE CITED

Agee, J.K. 1991. Fire history of Douglas-fir forests in the Pacific Northwest. Pp. 25-33 *in* L.F. Ruggiero, K.B. Aubry, A.B. Carey, and M.H. Huff, tech. coords., Wildlife and vegetation of unmanaged Douglas-fir forests. General Technical Report PNW-GTR-285, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Ore.

Alaback, P.B. 1984. A comparison of old-growth and second-growth forest structure in the western hemlock-Sitka spruce forests of southeast Alaska. Pp. 219-226 *in* W.R. Meehan, T.R. Merrell, and T.A. Hanley, eds., Symposium proceedings, American Institute of Fishery Research Biologists, Juneau, Alaska.

Arsenault, A. 1995. Pattern and process in old-growth temperate rainforests of southern British Columbia. Ph.D. diss., University of British Columbia, Vancouver, Canada.

Arsenault, A. and G.E. Bradfield. 1995. Structural-compositional variation in three age-classes of temperate rainforests in southern coastal British Columbia. Canadian Journal of Botany 73:54-65.

B.C. Ministry of Forests. 1989. Towards an old-growth strategy. Unpublished, submissions to workshop, Parksville, B.C., Canada, November 3-5.

B.C. Ministry of Forests. 1991. Vancouver Island's forests. B.C. Ministry of Forests, Inventory Branch, Victoria, Canada.

B.C. Ministry of Forests. 1992. An old-growth strategy for British Columbia. B.C. Ministry of Forests, Victoria, Canada.

Capp, J., B. Van Zee, P. Alaback, J. Boughton, M. Copenhagen, and J. Martin. 1992. Ecological definitions for old-growth forest types in south-east Alaska. R10-TP-28, U.S. Department of Agriculture, Forest Service, Alaska Region.

Chen, J., J.F. Franklin, and T.A. Spies. 1992. Vegetation responses to edge effects in old-growth Douglas-fir forests. Ecological Applications 2:387-396.

DeBell, D.S. and J.F. Franklin. 1987. Old-growth Douglas-fir and western hemlock: a 36-year record of growth and mortality. Western Journal of Applied Forestry 2:111-114.

Fierst, J., D. White, J. Allen, T. HIgh, and S. Green. 1992. Interim old-growth definition for Douglas-fir series. U.S. Department of Agriculture, Forest Service, Region 6, Portland, Ore.

Forest Land Use Liason Committee of British Columbia. 1989. Interim statement: Forest Land Use Liaison Committee consensus statement on old-growth forests. Forest Land Use Liaison Committee of B.C., Vancouver, Canada.

Franklin, J.F., K. Cromack Jr., W. Denison, A. McKee, C. Maser, J.Sedell, F. Swanson, and G. Juday. 1981. Ecological characteristics of old-growth Douglas-fir forests. General Technical Report PNW-118, U.S. Department of Agriculture, Forest Service, Portland, Ore.

Franklin, J.F. and T.A.Spies. 1991a. Ecological definitions of old-growth Douglas-fir forests. Pp. 61-69 *in* L.F. Ruggiero, K.B. Aubry, A.B. Carey, and M.H. Huff, tech. coords., Wildlife and vegetation of unmanaged Douglas-fir forests. General Technical Report PNW-GTR-285, U.S. Department of Agriculture, Forest Service, Portland, Ore.

Franklin, J.F. and T.A.Spies. 1991b. Composition, function, and structure of Old-growth Douglas-fir forests. Pp. 71-80 *in* L.F. Ruggiero, K.B. Aubry, A.B. Carey, and M.H. Huff, tech. coordrs., Wildlife and vegetation of unmanaged Douglas-fir forests. General Technical Report PNW-285, U.S. Department of Agriculture, Forest Service, Portland, Ore.

Gavin, D., K.P. Lertzman, L. Brubaker, and E. Nelson. 1996. Long-term fire histories in a coastal temperate rainforest. Bulletin of the Ecological Society of America 77(3):157.

Gavin, D., K.P. Lertzman, L.B. Brubaker, and E. Nelson. 1997. Holocene fire size and frequency in a coastal temperate rainforest. Bulletin of the Ecological Society of America 78(4):93.

Goward, T. 1993. Crown of the ICH: epiphytic macrolichens of old-growth forests in the Interior Cedar-Hemlock zone. Bioline 11:15-17.

Gulyas, G., T.J. Elm and P. Ackhurst. 1998. Structural attributes of forest stands. Contract report prepared for Forest Practices Branch, B.C. Ministry of Forests. Simon Reid Collins, Vancouver, B.C., Canada.

Habeck, J.R. 1988. Old-growth forests in the northern Rocky Mountains. Natural Areas Journal 8:202-211.

Habeck, J.R. 1990. Old-growth ponderosa pine-western larch forests in western Montana: ecology and management. Northwest Environmental Journal 6:271-292.

Hamilton, E. and A. Nicholson. 1991. Defining British Columbia's old-growth forests: discussion paper. Draft paper, B.C. Ministry of Forests, Research Branch, Victoria, Canada.

Hunter, M.L. Jr. 1989. What constitutes an old-growth stand? Journal of Forestry 87:33-35.

Juday, G.P. 1988. Old-growth forests and natural areas: an introduction. Natural Areas Journal 8:4-6.

Kneeshaw, D. and P.J Burton. 1998. Assessment of functional old-growth status: a case study in the Sub-Boreal Spruce zone of British Columbia, Canada. Natural Areas Journal 18:293-308.

Lertzman, K.P. 1992. Patterns of gap-phase replacement in a subalpine, old-growth forest. Ecology 73:657-669.

Lertzman, K.P. and C.J. Krebs. 1991. Gap-phase structure of a subalpine old-growth forest. Canadian Journal of Forest Research 21:1730-1741.

Lertzman, K.P., G. Sutherland, A. Inselberg, and S. Saunders. 1996. Canopy gaps and the landscape mosaic in a temperate rainforest. Ecology 77:1254-1270.

Lertzman, K.P. and J. Fall. 1998. From forest stands to landscape: the impacts of disturbance. Pp. 339-367 *in* D. Peterson and V.T. Parker, eds., Scale Issues in Ecology. Columbia University Press, New York.

MacKinnon, A. and T. Vold. 1998. Old-growth forests inventory for British Columbia, Canada. Natural Areas Journal 18:309-318.

Mehl, M.S. 1992. Old-growth descriptions for the major forest cover types of the Rocky Mountain Region. Pp. 106-120 *in* M.R. Kaufmann, W.H. Moir, and R.L. Basset, tech. coords., Old-growth forest in the Rocky Mountains and Southwest conference, Portal, Arizona, March 9-13, 1992. General Technical Report RM-213, U.S. Department of Agriculture, Forest Service, Fort Collins, Colo.

Meidinger, D. and J. Pojar (eds.). 1991. Ecosystems of British Columbia. Special Report, Series 6, B.C. Ministry of Forests, Research Branch, Victoria, Canada.

Morrison, P.H. 1988. Old growth in the Pacific Northwest: a status report. The Wilderness Society, Alexandria, Va.

Nicholson, A. and E. Hamilton. 1990. Old growth forest: problem analysis. B.C. Draft paper, Ministry of Forests Research Branch, Victoria, Canada.

Old Growth Definition Task Group. 1986. Interim definitions for old-growth Douglas-fir and mixed-conifer forests in the Pacific Northwest and California. Research Note PNW-447, U.S. Department of Agriculture, Forest Service, Portland, Ore.

Oliver, C.D. 1981. Forest development in North America following major disturbances. Forest Ecology and Management 3:152-168.

Oliver, C.D. and B.C. Larson. 1996. Forest Stand Dynamics (Update Ed.). John Wiley and Sons, New York. 520 pp.

Peet, R.K. and N.L. Christensen. 1987. Competition and tree death. BioScience 37:586-595.

Pojar, J., E. Hamilton, D. Meidinger, and A. Nicholson. 1992. Old growth forests and biological diversity in British Columbia. Pp. 85-97 *in* G.B.Ingram and M.R. Moss, eds., Proceedings of the Second Symposium of the Canadian Society for Landscape Ecology and Management, University of British Columbia, May 1990.

Pojar, J. and A MacKinnon (eds.). 1994. Plants of Coastal British Columbia. Lone Pine Press, Edmonton, Alta, Canada.

Quesnel, H.J. 1996. Assessment and characterization of old-growth stands in the Nelson Forest Region. Technical Report TR-013, B.C. Ministry of Forests, Forest Sciences Section, Nelson Forest Region, Nelson, B.C., Canada.

Raphael, M.G., S.L. Marquardt, and R.H. Barrett. 1989. Evaluating stand conditions to support integrated silvicultural prescriptions for timber and wildlife: snags and old-growth. Paper presented at Habitat Futures Workshop, Charles L. Pack Experimental Forest, Eatonville, Washington, October 16-20, 1989.

Rogers, C.A. 1993. Describing landscapes: indices of structure. Master of Natural Resource Management Report, Simon Fraser University, Burnaby, B.C., Canada.

Rolston, H. III. 1989. Values deep in the woods. Trumpeter 6:39-45.

Runkle, J. R. 1981. Gap regeneration in some old-growth forests of the eastern United States. Ecology 62:1041-1051.

Saunders, D.A., R.J. Hobbs, and C.R. Margules. 1991. Biological consequences of ecosystem fragmentation: a review. Conservation Biology 5:18-32.

Sierra Club of Western Canada. 1991. Ancient rainforests at risk. Final report of the Vancouver Island mapping project, Sierra Club of Western Canada, Victoria, B.C., Canada.

Spies, T.A. and J.F. Franklin. 1988. Old growth and forest dynamics in the Douglas-fir region of western Oregon and Washington. Natural Areas Journal 8:190-201.

Spies, T.A. and J.F. Franklin. 1996. The diversity and maintenance of old-growth forests. Pp. 296-314 *in* R. Szaro and D. Johnson, eds., Biodiversity in Managed Landscapes: Theory and Practice. Cambridge University Press, Cambridge, England.

Spies, T.A., J.F. Franklin, and M. Klopsch. 1990. Canopy gaps in Douglas-fir forests of the Cascade Mountains. Canadian Journal of Forest Research 20:649-658.

Spies, T.A., J.F. Franklin, and T.B. Thomas. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology 69:1689-1702.

Spies, T.A., W.J. Ripple, and G.A. Bradshaw. 1994. Dynamics and pattern of a managed coniferous forest landscape in Oregon. Ecological Applications 4:555-568.

Turner, M.G. 1989. Landscape ecology: the effect of pattern on process. Annual Review of Ecology and Systematics 20:171-197.

Tyrrell, L.E. and T.R. Crow. 1994. Structural characteristics of old-growth hemlock-hardwood forests in relation to age. Ecology 72:370-386.

Wells, R.W. 1996. Developmental trends of stand structure and tree mortality in coastal western hemlock forests. Master of Natural Resource Management Report, Simon Fraser University, Burnaby, B.C., Canada.

Young, J.A., W.A. Heise, K.B. Aubry, and J.F. Lehmkuhl. 1993. Development and analysis of a landscape-level GIS database to assess wildlife use of managed forests. Pp. 541-547 *in* Polaris Conferences, ed., Proceedings of 7th Annual Symposium on GIS in Forestry, Environment, and Natural Resources Management, Vancouver, British Columbia, February 15-18, 1993.

Appendix 1. "Ancient" Forests

Long intervals between catastrophic disturbances and the presence of species with great longevity produce forests that can legitimately be considered "ancient." The best known examples of such forests are the Douglas-fir and Sitka spruce forests of the southern coastal region of British Columbia, which established after fires, flooding, or windstorms mostly between 200 and 1,000 years ago. In these forests, individual trees from 600 to 1,000 years old are not uncommon, and individuals of several taxa can be found regularly with ages exceeding 1,000 years. Less well understood, but more common in the northern coastal area, are ancient forests where individual trees may only be 200–500 years old, but the forest itself is much older. This can occur when the late successional species, such as western hemlock, are not as long lived as their early successional counterparts (like Douglas-fir or Sitka spruce). Because the hemlocks established and grew in an established forest, a stand of 500-year-old hemlocks may in fact represent millennia of forest development. Large-scale fires may only occur every few millennia. Such ancient forests commonly occur in wet coastal areas where fires virtually never occur (Gavin et al. 1996, 1997) and the forest develops over many centuries through the slow, individual-by-individual replacement of trees. These forests also frequently occur at moderate to high elevations on good sites where wet summers combine with persistent spring snowpacks (and consequent snowmelt) to reduce the likelihood of fire. It is likely that the oldest individual trees in the Northern Pacific Coast region are yellow-cedars growing in such circumstances: individual trees are frequently found to be more than 1,000 years old and live to be much older than that (Pojar and MacKinnon 1994).

Appendix 2. Why does so much variation exist within and among forest types?

British Columbia extends over 11 degrees of latitude and 25 degrees of longitude, encompassing a huge range of physical variables that influence tree growth. Broad geoclimatic differences occur in factors such as temperature, precipitation, and soil. These variables affect forest structure and composition of a region, directly through the growth environment created, as well as indirectly by influencing disturbance regimes. On the west coast of Vancouver Island, for example, high levels of rainfall ensure that stand-destroying fires are relatively rare. As a result, in many areas of this region individual tree mortality significantly affects forest structure for very long periods of time (see Figure 2). Many of these forests are old for old growth and could be considered truly ancient (see Appendix 1). Although large-scale fires are rare, disturbances do occur on the west coast of Vancouver Island. For example, localized windthrow is common, and the dramatic stands of old-growth Sitka spruce in this region develop in the wake of periodic floods. The east side of Vancouver Island, on the other hand, is in the rain shadow of the central island mountains, and fires are more common, favoring Douglas-fir forests.

Local variation in abiotic components of the environment, such as slope, aspect, and elevation, can significantly influence soil moisture and sun exposure. This variability affects species dominance and growth rates and influences susceptibility to different types of disturbance. For example, a well-drained slope with southern exposure would be drier and more susceptible to fire than a valley bottom with northern exposure. Variation also occurs among different sites of a given forest type due to patchy disturbances. Finally, soil productivity varies among sites, affecting tree growth and size.