# ARCHITECTURAL ANALYSIS OF DOUGLAS-FIR FORESTS



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#### ABSTRACT

Kuiper, L.C. (1994). Architectural analysis of Douglas-fir forests. PhD thesis, Wageningen Agricultural University, The Netherlands, 186 pp, 62 figs., 18 tables, 342 refs., 62 terms in glossary, English and Dutch summaries. ISBN 90-5485-254-2

The architecture of natural and semi-natural Douglas-fir forest ecosystems in western Washington and western Oregon was analyzed by various case-studies, to yield vital information needed for the design of new silvicultural systems with a high level of biodiversity, intended for low-input sustainable forest management. In view of the discussions on the necessity of thinning in Douglas-fir plantations, thinning experiments in Germany and The Netherlands were analyzed by studying the distribution of various stemcrown- and increment parameters of individual trees, assigned to different social crown classes. Furthermore, the structural root system and the crown perimeter of 21 Douglas-fir trees were mapped to study relationships between root system structure and size, and stem and crown diameter and growing space, all of which relevant to tree stability. In the final chapter forty-three theorems are listed to discuss the hypotheses of the introductory chapter, and elements for the design of new silvicultural systems for Douglas-fir are presented.

### BIBLIOTHEEN LANDBOUWUNIVERSZENT WAGENINGEN

#### CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Kuiper, L.C.

Architectural analysis of Douglas-fir forests / L.C. Kuiper. - [S.l. : s.n.]. - Ill. Thesis Wageningen. - With ref. - With summary in Dutch. ISBN 90-5485-254-2 Subject headings: Douglas-fir / forestry / biodiversity ; forests.

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#### STELLINGEN

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1. De douglasspar is in staat om zich op successolle wijze te ontwikkelen in meerjarige opstanden, hetgeen een veel wijdere "bosteeltkundige amplitude" veronderstelt, dan in de praktijk doorgaans wordt toegepast.

(dit proefschrift).

 De diversificatie van het kronendak en de voortdurende initiatie en ontwikkeling van een groot aantal bosverjongings-eenheden, die uit schaduwverdragende boomsoorten zijn opgebouwd, tonen het belang aan van kleinschalige "verstoringen" binnen de dynamiek van natuurlijke douglasbossen.

(dit proefschrift).

3. Een case-study van een meer dan 1000 jarige bosopstand, waarin de douglas, als secundaire pionierssoort, ten minste twee generaties van de "climaxsoort" *Tsuga heterophylla* heeft overleefd, maakt een successie-theorie voor de douglas discutabel.

(dit proefschrift).

- 4. Als de uitbreiding van het douglas-areaal, zoals dat werd gerealiseerd in de eerste vijf jaren van het Meerjarenplan Bosbouw, maatgevend is voor het zojuist verschenen Bosbeleidsplan, dan zal er een struktureel tekort ontstaan aan hoogwaardig zaaghout uit het Nederlandse bos.
- Eén hectare geirrigeerde tuinbouw in de Soudano-Sahelzone van Kameroen verbruikt zoveel water, dat daarmee de dagelijkse waterbehoefte van ongeveer 2000 mensen in gevaar komt.
- 6. Gezien het ontbreken van daadkrachtige NGO's in veel west-Afrikaanse landen, zouden internationale organisaties op het gebied van ontwikkelingssamenwerking strategiën moeten ontwikkelen om binnen corrupte overheidsdiensten toch efficiënt te kunnen werken.
- 7. Sektoriële inspanningen op het gebied van ontwikkelingssamenwerking resulteren in het algemeen in een toenemende afhankelijkheid van donoren.
- Als beleggingsfondsen voor teakhout op Costa Rica hun clienten na 20 jaar een rendement van meer dan 20 procent voorspiegelen, dan getuigt dit van onvoldoende inzicht in de ervaringen die elders zijn opgedaan met tropische hardhoutplantages<sup>1</sup>).

<sup>1</sup>) Evans, J. 1992: Plantation Forestry in the Tropics, Oxford, 403 p.

9. Indien het waar is dat de mens slechts 15 % van zijn verstandelijke vermogens op een bewuste wijze benut <sup>2</sup>), dan zou elke onderwijsinstelling moeten overwegen om zowel bij staf als studenten die overige 85 % van het bewustzijn systematisch tot ontwikkeling te brengen.

<sup>2</sup>) Wallace, R.K. et al. 1972: The physiology of meditation. Scientific American 226: 84-90.

- 10. De kracht van aangepaste technologie zit hem in de beperking die je jezelf oplegt bij de toepassing ervan.
- 11. Het prettige van een baan in de tropen als ontwikkelingswerker is, dat je eens tijd hebt voor een goed boek, of om rustig na te denken over stellingen voor je proefschrift.

Stellingen behorende bij het proefschrift : "Architectural analysis of Douglas-fir forests".

Leen Kuiper, 10 mei 1994

#### PREFACE

In 1982 the decision was taken to study Douglas-fir forests using an architectural approach. The present book gives an overview of the results obtained. Preliminary results of this study have been published in a number of scientific papers, proceedings, journals, reports and students theses in the previous years. In sequential order, referring to the chapters of this paper, the following publications are to be quoted.

Chapter 2 rests upon Kuiper, L.C. 1988a. The structure of natural Douglas-fir forests in western Washington and western Oregon. Wageningen Agricultural University Papers 88-5, 47 p. A comprehensive summary about natural Douglas-fir forests was published in a dutch Forestry Journal: Kuiper, L.C. 1988b. Natuurlijke douglasbossen. Nederlands Bosbouw Tijdschrift 60 (5/6): 72-85. Basic data for both publications came from the MScthesis: Eyndhoven, L. van, Gisbergen, P. van and Kervel, W. 1986. Ontwikkelingen in de structuur van natuurlijke douglasbossen in de Verenigde Staten. Doctoraalverslag 86-28, Vakgroep Bosteelt en Bosoecologie, Landbouwuniversiteit Wageningen, 94 p.

Chapter 3 and 4 have not been published before. However, most of the information about genetic variation of Douglas-fir in chapter 4 was built upon the student report: Beuker, E. 1988. Genetic variation among elevational classes in a mature Douglas-fir stand. Msc. thesis Plant Breeding, Agric. Univ. Wageningen, 19 p.

Chapter 5 is based on two MSc-theses: Burg, R. van de and Weersink, H. 1988. Seminatuurlijke second-growth douglasopstanden in west-Washington. Deel 1: structuuranalyse. Doctoraalverslag 88-18, Vakgroep Bosteelt en Bosoecologie, Landbouwuniversiteit Wageningen, 120 p, and Janssen, P.T.H.M. and Vasseur E.R. 1989. Structuur van second-growth douglasopstanden op relatief arme groeiplaatsen in Washington (USA). Doctoraalverslag 89-28, Vakgroep Bosteelt en Bosoecologie, Landbouwuniversiteit Wageningen, 81 p.

Chapter 6 was published before in German as: Kuiper, L.C. und Dijk, G.J.E. van 1987. Strukturanalyse eines Douglasienstandraumversuchs in Baden-Wuerttemberg. Bericht D87-03 Institut fuer Waldbau und Waldoekologie, Landwirtschaftliche Universitaet Wageningen, 18 p.

Chapter 7 was derived from: Kuiper, L.C. and Schoenmakers, A.L. 1990. Evaluation of a ten year thinning experiment in douglas-fir. in: Oldeman, R.A.A., Schmidt, P. and Arnolds, E.J.M. (eds.). Forest components. Wageningen Agricultural University Papers 90-6: 48-56. This publication was based on the MSc thesis of Schoenmakers, A.L. 1987. Experiment met hoogdunning, laagdunning en niet dunnen in een douglasopstand. Doctoraalscriptie 87-19, vakgroep Bosteelt en Bosoecologie, Landbouwuniversiteit Wageningen, 30 p.

Chapter 8 was published as: Kuiper, L.C. and Coutts, M.P. 1992. Spatial disposition and extension of the structural root system of Douglas-fir. Forest Ecology and Management 47:111-125.

Chapter 9 is an original chapter dealing with discussion and conclusions.

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Maroua, Cameroun, July 1993 Leen Kuiper

"Forest ecosystems may not only be more complex than we think, they may be more complex than we <u>can</u> think" (Frank Egler; in: Dietrich 1993, p.100)

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Figure 1.1: Douglas-fir tree, 87 m tall, just before being cut for display at the Oregon Centennial Exposition at Portland in 1959. Note the size of the people standing at the base of the giant stem (courtesy Loggers Handbook, vol. 19 (1959): p.29).

#### 1. INTRODUCTION

#### Abstract

A review of the literature shows that both in its area of origin and in Europe, Douglasfir is a highly successful tree species, that grows fast, on a wide range of sites, and that is appreciated for its excellent wood. In this paper it is postulated that an architectural analysis of natural Douglas-fir forest ecosystems yields vital information, by comparing codified basic tree and forest characteristics, needed for the design of sustainable silvicultural systems with a high level of biodiversity and consequently low-management inputs ("do less and accomplish more"). This can serve the management of multiple-use Douglas-fir forest plantations. Several assumptions and hypotheses are formulated, to be tested by the case-studies in the following chapters.

#### 1.1 Douglas-fir

Everything seems to be large about Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco):

- in old growth stands tree dimensions of 90 m tall and diameters of 1.5 m wide are no exception (Franklin et al. 1981; Waring 1982; Dietrich 1992; see Figure 1.1);
- tree ages over 1000 years have been reported (Zobel et al. 1976; Hawk et al. 1978);
- Douglas-fir forests, which are among the worlds most productive forest types, at present cover an extended area in the Pacific Northwest of North America of about 5.000.000 ha (Klinka et al. 1981; Waring 1982; Kramer 1983; Harris 1984);
- Douglas-fir has a wide ecological amplitude, allowing it to grow under a variety of growth conditions (Franklin and Dyrness 1973; Keyes and Grier 1981; Otto 1984; Kuiper 1988a; Dong 1970; Bouchon 1982);
- its genetic variation is very large: thus many different provenances can be identified (Hoogh 1925, Silen 1979; El-Kassaby and Sziklai 1982; Merkle and Adams 1987; Rehfeldt 1983; Veen 1951; Kriek 1979; Yeh and O'Malley 1980; Yeh and Heaman 1982; Ruetz and Nather 1987; Larson and Kromann 1983);
- in Europe it is considered one of the most successful exotic species, highly appreciated for its fast growth and good timber quality (Schwappach 1920; Vries 1961; Dominik 1963; Chylaracki 1976; Decourt and Le Tacon 1979; James 1978; Kenk and Hradetzky 1984; Klinka et al. 1981; Oswald and Pardé 1984);

• a tremendous amount of literature on Douglas-fir is available (which is increasing year by year), indicating the growing interest in this species by researchers, silviculturists and forest managers all over the world, who have studied many aspects of its ecology, its soil and climate requirements, its genetics, its propagation, its wood quality and many other issues related to forestry (chapter 2).

All these papers are like pieces of a giant jigsaw puzzle, or rather of many different jigsaw puzzles which do not fit together well. Unfortunately, they fail to give a clear and comprehensive picture of the species in terms of its \*life cycle and its ecological and silvicultural requirements.

The method of architectural analysis as applied in this paper, certainly will not provide the key to put all the existing information together. Yet it has, in many similar studies (Hallé et al. 1978; Oldeman 1990; Walter 1982; Winckel 1980; Kuiper 1988a; Peters 1992) proved to yield valuable information with relevance to \*silviculture as it focusses on tree and forest \*architecture, the development patterns involved and natural rules which govern them. Mayers's profile diagrams of temperate forests are a form of systematic use of such an approach, to codify and compare basic tree and forest characteristics (Mayer 1984).

#### 1.1.1 History

In its area of origin in the Pacific Northwest of the U.S.A. Douglas-fir has played a major role in the development of western Oregon and western Washington, since the area became gradually inhabited by white man after the Lewis and Clark expedition of 1806 (Waring 1982). At that time truly impressive and very extensive old-growth Douglas-fir forests dominated the Pacific Northwest, which originally spanned a north-south distance of 800 km and occupied an area west of the Cascade mountains of approximately 7 million ha (Harris 1984). Natural Douglas-fir forests represented a valuable resource containing large volumes of high quality wood. So their elimination, commonly known as the "railroad loggings", began early and drastically at the end of the 19th and the beginning of the 20th century. In more recent years the characteristic railroad loggings have been largely replaced by cable logging systems and the use of logging trucks to transport the timber logs (Figure 1.2).

According to Harris (1984) the most notable changes that have taken place since the railroad loggings are a substantial reduction in total forest area and a "fragmentation" of remaining natural forests into progressively smaller patches isolated by even-aged plantations or by agricultural, industrial or urban development.

At present approximately 2 million ha of the landscape is covered by remaining old-growth Douglas-fir stands, most of which are confined to Federal lands. Of the latter, about 80 % is potentially available for logging (Society of American Foresters 1984). Many tracts of old-growth forests, especially on less accessible sites in the mountains, are permanently protected in reserves. These reserves occupy about 5 % of the original

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presettlement landscape (Franklin et al. 1981). It is well recognized that old-growth Douglas-fir ecosystems possess unique structural and functional characteristics, distinct from surrounding managed forests (Franklin and Waring 1979; Franklin et al. 1981; Harris 1984). Ironically, there is so much short-sighted economic pressure to accelerate the conversion of old-growth stands into Douglas-fir monoculture plantations, that the end of the unreserved old-growth forests is in sight (Franklin et al. 1981). Disposition of the old-growth forests thus has become an important and controversial issue in land-use planning in the Pacific Northwest (Old-growth Definition Task Group 1986). Dietrich (1992) describes this controversy in a most elusive way.



Figure 1.2: Road transport of Douglas-fir logs in western Washington (Journal of Forest History 1981, 25 (4): 235).

In western Europe, Douglas-fir was introduced in 1850 by the Scottish botanist Menzies. In Great-Britain it proved to be a fast growing, highly productive species with a relatively wide ecological amplitude (Anonymous 1890). In other European countries Douglas-fir was introduced a few years later on a wide range of sites, where it was often outgrowing native species such as Scots pine (*Pinus sylvestris* L.) or Norway spruce (*Picea abies* L.; Dissel 1899; Exoten-Commissie 1905; Berkhout 1918; Holland 1919; Stoffel 1923).

Douglas-fir was introduced in the Netherlands in 1860. Stands were established in the Royal Forests near Apeldoorn (Park het Loo) and on the Veluwe (Schovenhorst Estate) in 1881 (Schober 1893). The earliest records of Douglas-fir in the Dutch literature date from 1889 (Anonymus 1889). The area of Douglas-fir plantations in the Netherlands increased almost exponentially from 150 ha in 1923 to 16 000 ha in 1984 (Hoogh 1925; Veen 1951; Meerjarenplan 1986; Figure 1.3). Similar trends could be observed in other western European countries such as France, Belgium, West-Germany, Poland and Great Britain (Delveaux 1968a; Chylarecki 1976; Bouchon 1982; Oswald 1984; Oswald and Pardé 1984; Otto 1976; Kleinschmidt et al. 1987).

Douglas-fir proved to be a highly successful and productive species in many countries in the temperate zone (Spurr 1963; James 1978; Tol 1986). Approximately 500 000 ha of Douglas-fir plantations have been established outside its natural area in 1984, mostly in the form of even-aged monocultures. Small-scale experiments with mixed stands of Douglas-fir/Norway spruce, Douglas-fir/Scots pine, Douglas-fir/Japanese larch; and Douglas-fir/beech, some of which with very good results (Vanselow 1953; Wagenknecht 1956; Hattemer 1957; Oescher 1975; Nessel 1981; Dessel 1982) were done but largely disregarded. In the near future Douglas-fir may become even more important for upgrading wood production in western Europe (Otto 1976; Oswald 1984; Kenk and Hradetzky 1984; Kleinschmidt et al. 1987).

In the Netherlands, governmental plans have been approved to further increase the area of Douglas-fir stands from 16 000 to 45 000 ha by the year 2025. Many of these stands will be managed in accordance with the multiple-use concept, which includes non-timber objectives. This implies that more opportunities will be created for spontaneous processes such as natural regeneration, decomposition of larger amounts of coarse woody debris, growth over longer, more "natural" rotation periods, mixtures with other species, etc. However, it is uncertain how these management objectives can best be implemented.



Figure 1.3: Exponential increase of the area of Douglas-fir plantations in The Netherlands since 1910.

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According to Franklin et al. (1986) it will be a major challenge for future silviculturists to conceive forest management in such a way that maximum biodiversity is maintained. Much research will be needed to design and guide future developments. There is growing evidence (Schenck 1936; Fabijanowski 1978; Goor and Westra 1978; Franklin 1981; Franklin et al. 1981; Koop 1981 and 1989; Leibundgut 1982; Mayer 1984; Mayer et al. 1987; Oliver and Murray 1983; Oliver et al. 1986a; Walter 1982; Winckel 1980; Peters 1992) that at least some of the vital information needed for the development of silvicultural systems with a high level of ecological diversity, can be derived from studying the architecture and dynamics of natural forests.

#### 1.1.2 Baseline research in natural forests.

It is well recognized both in the european forestry tradition and in present-day timber management in the U.S.A. that natural forest ecosystems may provide information which can be profitably applied to forest plantation management (Twight 1973; Leibundgut 1978; Mayer 1976; Franklin 1981; Maser and Trappe 1984; Oliver et al. 1986a; Waring 1979; Oldeman 1990; Oliver and Larson 1990). This does not imply that nature-conformity is always considered best, but it does take into consideration that ecologically sound management principles should be based on the fact that nature is very complex. The basic principle is to maintain or enhance biodiversity whenever possible, including genetic, structural and spatial diversity (Franklin et al. 1986).

Intensive forest management regimes usually are sought for high uniformity in tree size and form. This implies a structural simplification of stands by elimination of subsystems such as dead standing trees and downed logs, by reducing the range of tree sizes and growth forms, and spacing trees geometrically. Often a rapid establishment of a fully stocked, closed-canopy conifer forest is the objective (Franklin et al. 1986; Worthington and Staebler 1961). This tendency toward simplification is a major concern to forest ecologists.

Harvest of stands managed for timber production normally occurs at the moment of transition from youth to maturity, thereby loosing the values of mature and old-growth phases of forest development. This simplification is not necessarily bad: much of it is required to achieve management objectives, but to think of such an approach as universal is considered unwise, because it leaves out major elements of the ecosystem (Oldeman 1990). Franklin et al. (1986) anticipate that non-timber objectives will be an integral part of many future forest management systems, especially in multiple-use forests. Many forest ecologists (Drew and Flewelling 1977; Franklin and Trappe 1968; Twight 1973; Leibundgut 1978, Franklin et al. 1979; 1986; Oliver et al. 1986a; Oliver and Larson 1990; Oldeman 1990) can prove that a well-balanced ecosystem functioning is a pre-requisite to develop sustainable silvicultural systems with relatively low management inputs.

#### 1.1.3 Architectural analysis

Simply speaking there are three different approaches to study natural forests, on a baseline as it were, against which we can measure the development potential of our managed forest stands: i.e. by counting, by weighing and by measuring. Counting refers to such disciplines as floristics and population dynamics; weighing is the domain of production ecology; and measuring provides the basis for architectural analysis (Oldeman 1990).

Allround-ecosystem research should incorporate and utilize all three approaches simultaneously; each for specific questions. Good examples of ecosystem research projects which integrated these approaches successfully are e.g. the Hubbard Brook project (Odum 1971; Borman and Likens 1979; Shugart and West 1981), the Swedish Coniferous Forest Project (Person 1980) and the "Waldschutzgebiete" project of the Forstlichen Versuchsund Forschungsanstalt Baden-Wuerttemberg (Buecking et al. 1979; 1982; 1985). For such allround approaches a team of scientists is required, studying the same location for an extended period of time. In the present study this was not possible, since the International Biological Program (I.B.P.) which favored such projects in the 1970's has run out, and no equivalent possibilities exist or existed in the Netherlands.

Extensive studies on floristics and classification have been carried out in the area of origin of Douglas-fir (Becking 1954; Mueller-Dombois 1959; Orlocci 1965; Daubenmire 1969; Hines 1971; Franklin and Dyrness 1973; Dyrness et al. 1974; Franklin 1979; Hawk 1979; Klinka et al. 1981; Otto 1984).

Research into Douglas-fir production ecology has gained much attention in the Pacific Northwest too (e.g. Abee and Lavender 1972a; 1972b; Sollins et al. 1980; Denison et al. 1972; Grier et al. 1986; Grier and Logan 1977, Waring et al. 1978; Long and Turner 1975; Overton et al. 1973; Weber 1977; Turner and Long 1975; Fogel and Cromack 1977).

Stand structure and stand dynamics have been studied in the Douglas-fir region by Zobel et al. (1976); Hawk et al. (1978); Franklin et al. (1981); Franklin and Hemstrom (1981); Stewart (1986); Oliver and Larsen (1990). Architectural analyses (concepts and terms used after Hallé et al. 1978), which include a detailed mapping of the vertical structure of these forest communities, have not been made so far (Kuiper 1988a).

According to Edelin (1977) the architecture of a tree is the expression of a balance between its development potentiality (genetically controlled) and the environmental stresses acting upon it. The architectural tree model is defined by Hallé et al (1978) as "the growth program which determines the successive architectural phases of a tree". Hence it gives rise to a differentiation sequence from seed to maturity. The architectural model expresses the framework of the shape of a tree at a certain moment as well as the laws of nature that govern its development.



Figure 1.4: Architectural models for conifer species: models of Rauh, Massart, Attims and Mangenot. In the juvenile phase Douglas-fir follows Rauh's model, but with increasing age it shifts towards Massart's model (after Edelin 1977; for model definitions cf. Hallé et al. 1978).

Among the 23 architectural models that have been defined for trees so far, the 4 models shown in Figure 1.4 are important for conifer species: i.e. those of Rauh, Massart, Attims and Mangenot (Edelin 1977). Different development strategies can be expressed in tree growth, which complicate its shape. Douglas-fir follows a development strategy which is intermediary between the model of Massart and that of Rauh. In the juvenile phase Douglas-fir trees follow Rauh's model, but with increasing age gradually develop Massart's model. Often the top of a Douglas-fir tree develops conforming to Rauh's model, whereas the lower parts of the crown should be considered more in correspondence with Massart's model. This is mainly due to an increase, with the order of branching in the intact tree, of secondary plagiotrophy (horizontal extension and dorsiventral architecture) during tree development. For these branches orthotrophy (vertical extension growth) is visible only at the branch tip, i.e at its extension zone. Douglas-fir branches of higher order often are plagiotropic or even ageotrophic (drooping).

Because a tree is exposed to environmental stress during its development, it seldom develops completely in accordance with its architectural model. The tree responds to that stress e.g. by activating resting buds, which develop an equivalent of the original structure of the tree. Oldeman (1974) introduced the term "reiteration" for this common process: the duplication of the original model of the tree from a meristem not contained in the embryo. Reiteration is any modification of the tree's architecture not inherent in its model. Basically two forms of reiteration can be distinguished: traumatic reiteration and adaptive reiteration. Traumatic reiteration (including replacement reiteration, or "trunk and branch regeneration"), which occurs when the apical meristem is destroyed and a lateral bud takes over, is very common. Adaptive reiteration is a development strategy used by a tree subjected to environmental stress. For most trees in temperate regions adaptive reiteration is the "normal" way of growth. Especially when a tree has reached the upper canopy of the forest, profuse adaptive reiteration can be observed as the main mechanism of crown expansion.

In Douglas-fir, considerable phenotypical variation can exist for bole and crown form characteristics (Campbell 1963). The form characteristics of Douglas-fir and its relative freedom from major defects of forks, crooks, sweeps and branchiness are important in reducing knots and compression wood, so increasing the quality and value of the timber. These wood quality traits are influenced by both environmental factors and silvicultural treatments (King et al. 1987; Champs 1980). However, there is growing evidence that at least some of these form characteristics are under some degree of genetical control. These include stem form, stem and branch sinuosity, polycyclic growth and lammas growth (Marcet 1975; Magnesen 1987; Adams and Howe 1987; Widmaier et al. 1987; Michaud 1987; Oliver and Larson 1990).

Silviculturally poor stem form is a common defect in Douglas-fir (Lines and Samuel 1987). Stem sinuosity, due to stem waviness within interwhorl segments, is one of the more noticeable form defects in Douglas-fir stems. Adams and Howe (1987) found a large amount of variation in stem sinuosity among 12 year-old siblings of Douglas-fir. It seemed more severe in faster grown provenances: fast growth rate associated with good sites was seen as a factor contributing to sinuosity. Moreover, Magnesen (1987) found

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that stem and branch sinuosity were correlated with tree vigour: the poorer stem form was found in coastal provenances. These displayed broad crowns and wavy stems and branches. However, in natural Douglas-fir stands in the Pacific Northwest the incidence of sinuosity was very low (Adams and Howe 1987).

When lateral buds show a tendency to polycyclic growth, this may have a detrimental effect on stem form: in the following year this frequently gives rise to forks. Michaud (1987) observed that on sites studied at lower elevations, the trees displayed a higher degree of polycyclic growth compared with those at higher elevations. Lammas shoots can enhance height growth considerably: Widmaier et al. (1987) found in Germany that lammas shoots ensured 50 % of total height growth in Douglas-fir. In a similar trial in France it represented 25-30 % of total height growth (Widmaier et al. 1987).

This illustrates that Douglas-fir tree growth and forest development are governed by complex genetic and environmental interactions, many of which are still poorly understood (Champs 1980; Decourt and Le Tacon 1979). To limit the scope of this study, a structure-based system hierarchy was used after Oldeman (1990). Our research is situated at the levels of "forest components", "eco-units" and "silvatic mosaics". The basic idea behind such a hierarchy is, that each system studied should both fit within the framework of a system at a higher hierarchical level, and can be explained in terms of its subsystems. Kuiper (1988a) describes this methodology in detail (see also chapter 2).

#### **1.2 Objectives**

An analysis of the architecture and dynamics of natural (or semi-natural) Douglas-fir forests was a major objective of this study, because of its relevance for the design of silvicultural systems with low management-input and consequently with more room for spontaneous developments such as competition, mortality and natural regeneration all within one stand. In other words: "do less and accomplish more". Management objectives should be met, but preferably with the least human interference. Leibundgut (1978b) expressed the basic idea behind a silvicultural system with low-management inputs very elegantly: "Ein Waldbauer soll raffiniert faull sein", i.e. "a silviculturist should possess refined laziness". Obviously Douglas-fir forests can be completely left alone and yet sustain themselves as they have been doing in their area of origin over the past millennia, but at best it is uncertain to what degree such forests will meet with most of the present day management objectives (e.g. what will be the penalties in terms of wood quality). And this is the more so for Douglas-fir plantations on exotic sites such as in western Europe (Figure 1.5).







Figure 1.5: Vertical diagrams of a Douglas-fir regeneration unit in The Netherlands illustrating its sequential development at a 5 years interval. Regeneration unit size was approximately 1.5 times the hight of surrounding 140 year old beech forest (*Fagus silvatica*). In this canopy gap previously an oak coppice stand (*Quercus robur*) had been planted, which was replaced by Douglas-fir in 1957. Note that at this stage of stand development, monitoring of the forest architecture at a 5 years interval already can provide vital information on stand dynamics.

In this paper an attempt is made to answer the question: "What information on forest architecture and forest dynamics is relevant for silviculturists to better define and design silvicultural systems with a high level of nature-conformity (German: naturgemaessigkeit), and well adapted to future human demands ". Such systems should be capable of producing high quality timber with a minimum of capital and labour input on a sustained yield basis, maintaining at the same time a maximum of spatial and architectural diversity, so as to meet with non-timber objectives. Hence a large portion of this paper is dedicated to the problem of describing and defining architectural diversity of Douglas-fir trees and forests. To do so systematically a number of assumptions and hypotheses have been formulated, based on the extensive body of literature and on common sense.

#### **1.3 Assumptions**

1. Some of the vital information needed to design silvicultural regimes for Douglas-fir with low management inputs, can be derived from studying the architecture of natural Douglas-fir forests.

2. Profile diagrams will be very helpful to codify and compare basic tree and forest characteristics, especially between natural Douglas-fir forests and Douglas-fir monoculture plantations on exotic sites in Europe.

3. Fundamental to the design and development of adaptable silvicultural systems, is to maintain or enhance genetic, architectural and spatial diversity whenever possible.

4. Only flexible silvicultural systems will be able to fulfill future human needs, including non-timber objectives, given the rapidly changing environmental conditions.

#### 1.4 Hypotheses

1. The traditional point of view in which Douglas-fir is considered a secondary pioneer species, developing into large, homogeneous, even aged stands after forest fires, needs to be changed when new insights into the architecture and dynamics of natural Douglas-fir forests become available.

2. The idea that Douglas-fir thrives best on large clearcut areas, and that the most natural silvicultural systems for Douglas-fir are even-aged monocultures, equally needs revision.

3. The present study will reveal that natural Douglas-fir forests possess architectural characteristics clearly distinct from Douglas-fir plantations.

4 In young coniferous forests natural tree competition leads to a very diversified forest architecture.

#### Introduction

5. To study the development of the tree population into distinct social tree classes will be helpful to better understand Douglas-fir stand dynamics.

6. A correlation can be found with objective tree parameters to distinguish between social classes in Douglas-fir.

7. In semi-natural stands with a high biodiversity the site productivity will not be fully allocated to the production of stem wood.

8. Non-thinned Douglas-fir stands in Europe will show similarities with architecture and tree development strategies of certain development phases of natural Douglas-fir stands.

In the following chapters several case-studies will be presented on natural and seminatural Douglas-fir stands in the Pacific Northwest (chapters 2, 3, 4, and 5) and on nothinning experiments with Douglas-fir in The Netherlands and Germany (chapters 6, 7 and 8). In chapter 9 the results of these case-studies are discussed and assessed in terms of their silvicultural meaning, referring to the original hypotheses. Furthermore, conclusions are drawn and suggestions are given for the design of new, improved silvicultural systems for Douglas-fir with a higher level of nature-conformity.







Two examples of logging systems: cable logging on a watershed in the Cascade mountains in western Oregon (above); and logging of second growth Douglas-fir stands by dragline (below; Stossel Creek, WA).

#### 2. THE ARCHITECTURE OF NATURAL DOUGLAS-FIR FORESTS IN WESTERN WASHINGTON AND WESTERN OREGON

#### Abstract

The architecture of 5 natural Douglas-fir stands, located on high-yielding sites in the Tsuga heterophylla zone in western Washington and western Oregon was analysed. Stand ages ranged from 50 to 1000+ years. Vertical diagrams and crown projection maps were used to identify developmental phases. The results show the spatial coherence between forest components by describing the characteristics of trees, eco-units and the forest mosaic for each plot in detail. From the results, general developmental trends were deduced. The architecture of natural Douglas-fir forests was shown to be very diversified in all developmental phases.

#### 2.1. Introduction

Though the northern temperate forest regions are well known floristically, our knowledge of the architecture and dynamics of their primeval forests is rather scanty. In Europe temperate forests have been so devastated and changed by man that very few natural stands are left for baseline studies (Leibundgut 1982; Mayer et al. 1987). In the Pacific Northwest area the situation is much better: about 5 percent of the original landscape, occupied by old growth forest ecosystems that have developed over a long period of time and essentially free of human disturbance, is protected in reserves (Franklin et al. 1981). Also there is still a considerable area covered by second growth stands that have developed naturally without human interference after the railroad loggings in the 1920's. Natural forests are particularly valuable in ecosystem research since typical components, processes and interactions in natural stands may be absent from the artificially simplified managed forest stands (Franklin et al. 1981).

#### 2.1.1 Objectives

The main objective of this case-study was to analyse the architecture of several natural Douglas-fir stands forming a chronosequence of ages ranging from 50-1000 years, on more or less comparable sites.

#### 2.2 Methods

The general features of each development phase of the forest are studied by analysing the size, architecture and distribution of the tree components and of the eco-units which build the forest mosaic. When these qualities are known at different ages a general idea of forest growth and development can be obtained. As was mentioned in chapter 1, in this study a structure-based system hierarchy has been used, from which the levels of forest components, eco-unit and forest mosaic were studied (Table 2.1). The basic idea behind this hierarchy is, that each system studied should fit within the framework of a system at a higher hierarchical level, and can be explained in terms of its subsystems.

Table 2.1: System hierarchy used in the present study, which is primarily based on structures (simplified after Oldeman 1990).

landscape site forest mosaic eco-units forest components organs tissues cells sub-cellular levels

#### Forest components

At the basic level forest components are distinguished. The architecture and functioning of trees and other forest components is explained by their organs. In case of tree components the subsystems are e.g. branch system, root system or reproductive system. Tree components form the building blocks of eco-units, which are considered to be their supersystem.

A set of functionally related components may be brought together in a \*compartment. A compartment is considered to be any set of abiotic or biotic components in a living system, that is delimited as a recognizable functional ensemble. It can be useful to identify compartments to provide a possibility for well-balanced abstraction. In silviculture e.g. different \*social classes among trees can be identified. Every social class is then considered to be a compartment, e.g. a set of specific forest components (trees in this case). Another example of a useful compartment could be coarse woody debris on the forest floor, or a population of myccorhiza.

In this paper different compartments of trees are distinguished according to the developmental stages the trees are going through, after Hallé et al. (1978). Potential trees are trees in a stage in which the final size and expansion has not yet been reached (trees with growth potential). Tree development during this stage may be interrupted by premature death or suppression. When the tree has reached its final expansion into the canopy or at a lower level, often by reiteration, it is called a tree of the present. Finally it becomes a degrading tree of the past (Hallé et al. 1978).

#### **Eco-units**

At the next integration level eco-units are distinguished: an interposition between forest components and forest mosaic as a distinct hierarchical level. A forest \*eco-unit is the smallest category of an ecosystem, of which the limits and lifespan have been defined by Oldeman (1990): every surface on which at one moment in time, a vegetation development has begun, of which the architecture, ecophysiological functioning and species composition are ordained by one set of trees until the end. The subsystems of eco-units are forest components; the supersystem that is built up by eco-units is indicated as a forest mosaic. Eco-unit development depends on the interaction between all of its components; not only its tree components. But it is convenient to start to explain an eco-unit by the trees that form the skeleton of the eco-unit. Once this is known, the eco-unit can also be explained in terms of other eco-unit components, such as mammals, birds, fungi or nematodes.

The state of an eco-unit, e.g. the interior organisation of an eco-unit, is described in terms of eco-unit size (small, medium and large) and by the architecture and size of its tree components. Eco-unit development is treated as a sub-process in succession. Eco-units come into existence (innovation phase), grow up and organise themselves (aggradation phase), remain organised during an extended period of time (biostatic phase) and become finally disorganised (degradation phase). Developmental phases have been defined in many different ways in literature. In this paper we will follow the Bormann and Likens (1979) concept, in which a "steady state shifting mosaic" takes the place of biostasis as meant above. This biostasis implies the breaking up of the original stand (large eco-unit) into a mosaic of smaller patches (small eco-units), due to natural mortality of large trees over time. When they die they leave a gap in which a young eco-unit grows up.

The presence of trees in different developmental stages is symptomatic for the development of that eco-unit. In its innovation phase an eco-unit contains new trees in the seedling stage, next to surviving saplings and root and stump suckers. In the aggradation phase all these trees, except for some small species and shrubs, are competing and have further growth potential. The biostatic phase is structured by layers, determined exclusively by trees of the present. In the biostatic phase potential trees survive in a suppressed state or die prematurely as ordained by layer disposition. The degradation phase is characterised by the death and decay of trees of the present. If these trees do not die at the same time, that eco-unit splits up in smaller ones corresponding to the volumes of the trees or tree groups that have successively disappeared. In this way the event that caused the start of the development of an eco-unit is considered too: the zero event in small sized eco-units e.g. is a chablis (Hallé et al. 1978) or the death and decay of large standing trees forming canopy gaps in different ways. Two important processes lie at the basis of eco-unit development: \*fragmentation and \*fusion. Fragmentation is a diagnostic symptom of a degradation phase, which may be either abrupt or very prolonged. When fragmentation of a large sized eco-unit proceeds, the innovation phase of smaller forest eco-units follows. The early aggradation phase then can be extremely heterogeneous,

whereas the later aggradation phases, through the process of fusion, are characterised by seeming homogeneity. Fusion is the formation of larger eco-units by converging development of neighbouring smaller ones.

#### Forest mosaic

At the highest level the forest mosaic is dealt with, which can be considered as a mosaic of different eco-units as subsystems with a different size or in a different developmental phase or both. Site conditions form the supersystem for this level: macroclimatic regulation e.g. occurs at the forest mosaic level, whereas biotic regulation usually is predominant at the eco-unit level. No single small eco-unit can be thought of without considering its adjacent units and its place in the forest mosaic. If the forest is built up entirely of very small single-tree-eco-units, perhaps a mixed stand model is a more useful and more practical concept than a model of a mosaic built by eco-units. In any case this is so as long as research questions do not concern very small organisms but are centered upon trees. But in many other situations eco-unit models describe the size and limits of the ecosystem and its subsystems that have to explain it, in a very comprehensive way. It should be noted, however, that the identification of the spatial limits of eco-units still is a major problem in ecosystem architecture analysis. Small sized eco-units may show fusion and form a mosaic that can barely be distinguished from a large, even aged eco-unit without extensive measuring, such as increment core analysis. Although in many old-growth stands the trees in the canopy appear to be even-aged, Franklin et al. (1979) reported that the age class distribution of Douglas-fir trees was often relatively wide.

Note that the "classical" stages of stand development as e.g. described by Leibundgut (1982) and Mayer (1978; 1984), do not make a sharp distinction between forest mosaics and eco-units (Figure 2.1). The commonly used classification of natural forests in the Pacific Northwest in second growth stands, mature stands and old-growth stands refers to the forest mosaic level rather than to the eco-unit level. It is possible that a stand is built up by one single eco-unit, but this seems to be rather exceptional in natural forests.

In this case study forest architecture is analysed in detail by graphical methods derived from those used by Hallé et al. (1978) in the Tropics, which are especially adapted to heterogenous forests, using vertical diagrams to analyse forest architecture. They give a clear diagnosis of what the forest really looks like. In Europe such methods have been applied successfully for more than a century now for both managed and unmanaged forest stands (Knuchel 1944; Leibundgut 1959; Mayer 1984). Most remnants of natural forests in Europe have been analysed this way, beautifully illustrating the development patterns observed in these different forest communities (Leibundgut 1978 and 1982; Mayer 1976 and 1984; Zukrigl 1970; Hillgarter 1971; Koop 1981; Winckel 1980; Vyskot 1978; Pintaric 1978; Pruca 1985). A good example in the U.S.A. is the work of Oosterhuis et al. (1982) who used vertical diagrams in a similar way to analyse the architecture of deciduous forest stands in southwest Virginia. In the Pacific Northwest extensive work has been done by Franklin and his group on the spatial distribution of stems, snags and logs in more than 60 reference stands throughout the area (Hawk et al. 1978). In natural Douglas-fir forest ecosystems a great amount of fundamental research has been done (Table 2.2). A detailed description of the vertical structure of these forest communities so far has not been made.



Figure 2.1: Natural forest development stages. A = common forest classification in the Pacific Northwest. B = classical forest development phases in central Europe (after Leibundgut 1982; Mayer 1984). C = predominant eco-units at the forest mosaic level (inspired by Oldeman 1990). The "*Plenterwaldaehnliche Entwicklungsphase*" (in the middle), which is a forest mosaic of very small eco-units, may either result from a stable degradation phase (*Zerfallsphase*) or from a prolonged regeneration phase (*Verjuengungsphase*), and exists only temporarily. It usually develops into a closed second growth stand (*Jungwaldphase*) or mature stand (*Optimalphase*).

Table 2.2. Survey of fundamental research in natural Douglas-fir forest ecosystems over the past 20 years.

Floristics and classification: Franklin and Dyrness (1973); Dyrness et al (1974); Franklin (1979); Hawk (1979); Otto (1984).

Structure and dynamics: Long (1973); Juday (1976); Zobel et al. (1976); Hawk et al. (1978); Franklin and Waring (1979); Means (1981); Franklin et al. (1981); Franklin and Hemstrom (1981); Hemstrom and Franklin (1982); Steward (1986); Oliver and Larson (1990).

Biomass distribution and production budgets: Fredriksen (1972); Denison et al. (1972); Overton et al. (1973); Grier and Running (1974); Turner (1975); Fredriksen (1976); Grier and Logan (1977); Weber (1977); Waring et al. (1978); Fogel and Hunt (1979); Turner (1981); Gholz (1982); Santantonio and Hermann (1985).

Nutrient cycling: Dice (1970); Abee and Lavender (1972); Miller et al. (1976); Sollins et al. (1980).

Foliage mass and organic matter: Grier and Waring (1974); Long and Turner (1975); Turner and Long (1975); Gholz et al. (1976); Fogel and Cromack (1977); Gholz (1982); Massman (1982).

Snags and forest floor: Grier and McColl (1971); Trappe and Maser (1977); Cline et al. (1980); Maser and Trappe (1984).

Mosses and epiphytes: Pike et al. (1972); Pike et al. (1975); Pike et al. (1977); Carroll et al. (1980); Binkley and Graham (1981).

Invertebrates: Mispagel and Rose (1978); Voegtlin (1982); Deyrup (1985).

Wildlife and avifauna: Anderson (1970); Balda (1975); Wiens and Nussbaum (1975); Mannan (1977); Forsman et al. (1977); Black and Taber (1977); Meslow (1978); Maser et al. (1979); McClelland et al. (1979); Forsman (1980); Bowman and Harris (1980); Mannan et al. (1980); Meslow et al. (1981).

#### 2.2.1 Vertical diagram method

Analysing the architecture of forest stands by making pictures is virtually impossible in the old growth stands in the Pacific Northwest due to the height and massiveness of the dominant trees. Canopy heights often reach nearly 85 meters (Harris 1984; Franklin and Waring 1979; Oliver and Larson 1990). On the other hand making pictures of edges of clearcut areas, especially when combined with some tree height measurements, will quickly give a first impression of the forest architecture. This can be done if the clearcut was established no longer than 2 or 3 years ago so that the trees have not yet responded too much to the sudden change in microclimate. Within forest stands a reliable picture of its architecture can only result from accurate measurements of stump positions, tree heights and crown widths and by recording the measurements on scale drawings.

The study of forest architecture with vertical diagrams is in many ways very similar to the work of a histologist studying particular cells and tissues of an organism under a microscope, but on a different scale. Note that the selection of the transect plot locations is not a random process. Being a structural approach and because structures by definition are characterized by non-random deviations from averages, it is essentially non-statistical. It would not make any sense for a histologist to start making sections randomly, nor for that matter in a systematic grid pattern, and the same is true for a forest structure analist. Rollet (1974) clearly demonstrated the weak points of statistical methods in forest architecture research.

It is very essential to this approach to carefully select the transect plots and restrict their location to those 'forest-tissues' from which one wants to obtain detailed information. If aerial photographs or stem maps are available a preliminary survey can take place from behind the desk, but in most cases a field survey is necessary. If one is completely unfamiliar with the area or with the forest community it may be a good idea to first run a line-transect through the stand and measure only those trees whose crown projection areas intersect with the line.

This brings up the second similarity with microscope work, namely the question of section thickness: too thick a section will give a non-transparent image, whereas too thin a section will not yield an optimal amount of information, and will e.g. leave holes in the diagrams. The section thickness depends on the size of the trees in the specific forest community under study. As a general rule of thumb the transect width should be somewhere between 1/3 and 2/3 of the height of the dominant species (Oldeman 1974). For coniferous forests, however, a better measure seems to be a width of 1 to 2 times the crown diameter of the dominant trees (Mulder and De Waart 1985), because conifers are much more slender in relation to their heights than hardwood species. For most forest types in the Pacific Northwest a transect width of 10 to 15 meter will do; in young stands 5 meter usually is sufficient. If one wants to examine the structure of the shrub layer or of the ground vegetation, one has to reduce the width of the section accordingly, but the same general rules apply.

After the selection of the plot location one starts with running a line through the stand e.g. 50 or 100 m long, marked with flagging tape or poles. The slope is measured at 10 meter intervals. If necessary a slope correction is made: e.g. 10 meter on the horizontal plane (the scale paper) will be somewhat longer along the slope in the forest. Perpendicular to the baseline 10 meter squares are laid out and the plot is conveyed to millimeter or inch paper on scale. All stump positions of the trees inside the plot are mapped and the trees are numbered. Diameters on breast height are measured. Crown projection areas on the horizontal plane are estimated as follows: beginning from the stem one proceeds towards the periphery of the crown looking upward until one reaches the very end of it. The distance of this point to the stem is measured. When the crowns are regular in shape this is to be done in at least 4 directions (N, E, S, and W). Irregular crowns are measured on more points. Many times a few limbs stretch out far beyond the average crown circumference. These too have to be measured. The crown projection shapes are drawn on the stem map. Dead stumps and logs are included. After this the newly constructed crown projection map is checked in the field. Often one is surprised to see how well the crown shapes fit. Oldeman (pers. comm.) made a rapid check of the accuracy of this naked-eye estimate in Finland by performing a parallel series of

observations with a Cajanus tube. This is an instrument designed for perpendicular branch tip observation. The accuracy of both methods was comparable, as judged from the resulting crown maps. If the crown shapes do not fit entirely, some adjustments have to be made.

The following measurements of every tree in the plot were made: topheight, height of crown base and height of typical branch systems below the actual canopy, the height where the crown is widest and where irregularities appear in the crown, forks in the stem, etc. A sketch is drawn of the shape of the tree seen in side view. This is always done from the same direction, necessarily drawn perpendicularly to the baseline, in order to avoid showing the wrong face of the tree in the drawing. Tree species and number are recorded along with some observations on the trees general state of health, its social position, fire scars, etc. In fact everything worth mentioning should be included in the field notes.

Behind the drawing table these sketches are worked out on scale and are put in place with the help of the crown projection map, beginning with the trees closest to the front line and proceeding from left to right. This is also the procedure when reading vertical diagrams. The side view and the crown projection map correspond to transversal and radial sections in microscopy. A final check is made in the forest to see if no information has been omitted and then the document is ready for further analysis. In addition to the drawings a number of graphs and tables are constructed to summarize stand data.

With this vertical diagram method a stand and its major components is recorded at one particular moment in its development. To analyse development patterns, ideally the same stand should be recorded with regular intervals over an extended period of time (Figure 1.5 and 2.2). Often this is not possible. To overcome this problem, a chronosequence of ages can be established by selecting different stands of various ages on comparable sites with a similar developmental history.

This method, with its shortcomings and merits, was used in the present study. A limitation to this approach was the lack of natural Douglas-fir stands in all age classes: major disturbances, linked with the regeneration of Douglas-fir forests, apparently have occurred at large intervals. The result is that only certain age classes (50-80 years old; 100-200 years old; over 400 years old) are present.

#### 2.2.2 Accuracy of the measurements

Of all trees in the sample plots, usually  $100 \times 10$  m large, the position of the center of the stump was measured with an accuracy of plus or minus 20 cm. Crown radius was measured in at least 4 directions with an accuracy of 0.5 m. For very tall trees the accuracy of the crown radius will be in the order of plus or minus 1 m. Tree height, crown base, forks and epicormic branches along the stem were measured with a Suunto tree height measuring device using the percent-scale. This had the advantage of not having to use fixed distances, but instead more flexibility was possible in the measurement

position to the tree that was being measured. Slope corrections were made and the actual heights thus calculated, are accurate within a range of plus or minus 1 m (except for the very tall trees over 80 m: their accuracy will be in the order of plus or minus 2.5 m). Crown base is defined as the height of the first whorl with more than two green branches, from which, pointed upwards, the closed crown extends.

Individual tree volumes for Douglas-fir, western hemlock and western red cedar were calculated from volume tables of USDA-Forest Service (1955); Mc Ardle (1961) and Mc Ardle et al. (1971), using diameter at breast height (d.b.h.) and tree height as input variables (after converting them to inches and feet respectively). Different tables were used for young and old stands. Calculated mean values of various stand parameters are based on 0.1 ha plots, unless mentioned otherwise. Number of stems/ha refer to all trees with d.b.h. over 5 cm.



Figure 2.2: Recording the architecture of a Douglas-fir stand by vertical diagrams at a 7 years interval (Schovenhorst Estate, Putten, Netherlands).

Most trees in the plots were bored at breast height for age determination and for analysis of basal area increment. The cores were temporarily stored in flexible plastic drinking straws and later on were glued on strips of cardboard. Small trees were bored right through the center of the stem; trees thicker than 60 cm were bored as far as possible with a 30 cm increment core, and the radial distance to the tree core, if missing, was estimated. By analysing diameter growth during the early years of tree development on stumps of nearby clearcut areas, the number of annual rings missing was estimated. Note that ages in this report are established from cores at breast height.

Strictly speaking trees with widely different ages belong to different eco-units. However, when age differences are three years or less, trees are considered to belong to the same eco-unit: they may well have started their development in the same year, but there may have been a difference of a few years in reaching breast height, or the innovation phase may have covered several years of colonization by the trees.

#### 2.2.3 Research sites

Research sites were restricted to the *Tsuga heterophylla* zone in Washington and Oregon (Figure 2.3). The plots were sampled on sites where soil moisture conditions ranged from moist to wet. Preferably level sites were selected, or otherwise sites whose slopes were less than 50 percent. In some cases reference stands established by Hawk et al. (1978) were used. The actual location of the transect plots within each stand was carefully selected after a field survey. In the reference stands case, they were selected after examining the existing stem maps combined with a field survey. Because the focus of this study was on Douglas-fir as a component of natural Douglas-fir forests, the location of the plots in the older stands was such that a maximum number of Douglas-fir trees were situated within the transect strip. For the younger stands a representative plot was selected, not necessarily containing a maximum number of Douglas fir trees, because in these stands there were always enough Douglas-fir trees.

Note that for the old-growth stands the figures in this paper represent the upper limit of what actually can be found in natural Douglas-fir forests. Conversion into one hectare stand parameter values, extrapolated from 0.1 ha plots with a more than average number of Douglas-fir trees, will be somewhat overestimated, and is unrealistic anyway because of the fact that such homogeneous hectares do not exist in nature. Basal area and total standing volume e.g. can have extremely high values. However they are representative of patches within these forests. As such, they are very characteristic of the mosaic pattern of these forests.

In this paper vegetation types refer to Dyrness et al. (1974) and Franklin and Dyrness (1973). The synecological classification of Dyrness et al. (1974) is based on shifts in species dominance rather than on differences in species composition. Only a few species show restricted ecologic amplitudes and these are generally limited to extreme habitats (e.g. *Holodiscus discolor* and *Oxalis oregana* on dry and very wet sites respectively). On modal sites high-fidelity species are rare or lacking. Classification of units on modal sites

thus generally is based upon shifts in dominance or relative abundance. Polystichum munitum and Gaultheria shallon e.g. are present in almost every forest community. But they are characteristic for wet and dry sites respectively when showing great abundance and a high cover. In the Tsuga heterophylla zone indifferent species of widespread occurrence include Berberis nervosa, Vaccinium parvifolium, Achlys triphylla, Linnaea borealis and Acer circinatum. Forest communities occupying the extremes of the moisture gradient are the Tsuga heterophylla/Polystichum munitum-Oxalis oregana association at wet sites (Tshe/Pomu-Oxor), and the Pseudotsuga menziesii/Holodiscus discolor association at dry sites (Psme/Hodi). Of the more commonly occurring communities situated on modal sites, the Tsuga heterophylla/Rhododendron macrophyllum/Berberis nervosa association is considered to be the climatic climax (Dyrness et al. 1974).



Figure 2.3: Research sites in western Washington and western Oregon.1) Humptulips, Olympic Peninsula (WA); 2) Carbon river, Mount Rainier National Park (WA); 3) Hugo Peak, C.L. Pack Experimental Forest, Eatonville, La Grande (WA); 4) Ohanapecosh, Mount Rainier National Park (WA); 5) Reference Stand 27, H.J. Andrews Experimental Forest (OR).

#### 2.3. Results

#### 2.3.1 Architecture and development of eco-units and forest mosaic.

The following case-studies, analysing the architecture of natural Douglas-fir stands in sequential age order, have been described in detail by Kuiper (1988a).

Humptulips:	50 years old	(Figure 2.4)
Hugo Peak:	150 years old	(Figure 2.5)
Ohanapecosh:	250 years old	(Figure 2.6)
Reference Stand 27:	400 years old	(Figure 2.7)
Carbon River:	1000 years old	(Figure 2.8)

The Humptulips, Hugo Peak and Carbon river plots belong to the *Tsuga heterophylla*/ *Polystichum munitum-Oxalis oregana* association and occupy good sites. The Ohanapecosh stand and Reference stand 27 occupy relatively moist, modal sites and thus can also be considered to be characteristic of relatively good sites. Unfortunately, these 5 stands represent an elevation range of 150-870 m. This means that complex temperature factors might modify a general pattern of forest development. In the ideal situation for research the plots would all belong to the same forest association and would be located within a narrower elevation range. This was not possible because such a range of stands could not be found.

In the second growth Humptulips example (Figure 2.4), stand architecture seems to be quite uniform: there is only a single stratum; the forest canopy is very dense and closed and understory vegetation is only sparsely developed. Although there may be a large number of eco-units due to a heterogeneous situation during the innovation phase of stand development, the overall picture at the age of 50 is one of uniformity, for which the process of fusion is largely responsible. The individual trees show considerable differentiation in total height, crown length, crown shape and tree volume, and can easily be grouped together in different compartments (\*social classes, Leibundgut 1959). Uniformity is apparent, but in reality there is a lot of variation and differentiation in natural second growth stands.

Mature stands generally are characterised by a greater stratification of the canopy: in the Hugo Peak example (Figure 2.5) the forest canopy is more open, and an upper stratum can be clearly distinguished from a middle stratum. Small groups of western hemlock form a lower stratum. Differences in size and shape of the overstory Douglas-fir trees become more pronounced. The Ohanapecosh stand (Figure 2.6) is typical for the point of transition between mature stands and old-growth stands: the canopy is more heterogeneous, more open and a lower stratum of western hemlock is well developed. Many eco-units are built up of trees which have attained their maximum size and reiteration will be the predominant growth activity from then onwards. The Douglas-fir trees still have paraboloid-shaped crowns, but the distinction between the lower whorls and epicormic branches along the stem becomes less pronounced.


Figure 2.4: Vertical diagram and crown projection map of the Humptulips plot (50 years old). Tree numbers are written on the crown projection map; tree ages are indicated above the tree tops.  $\square = Douglas$ -fir;  $\square = western hemlock$ .



Figure 2.5: Vertical diagram and crown projection map of the Hugo Peak plot (150 years old). Tree numbers are written on the crown projection map; tree ages are indicated above the tree tops.

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Figure 2.7: Vertical diagram and crown projection map of Reference Stand 27, 400 years old.



Figure 2.8: Vertical diagram and crown projection map of the Carbon River plot (1000 + years old).

An example of a typical old-growth stand is given by Reference stand 27 (Figure 2.7): an open multi-layered forest canopy, fragmented into many different eco-units, of which the biostatic ones are built up of truly impressive Douglas-fir trees with highly individualistic crown shapes and epicormic branches all along their massive trunks. A second layer is built up of fully grown, long-crowned western hemlocks and western red cedars. Two to three strata of western hemlock trees in various sizes and ages can be found, waiting for an opportunity to penetrate the canopy. And below that, often a sparsely developed third layer of *Taxus brevifolia* is present. In some eco-units a shrub layer is well developed, including species like *Rhododendron macrophyllum, Acer circinatum* and *Cornus nutallii*. Standing dead trees, snags and rotten stubs are common. On the forest floor numerous logs in various states of decay are present, often covered by a dense blanket of mosses. The patchy ground vegetation consists of ferns, huckleberries and western hemlock saplings. The forest structure is a mosaic of different eco-units; is very heterogeneous; and offers an unique habitat to a number of rare organisms.

A super old-growth Douglas-fir stand is exemplified by the 1000 year old Carbon River stand (Figure 2.8). Fragmentation of the biostatic eco-units has proceeded to the extent that only a few large Douglas-fir trees are still present, but they are very tall and very impressive. The forest consists mainly of a mosaic of western hemlock and western red cedar eco-units. Both species form a canopy layer somewhat beneath the scattered Douglas-fir trees. Below this layer there is a continuum of hemlock regeneration in all sizes and ages, so that no distinct strata can be distinguished. The forest structure is very diverse. The amount of dead wood, both standing and down on the forest floor is very large.

This general pattern of eco-unit and forest mosaic development can also be expressed by a number of stand mensurational data (Table 2.3):

Α	В	С	D	Е		
470	490	410	370	310		
225	160	160	130	60		
48	33	47	35	20		
57	133	156	193	210		
900	2500	2900	3700	4300		
	A 470 225 48 57 900	A     B       470     490       225     160       48     33       57     133       900     2500	A     B     C       470     490     410       225     160     160       48     33     47       57     133     156       900     2500     2900	ABCD4704904103702251601601304833473557133156193900250029003700		

Table 2.3: Summary of stand data for the five plots: A=Humptulips; B=Hugo Peak; C=Ohanapecosh; D=Reference Stand 27; E=Carbon River.

N/ha = total number of trees per ha; N Psme = number of Douglas-fir trees per ha; BA = total basal area per ha; V = total standing volume per ha.

40

With increasing age the diameter distribution becomes increasingly wider due to the greater diversification of the canopy and as a result of the continuous innovation and development of eco-units built up of shade tolerant species (Figure 2.9). The spatial distribution of basal area becomes increasingly more heterogeneous, as patchiness increases (Figure 2.10). Stand mean values for basal area and total standing volume keep on increasing. The number of Douglas-fir trees gradually declines both absolutely and relatively, whereas the more shade-tolerant species become more numerous (Table 2.3). Mean diameter and mean volume of the dominant trees keep on increasing with age (Figure 2.11).



Figure 2.9: Diameter distributions, which become increasingly wider with age. Also their shape changes, due to the differentiation and stratification of the forest canopy and the continuous initiation and development of eco-units with shade tolerant species.



Figure 2.10: Basal area increases with age, and its spatial distribution becomes more and more heterogeneous, as the process of fragmentation proceeds.

Figure 2.11: Mean values for tree height, d.b.h and volume of the 100 tallest trees per ha, for stands at different ages. Note the regular increase for both d.b.h and tree volume and the regularly increasing uncertainty interval, pointing to fragmentation, causing mean values to become less and less relevant for a stand.

In Figure 2.12 the general pattern of Douglas-fir forest development in the absence of major disturbances, on relatively good and on relatively poor sites within the *Tsuga heterophylla* zone is summarized schematically. Also forest development on very poor (marginal) sites is hypothesized: it is suggested that on marginal sites second growth stands will hardly reach maturity and degradation will start very soon. Although some observations in Douglas fir stands on exotic sites in Europe point in this direction, this is still scarcely more than speculation in an area of research that needs more attention.



Figure 2.12: Summary of a general pattern of forest development within the *Tsuga heterophylla* zone, in the absence of major disturbances, for relatively good sites and for poor sites. Forest development on marginal sites is hypothesized, after data from The Netherlands. The transition between the different development phases is gradual. Note that on good sites the old-growth phase continues for many centuries, whereas on relatively poor sites this phase will develop much sooner into a degradation phase. On marginal sites the old-growth phase may be very short and abrupt or may not be present at all.

## 2.3.2 Architecture and development of individual trees

The general architecture of Douglas-fir trees is characterised by Massart's model (Hallé et al. 1978). Trees in young stands have uniform crowns with a paraboloid shape and relative crown lengths of approximately 40 %. The crown of mature trees is uniform in the upper parts, but becomes increasingly more irregular in the lower parts: a few epicormic branches are present below the actual canopy. The large, deep, irregular old-growth Douglas-fir crown is characterized by a total lack of uniformity. Its shape is highly individualistic due to reiteration processes. According to Franklin et al. (1981) their physiognomy resembles "a bottle brush with many missing bristles". In the lower two-thirds of the crown there often are gaps of many meters on one side of the tree. Epicormic branches prevail and it is difficult to describe where the actual crown stops and epicormic branches along the stem begin. Fan-shaped epicormic branch systems are very typical. The upper part of some old-growth trees have a more regular shape, with more numerous branches resembling those of younger trees. Very often the entire tree-top is broken out. In some cases replacement-reiteration of a lateral branch can be observed.

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10-						
tree age	уг	50	150	250	400	1000
height	m	43	70	71	75	81
dbh	cm	65	120	107	129	176
volume	m3	4	22	18	27	55
crown base	m	28	40	40	43	49
crown width	n n	7	8	8	9	10
crown lengt	h %	43	45	37	43	38

Figure 2.13: Silvidiagram of individual tree development on relatively good sites. The characteristics of a stand mean dominant tree are presented here.

The characteristics of an 'average' dominant Douglas-fir tree in chronosequencial order are presented in the form of a silvidiagram (Figure 2.13). To construct such a silvidiagram for each of the above mentioned stands the mean tree height, d.b.h., volume, crown base, crown length and crown width was calculated for the 100 tallest trees/ha, and the crown shape of a representative tree was used for illustration.

# 2.4. Discussion

A detailed analysis of stand and tree structure with vertical diagrams can be useful to identify development phases in coniferous forests dominated by Douglas-fir in the Pacific Northwest. The use of vertical diagrams has the advantage that the spatial coherence of forest components becomes visible and that the information is presented in such a way that it is both illustrative and transferable. Some aspects become obvious which would have otherwise remained obscure: e.g. the 1955-freeze in the Humptulips plot, the size and shape of gaps in the canopy, or patterns in tree mortality and regeneration. The results of this study indicate that natural Douglas-fir forests are very heterogeneous and diversified: great variation can be found between individual trees; between eco-units and on the level of the forest mosaic.

Trees vary so much in age, size, shape and growth potential that they can easily be grouped together into different compartments of social classes, each with its own typical distribution pattern of various tree and stand parameters. Distinguishing different social classes can be useful when analysing the structure of second growth stands and of mature stands. In old-growth stands every single tree is so unique and completely different from its neighbours, that it is of no use to distinguish different tree compartments.

Douglas-fir is commonly believed to be a secondary pioneer species, that regenerates and establishes itself after extensive forest fires in the form of large, even-aged stands. However, this study indicates that in natural Douglas-fir forests eco-units in general are very small and heterogeneously distributed, so that it is more realistic to think of Douglas-fir stands in terms of a mosaic of eco-units rather than of one large, even-aged unit. The further stand development proceeds, the more heterogeneous the stands and their components will become. With increasing age Douglas-fir stands go successively through a second growth phase, a mature phase and an old-growth phase. The transition between the various phases is a gradual one: the old-growth phase may extend over many centuries before its biostatic eco-units gradually degradate by the process of fragmentation. According to Franklin et al. (1981) the stratification and diversity of old-growth canopies are responsible for an important micro-climatic buffer, by which old-growth stands provide a habitat for several unique plant and animal communities. Many species of epiphytic plants (mosses and lichens), invertebrates and insects are housed in old-growth canopies as well as several rare vertebrates like the northern spotted owl, northern flying squirrel and red tree vole (Franklin et al. 1981). Thus biostatic and degrading eco-units of Douglas-fir forests not only are very valuable from the viewpoint of nature conservation (Dietrich 1992), but also for the functioning of a well-balanced ecosystem (Maser and Trappe 1984; Maser et al. 1979).

In comparison with old-growth stands, second growth stands are characterised by relative uniformity. Note that this is only relative: in fact the structure of young stands is often very diverse and heterogeneous. This may be partially due to the heterogeneity of the situation after the zero-event, with dead wood irregularly spread over the surface, irregular seed dispersal, micro-relief and competing understory vegetation (Koop 1981, for German broadleaved "Urwald").

This leads to the question whether or not plantations of Douglas-fir, which are established all over the world in the form of even-aged monocultures, can provide all silvicultural requirements for optimal tree development. The present results indicate that a mixture of small-sized eco-units, which consist of only a limited number of trees, is a much more natural setting to grow Douglas-fir trees. This may be one of the reasons that strip cutting systems and selection cutting systems used in Douglas-fir silviculture in Europe are so successful. When the individual trees are exposed to a variable set of growth conditions in different eco-units, only certain trees will reach dominance and a relatively large proportion of trees will play a subordinate role in stand development. This leads to a very diversified situation, in which the growth potential of the trees is being utilised in a more nature-conform way, compared with the artificially simplified growth conditions in even-aged plantations. This certainly will affect tree growth, and, most likely, the other forest components as well: some of these organisms might depend on a more natural and diversified silvicultural system. Many of the ecological interactions between the various forest components are poorly understood, but there is growing evidence that a diversified forest structure is a necessity for a number of organisms, which play an important role in the decomposition of organic matter (Maser and Trappe 1984; Grier and McColl 1971; Trappe and Maser 1977; Fogel and Cromack 1977; Mispagel and Rose 1978), in nutrient cycling (Miller et al. 1976; Pike et al. 1972; 1975; Fogel and Hunt 1979; Maser et al. 1979) and in seed dispersal (Balda 1975; Bowman and Harris 1980).

It should be noted that not only old-growth Douglas-fir stands, but also second-growth stands provide excellent "field-laboratories" for baseline studies. This has relevance for Douglas-fir silviculture and plantation management. Because many second-growth stands are being harvested in western Washington and western Oregon, it should be a matter of concern to policy makers to preserve sufficient areas of unmanaged second-growth stands as natural research areas, including different sites, different genotypes and stands with different developmental histories (Harris 1984; Oliver and Larson 1990; Dietrich 1992). European foresters have become very aware of the values unmanaged forests can provide for basic research, perhaps because there are so few examples of virgin forests left in Europe.

# 3. ARCHITECTURE, DYNAMICS AND BIODIVERSITY OF OLD-GROWTH DOUGLAS-FIR STANDS

#### Abstract

Developmental aspects of Douglas-fir ecosystem functioning are related to the complex structural and spatial variability of old-growth stands, described earlier in this paper. The biodiversity of the forest canopy and the continuous initiation and development of numerous regeneration-units built by shade tolerant species, and their comparison with other studies on non-tree components of such stands, demonstrate the importance of small-scale dynamics of old-growth Douglas-fir forests.

# 3.1 Introduction

Old-growth Douglas-fir stands represent unique and very valuable forest ecosystems (Franklin and Trappe 1968; Franklin and Waring 1979; Meslow 1978; Harris 1984, Kuiper 1988a), in which on the average more than 100 different regeneration-units per ha can be identified, as will be seen later on in this chapter (Table 3.2). This demonstrates the importance of relatively small-scale dynamics of natural Douglas-fir stands. Similar patterns of forest development were reported by Stewart (1986) for old-growth Douglas-fir stands in the transition zone between the *Tsuga heterophylla* zone and the *Abies amabilis* zone in western Oregon (Figure 3.1).

Over the last decades a large amount of information has become available on the structural features of old-growth Douglas-fir stands. Cline et al. (1980); Franklin et al. (1981); Graham and Cromack (1982) and Maser and Trappe (1984) among others, have stressed the importance of the existence of large amounts of dead wood. The canopy of old-growth Douglas-fir trees has been studied extensively by Denison et al. (1972); Denison (1973); Pike et al. (1977) Caldwell et al. (1979); Carroll (1979a and 1979b). Even a single old Douglas-fir tree might be considered an ecosystem of its own, with complex interactions between the various canopy components, which play an important role in the nitrogen cycle and in various food chains (Carroll 1979b; Voegtlin 1982). On the forest mosaic level, the heterogeneous and well-layered vertical architecture of the old-growth Douglas-fir forest canopy seems to be responsible for the buffering of specific climatic and biological conditions which enhance the development of large populations of microorganisms and epiphytes (Franklin et al. 1981). Franklin et al. (1979) demonstrated that the presence of several rare organisms in old-growth stands is directly linked to their complex architecture. The wide spacing of trees in old-growth stands provides flying room for predators such as owls and sunlight for a second layer of young trees, turning a grove into a kind of multilayered apartment building (Dietrich 1993). Old-growth is warmer and more snowfree in winter, providing animals with better shelter and feed. It is cooler in spring and summer, conserving snow and soaking up rain, preventing flooding and erosion. More realistic, graphical models of the architecture of old-growth Douglas-fir stands, such are presented in this paper, are helpful to study those organisms in the context of the entire forest ecosystem. In previous chapters the architecture of natural

Douglas-fir forests was analysed in detail. Chapter 3 provides additional information on various aspects of Douglas-fir ecosystem functioning, which are directly related to the structural and spatial variability, as the "forest skeleton" described earlier in this paper.



Figure 3.1. Vertical diagram and crown projection map of a 1000+ years-old stand in the transition zone between the *Tsuga heterophylla* zone and the *Abies amabilis* zone in western Washington (Chinook Creek, Mount Rainier National park).



Figure 3.2. The author in front of a giant western red cedar tree; the same tree as indicated on the vertical diagram of figure 3.1 at 30 m on the base-line (Chinook Creek, Mount Rainier National park).

## 3.2 Material and methods

Vertical diagrams of 5 old-growth Douglas-fir stands, located within the *Tsuga heterophylla* zone in western Washington and western Oregon, of which stand ages ranged from around 250 to 1000 years, provide a comprehensive model of their architectural and spatial heterogeneity, which forms the "backbone" to better understand the complex ecosystem functioning, as referred to in the literature. No detailed description is presented here of the architectural variability itself, but rather of the functional aspects related to it. All plots were selected in "Reference Stands" established by Hawk et al. (1978). Table 3.1 gives further plot information. Vegetation types are after Franklin and Dyrness (1973).

plot	Ohanap.	R.S. 30	R.S. 27	R.S. 2	Carbon R.
location 1)	Α	В	B	В	A
altitude (m)	670	1000	870	510	600
exposition	W	-	-	NW	-
inclination	12%	-	-	35%	-
vegetation type 2)	1	2	3	4	5
plot size (ha)	0.12	0.12	0.10	0.10	0.13

Table 3.1: Plot location

A = Ohanapecosh and Carbon River stands in Mount Rainier National Park (WA); B
= Reference Stands in the H.J. Andrews Experimental Forest (OR).

 1 = Tsuga heterophylla - Abies amabilis / Polystichum munitum association; 2 = Tsuga heterophylla - Abies amabilis / Linnea borealis association; 3 = Tsuga heterophylla - Abies amabilis / Rhododendron macrophyllum / Linnea borealis association; 4 = Tsuga heterophylla - Abies amabilis / Berberis nervosa association; 5 = Tsuga heterophylla / Oplopanax horridum association (after Franklin and Dyrness 1973).

## 3.3 Results

## 3.3.1 Architectural aspects

Vertical diagrams of the architecture of old-growth Douglas-fir stands on modal to moist sites in the *Tsuga heterophylla* zone in western Washington and western Oregon, are given in Figures 3.2 and 3.3; three other such diagrams were presented earlier (chapter 2).

The following developmental trends can be deduced from the architectural data:

The forest canopy of the 250 year-old Ohanapecosh stand (Figure 2.6) is still relatively dense and has unclear layers. Douglas-fir forms a stratum clearly distinct from western hemlock, although western hemlock begins to penetrate the Douglas-fir canopy in some gaps.

In the 400 year-old stands (Figure 3.2, 3.3 and 2.7) the forest canopy is open and multi-layered and fragmented into many different regeneration-units (Table 3.2). The upper layer is built up by impressive Douglas-fir trees; often a second layer consists of fully grown and long-crowned western hemlocks and western red cedars (*Thuja plicata* Donn); two to three strata of western hemlock in various sizes and ages are present, waiting for an opportunity to penetrate into the canopy; and often a sparsely developed third layer of Pacific yew (*Taxus brevifolia* Nutt.) can be found. In some regeneration-



Figure 3.2. Vertical diagram and crown projection map of 400 year old Reference Stand 30 in H.J. Andrews Experimental Forest (western Oregon).



Figure 3.3. Vertical diagram and crown projection map of 400 years old Reference Stand 2 in H.J. Andrews Experimental Forest (western Oregon).

units a shrub-layer is well developed with species like Pacific dogwood (*Cornus nutallii* Aud. ex T. and G.), vine maple (*Acer circinatum* Pursh.), Pacific rhododendron (*Rhodo-dendron macrophyllum* G. Donn.) and golden chinkapin (*Castanopsis chrysophylla* (Dougl.) A. DC.). Standing dead trees and snags are very common. On the forest floor numerous logs in various states of decay are present, often covered by a dense blanket of mosses. The patchy ground vegetation consists of ferns, huckleberries and western hemlock saplings.

The 1000 year-old Carbon river stand (Figure 2.8) exemplifies the final stages of Douglas-fir stand development in the absence of major disturbances. Fragmentation of biostatic regeneration-units has proceeded to the extent that only a very few large Douglas-fir trees are present. The forest consists mainly of western hemlock and western red cedar units, which form a canopy layer beneath the scattered surviving giant Douglas firs. Below this layer there is a continuum of hemlock regeneration in all sizes and ages so that no clear strata can be distinguished. The amount of dead wood, both standing and lying on the forest floor is very large (Franklin et al. 1981). The diversification of the forest canopy and the continuous initiation and development of regeneration-units built up by shade-tolerant species, has resulted a very heterogeneous forest mosaic architecture.

In Table 3.2 some of the old-growth stand characteristics are summarized. Total biomass in the old-growth forests of the Pacific Northwest is typically four times that of the densest tropical rain forests (Dietrich 1993). The extremely high values for basal area and total standing volume result from 0.1 ha plots, containing more than an average number of huge Douglas-fir trees. Mean stand values for 1 ha plots would have been considerably lower. Nevertheless, such relatively dense patches do exist and these values should be considered representative for the mosaic of eco-units characteristic of old-growth Douglasfir stands. In forest mosaics, the distribution of biomass and volume is as least as important as their average amounts (cf. chapter 4).

The diameter distributions (Figure 3.4) support a sequential development pattern. When proceeding from stand age 250 years to age 1000 years the diameter distribution becomes increasingly wider and the shade-tolerant species become more frequent and form distinct groups compared with Douglas-fir. In the Ohanapecosh stand, Douglas-fir still clearly dominates both in size and in number. In the 400 year-old stands the number of Douglas-fir trees has declined and has shifted entirely to the higher diameter classes. The gradual transition towards the potential climax, i.e. western hemlock forest, has proceeded further in Reference Stand 2 than in the two other 400 year-old stands. The transition is most pronounced in the 1000 year-old Carbon River stand (Figure 3.4). The same trend is reflected by the tree species distribution in Table 3.2, in which the number of Douglas-fir trees per ha decreases significantly in comparison with the number of shade-tolerant species. On these sites western hemlock is considered a potential climax, mainly because of the dominance of western hemlock in the understory and in all the lower diameter classes, which suggests its eventual climax role (Franklin and Dyrness 1973). The data thus seem to confirm the traditional climax theory for the Tsuga heterophylla zone as described e.g. by Munger (1940) or by Orloci (1965). The architectural mosaic configuration corresponds well to the state of "eco-unit equilibrium", as described by Oldeman (1990)

Plot	Ohanap	RS 30	RS 27	RS 2	Carbon River	
Stand age	250	400	400	400	1000	
Number/ha	470	450	370	400	310	
Basal area/ha	156	178	193	121	210	
Total volume/ha	2900	2800	3700	2200	4300	
Tree species distribution (% of N)						
Psme <sup>1</sup>	50	30	35	25	20	
Tshe	42	45	27	60	76	
Thpl	-	13	20	4	4	
Tabr	2	12	18	11	_	
Abam	6	-	-	-	-	
Stratification (species	; mean heig	ght in m)				
upper layer: <sup>2</sup> middle layer:	Psme 75	Psme 75 Thol 45	Psme 80 Thpl 45	Psme 75	Psme 90 The 55	
lower laver:	Tabr 10	Tabr 10	Tabr 10	Tabr 15	Tupi 55	
upper stratum:	Tshe 30	Tshe 40	Tshe 50	Tshe 40	Tshe 45	
lower stratum:	Tshe 10	Tshe 15	Tshe 15	Tshe 15	Tshe 10	
Regeneration-units: n	umber/ha					
aggradation phase <sup>3</sup>	32	41	10	50	61	
biostatic phase	48	41	50	50	23	
degradation phase	24	25	50	10	46	
total/ha	104	107	110	110	130	

Table 3.2: Summary of stand data for 5 old-growth Douglas-fir plots

<sup>1</sup>)Psme = Pseudotsuga menziesii; Tshe = Tsuga heterophylla; Thpl = Thuja plicata; Tabr = Taxus brevifolia; Abam = Abies amabilis.

<sup>2</sup>) Layers are built up only by "trees of the present"; strata may be built also by "trees of the future" (terms used after Hallé et al. 1978).

<sup>3</sup>) Classification of development phases of regeneration-units are based on the architecture and growth potential of the tree components of each unit, as described by Oldeman (1990).



Figure 3.4. Diameter distribution (d.b.h.) for the five old growth plots. = Douglas-fir; = western Hemlock; = western Red Cedar; = Taxus brevifolia. Diameter classes at 10 cm interval; number of trees per ha.

## 3.4 Discussion

One should be careful to suggest universally valid developmental patterns by establishing a dated chronosequence of old-growth Douglas-fir stands. Franklin and Waring (1979) have provided some evidence that 250 year-old Douglas-fir stands may have had a different developmental history compared with 400 year old stands. Climatological changes too may have occurred over the past centuries. Even some slight changes in climatological conditions over a period of several centuries, like a shift of 1-2 weeks in the length of the growing season, or the occurrence of 3 subsequent years of relative drought instead of 1 dry year per century, may have affected and modified developmental patterns. The architecture of the Ohanapecosh stand shows features more characteristic of mature stands than of typical old-growth stands, even though its age of 250 years would clearly rank it among the old-growth stands (Old-growth definition task group 1986): stand density in the Ohanapecosh plot is quite high, total volume is high and the h/d-ratio of the individual Douglas-fir trees is higher than one would expect for trees this age (mean h/d-ratio is 75; S.E. =13; n=29).

Furthermore, in the Carbon river example we are faced with the peculiar situation that a "serial species", Douglas-fir, outlived at least two generations of western hemlock. And no one can tell how long it will take before the last Douglas-fir finally will have disappeared there. This makes any climax theory for Douglas-fir stands rather hypothetical. An analogous dilemma has been met by Koop (1981) with long lived pioneer oaks (*Quercus robur* L.) surviving several generations of European beech (*Fagus silvatica* L.); the said to be climax species. All in all, the patterns rather support the new paradigm of irreversible developments in which initial conditions are determinants (Oliver and Larson 1990; Prigogine and Stengers 1984) than the classical hypothesis of cyclic succession.

#### 3.4.1 Functional aspects

To give an example of the need for more realistic models in canopy studies, Carroll (1979b) clearly indicated how various ecosystem processes were linked to the complex structure of old-growth Douglas-fir canopies. For instance during the transition from a dry to a wet canopy important changes occurred in the leaching potential of canopy components for dissolved nitrogen. The moisture status of the canopy is directly related to canopy architecture. Because the bulk of nitrogen in solution was in organic form, leached organics play an important role in the functioning of canopy ecosystems (Hence the term "phyllosphere", introduced by Ruinen (1956), by analogy with the rhizosphere of roots).

The stream of nutrient salts and metabolites excreted by the cuticula of leaves or needles, serve as the nutrient medium of the epiphyllic micro-vegetation, while on the other hand nitrogen-fixing bacteria offer a constant source of bound nitrogen, which may either be taken up directly by the leaves and then transported through the trees, or it may also be washed off by the rain together with the leaf excretions and, via the soil, reach the ordinary upward nutrient stream (Ruinen 1956). Leached organics can serve indirectly as a base for many canopy food chains. The phyllosphere is first colonized by bacteria, actinomycetes and fungi. The nutrients supplied by leaf exudates and by the *Azotobacter* population provide an adequate substrate for successive colonizers: algae, yeasts and lichens appear and a mixed population of other unicellular organisms such as flagellates, amoebae, myxomycetes and ciliates develops, which feeds on the other micro-organisms. Arthropods may follow in due course. Under conditions of adequate humidity, temperature, nutrition and longevity of the leaf, mosses, ferns, phanerograms and epiphytes may develop. Such a much expanded phyllosphere population presents conditions for colonization by still more micro-organisms in the tangle of roots and on the leaflets of the epiphyllic vegetation (Ruinen 1961).

In the study by Carroll (1979b) subtle and pervasive effects of the arthropod fauna on nutrient exchanges within the canopy could be noted. Distribution of arthropod communities throughout the canopy was often highly aggregated. Microarthropods associated with needles and twigs, such as mites, were very abundant in the canopy. According to Carroll (1979a) the canopy microfauna may significantly affect standing crops of microepiphytes and thus indirectly affect patterns of nutrient exchange within the canopy. Defoliating and sucking insects appeared to be of little importance in old-growth Douglas--fir canopies: less than 1 % of the new foliage is consumed by caterpillars each year. This may be partly due to the large number of spiders and other predators found in the canopy (Denison 1973). Ruinen (1974), by studying trees and shrubs growing in humid tropical conditions, demonstrated that the microbial layers of the phyllosphere showed marked differences in species composition and surface spread, which are seemingly characteristic for particular tree species. Not only did different plant species show striking differences in their phyllosphere populations of micro-organisms, but different leaves of one and the same tree showed variations depending on the position of the leaf in the canopy and on the age of the leaves (Ruinen 1974). This illustrates that realistic models of the canopy structure are urgently needed to provide a framework for the interrelatedness of various canopy components and functions that are linked to specific canopy structures.

Not only in the tropics a phyllosphere population capable of nitrogen fixation exists. Under all perhumid conditions such as forests in the cloud belt of mountains, a heavy microbial growth prevails. Moisture is a major factor in the development and survival of the leaf surface population, providing space and enabling the exchange of metabolic products in the ever-changing food web. The moisture at the upper leaf surface caused by dew, mist condensate and rain results in a rapid growth of invading microbes, which are for the greater part motile and move freely in the moisture film (bacteria, flagellates, etc.), or spread passively on slime and excreted products (blue-green algae) but also by filamentous growth in the liquid (fungi, blue-green algae). Nutrients accumulating on the outside of the leaf during the day may subsequently be re-absorbed together with the metabolic and decomposition products from the phyllosphere population during the nightly wetting of the leaf surface by dew. This special advantage of the phyllosphere where the soluble products of nitrogen-fixation are transferred directly by the leaf into the plant body, is of outstanding importance in the forest canopy where long-distance transport and losses are greatly reduced by cycling in the upper strata, as is suggested by the nutrient content in wood and bark increasing with the height of the trees (Ruinen 1974).

Another well documented architectural feature of natural Douglas-fir forests is the existence of large amounts of dead wood, both standing snags and logs down on the forest floor (Franklin and Waring 1979; Cline et al. 1980; Franklin et al. 1981). Trees in temperate climates decay slowly, thus making the ground a crisscrossed obstacle course of fallen logs. Old-growth forests leave so much woody debris and half-decayed logs on the ground that it can be difficult to simply walk through (Graham and Cromack 1982). Dead wood is an important component in nutrient and energy cycling; it is a site for nitrogen-fixation; it is a buffer and source of soil organic matter and especially snags are very important for wildlife (Abee and Lavender 1972: Balda 1975; Maser and Trappe 1984; Cosijn et al. 1983; Burghouts 1993). Leaving dead snags in a forest stand will increase bird numbers by 30 percent. Seventy percent of Pacific Northwest amphibians and eightyfive percent of the region's reptiles need downed logs to survive: they live in the wet, rotting hollows (Dietrich 1993). Monitoring the distribution pattern of snags and logs, which can easily be incorporated in vertical diagrams and crown projection maps, will vield vital information for both ecosystem research and forest sanitation management. Because dead wood is a transitory structure it must be continuously produced to fulfill all of its functions (Franklin et al. 1986). Old growth forests house some 150 species of mammals and perhaps 1500 species of invertebrates (Devrup 1975). More than 100 species of birds, fish, reptiles and mammals depend on old-growth ecosystems, of which the most famous one has become the Northern Spotted Owl (Forsman et al. 1977; Forsman 1980).

This rare owl played a crucial role in the region's political debate over the past 15 years between environmentalists and the timber industry about setting aside large areas of oldgrowth forests as owl-habitat conservation areas (being charged as a battle between "tree huggers" and "timber beasts"). By the end of the 1980's it was clear old-growth forest was nearly exhausted from private lands, and the bulk of the old-growth was gone from state-owned lands as well. Finally, in 1990 the U.S Fish and Wildlife Service took the decision that the Northern spotted owl was endangered, due to the overcutting of the remaining old-growth forests by the timber industry. Under the Endangered Species Act, logging that would harm the bird, would be prohibited. As a consequence, over 3.5 million hectares of timberland was set aside as habitat area for the spotted owl. The Bush administration, aware of the hardship that the owl conservation strategy would cause the region's timber industry, asked some government scientists to review the report on "A conservation strategy for the Northern Spotted Owl", and if possible, to discredit it. After review, they announced they couldn't. The report represented the best owl biology available. The wood industry was deflated. For two decades it had fought over the oldgrowth issue, fairly successfully, to confine park and wilderness areas to the high alpine country of little commercial value. Now it had been beaten by a bird (Dietrich 1993).

Another interesting example of a species that houses uniquely in the canopy of oldgrowth Douglas-fir forests is the red tree vole. Some tree voles descend from their branches to eat truffles buried in forest humus. The truffles are fungus colonies that develop from mycorrhizal fungi. The voles eat the truffles, scamper to new sites, and excrete droppings that contain undigested mycorrhizal spores, by which other trees may be inoculated (Trappe and Maser 1977; Maser et al. 1979). Similarly, many more examples can be given. All these architectural and functional features of forest ecosystem biodiversity tally with the thorough and close confrontation with architectural data in the present chapter. The architectural analysis contributes to bring these features into focus by allowing to map the life spaces of organisms on the horizontal and vertical diagrams (e.g. Stocki 1983). More complete studies in this respect remain to be done, making use, among others, of modern means of access to forest canopies (Hadley and Schreckenberg 1990).





Figure 3.5: Large amounts of coarse woody debris on the forest floor of old-growth forests, making it difficult to simply walk through.



Two examples of old growth Douglas-fir stands in western Washington.

## 4. MATURE DOUGLAS-FIR STANDS IN WESTERN WASHINGTON

#### Abstract

The architecture, age distribution and genetic variability of Douglas-fir in a 500 m long elevational transect on a slope in a mature Douglas-fir stand was analysed, using stand architecture diagrams. The transect was divided in four sub-plots, corresponding to different elevational classes. A total of 200 trees were cored at breast height for age determination; for 100 Douglas-fir trees the genetic variation of ten isozyme loci was related statistically to variation in tree height and diameter at breast height. The proportion of variation between elevational classes was significantly higher for the quantitative parameters than for the isozyme variation and was related to the site gradient. The relatively wide age distribution in all four sub-plots indicates that Douglas-fir develops successfully in multi-aged stands, so that it has a wide "silvicultural amplitude".

## 4.1 Introduction

A better understanding of the architecture and age structure of natural Douglas-fir forests is required in many areas of forestry and is especially relevant for forest ecology and for Douglas-fir silviculture (Hillgarter 1978; Leibundgut 1982; Oliver et al. 1986a; Oldeman 1990). Douglas-fir is commonly believed to be a secondary pioneer species in the *Tsuga heterophylla* zone in the Pacific Northwest, where it becomes established in large even-a-ged stands after major forest fires. However, in early the stages of secondary succession following either wildfires or logging and burning, there is a large variation in (micro)site conditions, due to a wide range of degrees of burning severity and subsequent heterogeneity of the vegetation. This may cause an extension of the phase of stand establishment over several decades (Franklin and Dyrness 1973; Franklin et al. 1979; Hemstrom and Franklin 1982). In fact, Douglas-fir trees may continue to regenerate after major disturbances for several decades where growth is slow before the available \*growing space becomes reoccupied, resulting in a wide age range in the stand (Oliver and Larson 1990).

An analysis of the age structure of 50 year-old, semi-natural, second-growth Douglas-fir stands in western Washington showed an age range of at least 10 years for the dominant trees (chapter 5). Oliver and Larson (1990) refer to such a group of trees regenerating after a disturbance as a "cohort". The age range within a single cohort may be as narrow as 1 year or as wide as several decades, depending on how long trees continue invading after the disturbance. Although it is well established that site and micro-site factors have an influence on the structure and development of a forest stand (Leibundgut 1982; Mayer 1984; Dyrness et al. 1974; Zobel et al. 1976), surprisingly little research has been done so far as to these aspects of forest ecology in heterogeneous and essentially multi-aged natural Douglas-fir stands.



Figure 4.1. Transect strip on the East slope of Hugo Peak (Eatonville, WA), 500 m long, with its sub-division of plots A, B, C and D.

## 4.2 Material and methods

#### 4.2.1 Research site

In a 500 m long and 10 m wide transect plot in a mature Douglas-fir stand in western Washington, tree and forest architecture were analysed by graphical methods derived from those used by Hallé et al. (1978); see chapter 2. The american Douglas-fir transect plot is located at 550 m above sea level on the east slope of Hugo Peak in the C.L. Pack Experimental Forest of the University of Washington, near La Grande (Eatonville, WA), 25 miles west of Mount Rainier. The area is of volcanic origin and the higher elevations are generally characterized by colluvium and residual soils formed from andesite. The rainfall average is approximately 1100 mm per year; mean annual temperature is 9.5 degrees C. Detailed plot information is given in Figure 4.1.

## 4.2.2 Measurements

In the transect plot diameter at breast height (d.b.h.), topheight, height of crown base and crown width were measured for all trees. The trees then were drawn to scale on vertical diagrams and crown projection maps.

Tree ages were determined by taking increment cores at breast height, using a 30 cm increment borer. From trees larger than d.b.h 60 cm (over 30 % of all trees sampled) the missing number of growth rings was estimated. To do this accurately, radial stem development of 50 Douglas-fir stumps on a nearby clearcut area was analysed along 4 different radii. This made it possible to keep track of growth layers by width pattern, so as to account for missing or incomplete rings. Because early radial development of Douglas-fir was characterised in this case by wide and regular growth rings, age estimates were considered accurate within a range of plus or minus 2 years in case less than 10 growth rings were estimated to be missing, and plus or minus 5 years in case more than 10 rings were estimated to be missing. All cores were analysed under a computer mounted dissecting microscope (positiometer). The cores from suppressed western hemlock trees (Tsuga heterophylla (Raf.) Sarg.) were carefully examined in the same way and their radial growth pattern was also compared with that of stumps of similar trees on an adjacent clearcut area. However, their age estimates are less certain, because it is known that suppressed western hemlock trees in some years may omit the formation of growth rings altogether. It is possible that this holds true for suppressed Douglas-fir as well. The number of growth rings of all suppressed trees thus represents a minimum assessed age at breast height.

Some information about the developmental history of the stand was obtained from analysis of cores taken from a few still existing fire-scarred trees of the previous Douglasfir generation and of a number of stumps of the previous stand on a nearby clearcut area.

#### 4.2.3 Isozyme analysis

Vegetative buds were sampled from branches of 106 different trees with a shotgun, using pheasant-duck cartridges. Approximately seven vegetative buds per tree were collected and their meristems were used for isozyme analyses. The procedures for electrophoresis and chemical analysis were described by Conkle et al. (1982) and Cheliak and Pitel (1984). To describe the levels of genetic variability, allele frequencies were measured and a fixation index was calculated after Hartl (1980). Seven enzyme systems were used, including *Glucose-6-phosphate dehydrogenase (G6P), Isocitrate dehydrogenase (IDH), Phosphoglucomutase (PGM), 6-Phosphogluconate dehydrogenase (6PG), Phosphoglucose isomerase (PGI), Melate dehydrogenase (MDH) and Glutomate dehydrogenase (GDH). There were ten scorable loci in these isozyme systems. For each locus the different electrophoretic bands were marked according to their frequencies and relative migration distance compared to the most frequent allele; the migration distance of which was defined as 100 %. The variation of tree height and diameter at breast height between the elevational plots was analysed statistically with covariance analysis (Hicks 1982). Tree age was the covariant.* 



Figure 4.2. Vertical diagram and crown projection map of the 10 x 110 m plot Hugo Peak A. Tree ages are indicated above the trees.

## 4.3 Results

The variation in tree and stand architecture along the site gradient on Hugo Peak is presented in Figure 4.1: the total number of trees/ha and the number of trees/ha with d.b.h. over 20 cm were highest in plot A, but almost identical in the other three plots. When proceeding from plot A to plot D there was a decline in the number of Douglas-fir trees per ha, whereas total standing volume for all species per ha showed a pronounced increase from top to bottom. Profile diagrams are presented for the four sub-plots of Hugo Peak in Figures 4.2 to 4.5. The strip between the 30 and 60 m along the baseline of the transect is illustrative of the very complex age structure (Figure 4.6).



Figure 4.3. Vertical diagram and crown projection map of the 10 x 110 m plot Hugo Peak B. Tree ages are indicated above the trees.



Figure 4.4. Vertical diagram and crown projection map of the  $10 \times 100$  m plot Hugo Peak C. Tree ages are indicated above the trees.



Figure 4.5. Vertical diagram and crown projection map of the  $10 \times 130$  m and  $10 \times 50$  m plots Hugo Peak D. Tree ages are indicated above the trees.



Figure 4.6. Detail of part of the Hugo Peak A plot between 30-60 m along the baseline with many small regeneration-units. Tree ages are indicated above the trees.

The distribution of tree height, diameter, and of relative crown lengths of Douglas-fir (Figure 4.7) showed a clear shift towards the higher classes when proceeding from the top of Hugo Peak towards the bottom. Mean values of tree height, d.b.h., volume, h/d-ratio and crown lengths for the 100 tallest trees/ha also increased considerably (Figure 4.8), but so did the standard errors, which indicates that mean values are less relevant than the actual values to analyse tree and stand architecture in natural Douglas-fir forests. For explanatory purposes in particular, when architectural diversity increases the immediate environment of each tree becomes more important than the average stand environment (Rompaey 1993).



Figure 4.7. Comparison of height distribution, diameter distribution and distribution of relative crown lengths for Douglas-fir between the four Hugo Peak plots. When proceeding from plot A to plot D a shift towards the higher classes is apparent.  $\blacksquare = Douglas$ -fir;  $\blacksquare = western$  hemlock;  $\blacksquare = western$  red cedar.



Figure 4.8: Mean tree parameter values with their 95 % interval of confidence for tree height, d.b.h, tree volume, h/d-ratio, crown length and crown percentage, for the 100 tallest trees/ha in the four sub-plots on Hugo Peak (A,B,C and D).
	gene	diversity			
locus	(1)	(2)	(3)		
G6P	0.5267	0.5036	0.0439		
IDH	0.2475	0.2436	0.0158		
PGM	0.2451	0.2413	0.0155		
6PG I	0.0649	0.0641	0.0123		
6PG II	0.0000	0.0000	0.0000		
PG1 I	0.0000	0.0000	0.0000		
PG1 II	0.0469	0.0469	0.0000		
MDH I	0.0554	0.0526	0.0505		
MDH II	0.3169	0.3125	0.0190		
GDH	0.0000	0.0000	0.0000		
average	0.1503	0.1465	0.0157*		
S.E.	0.0560	0.0541	0.0058		

 Table 4.1: Analysis of gene diversity and degree of differentiation for ten loci between four elevational plots.

(1) total gene diversity; (2) gene diversity within plots; (3) degree of differentiation between elevational plots

\* significant: p < 0.01

Table 4.2: Analysis of covariance of tree height and diameter at breast height with tree age as the covariant for Douglas-fir between the elevational plots.

Source	DF	SumSq	MeanSq	F	SumSq	MeanSq	F
		Height			Diar	neter	
Plots	3	2362.16	787.39	13.014**	3976.87	1325.62	2.943*
Age	1	1007.00	1007.00	16.644**	1972.23	1972.23	9.378*
Residual	57	3998.60	60.50		2567.51	450.48	-
Total	61	6817.84	-	-	31626.61	-	-

\*\* significant p < 0.01

\* significant p < 0.05

D.F = degrees of freedom; SumSq = sum of squares; MeanSq = mean squares; F = test variable.

The values for the proportion of genetic differentiation between the elevational plots (Table 4.1) ranged from 0 to 0.050, with a mean value of 0.016 (significant at p < 0.01). This means that about 1.6 % of the detected overall genetic variation might be ascribed to variation between elevational plots. The rest (i.e. 98.4 %) existed within and independently of the elevational plots (Beuker 1988).

Covariance analysis indicated that there were significant differences between the elevational plots in tree height and d.b.h., but these differences were partly due to differences in tree age (Table 4.2). From the sum of squares it was estimated that about 35 % of the overall variation in tree height on Hugo Peak existed between the elevational plots and that 15 % of the overall variation was due to differences in age. For d.b.h. the variation between elevational plots was estimated to be 13 % of the overall variation, and 6% of the overall variation was due to differences in age.

## 4.4 Discussion

## **Developmental history**

The forest at Hugo Peak is believed to originate from a major fire about 180 years ago. Hemstrom and Franklin (1982) indicate that intense forest fires usually obliterate previous stands, leaving only a few scarred survivors. On hill-tops fires tend to be more intense than at the base of a slope, because heated gasses ascend. Apparently this is what happened at Hugo Peak at that time, because at the base of the slope still a few old fire-scarred Douglas-fir trees are present. These trees are estimated to be about 350 years old now. There are some indications from a partially overgrown fire scar on a dead western red cedar tree that about 180 years ago perhaps two fires occurred 10 years apart from each other. The first fire may have killed most of the forest but may not have burned it down completely, leaving behind a considerable amount of dead wood as potential fuel. A second fire then of course could have followed. The few survivors, no more than 5 or 6 trees in the whole Hugo Peak area, consequently were the principal, perhaps the only source for regenerating the area.

The age distribution (Figure 4.9) shows that the regeneration of Douglas-fir was spread over more than 100 years. This is a rather long establishment period, especially on an eastward facing slope (Harris 1984). Hemstrom and Franklin (1982) report that the wave of regeneration, which begins soon after a fire, produces a skewed age structure, with the number of trees regenerating in a single year generally rising to a peak within 20 years. This number may drop to a low level within 50 years or may continue at slowly declining levels for 100 to 150 years (Franklin et al. 1979). The pattern of regeneration at Hugo Peak therefore is not exceptional. Regeneration probably took place in more than one wave: the first one originating from the 5 or 6 scarred trees, the seeds of which generated only a limited number of trees, i.e. about 15 % of the total number of stems present today. The second and largest regeneration wave probably appeared at the time that these trees started to bear fruits in their turn and were responsible for regenerating most of the area: 70 % of the present Douglas-fir trees is between 130 and 150 years old. In later

later years the remaining gaps gradually filled up, accounting for 15 % of the total Douglas-fir regeneration.

Patterns of species dominance and changes in stand architecture are not the result of obligatory \*rules of nature which forest stands must follow. They are simply the result of interactions between plants and are emergent properties of these different interactions (Oliver and larson 1990). After a major disturbance new herbs, shrubs and trees reoccupy the available growing space, depending on the type of disturbance, competing vegetation, availability of seeds from surrounding areas, suitability of microsites for growth, and predation by animals. The competitive advantage of some species over other species which invade later, often allows them to dominate other species for many years or even centuries. As a result the species composition and forest architecture in a stand are largely the result of the type of disturbance which initiated them. Tree species such as Douglas-fir can begin growth at the same time as the rapidly growing invading herbs (often annual and biennials), but generally are not so numerous, do not grow so rapidly at first and do not produce seeds until they become older (Oliver 1978; Wierman and Oliver 1979). Trees such as western hemlock can either predominate the site soon after a disturbance or become dominant later in their lives, depending on the site and on the other plants present on the area (Franklin and Dyrness 1973). The age range of invading plants, therefore, is limited by the time it takes the growing space to become reoccupied. herbaceous and shrub communities may at times pass through stages of development similar to forest stands, but over the course of a few years during the stand initiation stage, or later on during the understory reinitiation stages of forest stand development, as the forest canopy opens up by the process of fragmentation (Oliver and Larson 1990).

The results of the isozyme analysis in this study indicate that the genetic variation between the elevational plots was only 1.6 % of the total detected isozyme variation. This is consistent with values reported by Yeh and O'Malley (1980) and by Merkle and Adams (1987).

A shift in gene frequencies from the top of Hugo Peak towards the bottom of the slope had been looked for in this study. It could have partially explained the observed differences in tree development in the Hugo Peak example. But the present results indicate that genetic variation cannot be considered a main or even significant cause of differences in tree development along the Hugo Peak transect. Most of the differences in tree size and tree architecture between the elevational classes therefore must be adjustments to site influences. Shifts in soil texture and moisture availability along the transect are likely to be the prime causes.

Rompacy (1993), when analysing forest gradients in tropical rain forests of West Africa, also found that gradients in moisture availability explained the elevational trends along slopes for tree density, species composition, basal area and stem biomass. In his studies, species composition changed form "drier" species upslope to "wetter" downslope; tree density decreased towards the wet end of the gradient from upper slope to lower slope; a general trend of increasing basal area and of total standing volume of the large tree species was found towards the wet end of the gradient (Rompaey 1993).



Figure 4.9. Age distribution of 235 trees in the Hugo Peak transect. Note the wide range of ages for Douglas-fir: regeneration of Douglas-fir took place over a period of more than 100 years. Different regeneration waves can be identified.  $\blacksquare$  = Douglas-fir;  $\square$  = western hemlock;  $\square$  = western red cedar.



Figure 4.10. Edge of a recent clearcut area adjacing Hugo Peak. Since most of the trees on subplot D have been cut, the trees on the picture represent the lower part of Hugo Peak subplot C (photo E. Beuker).

The Hugo Peak transect is an example of the influence of site quality upon the architecture and development of a forest community dominated by Douglas-fir. Parameters that are obviously linked to a gradient in soil texture and moisture availability are: number of Douglas-fir trees/ha, total standing volume, diameter distribution, tree height distribution and distribution of relative crown lengths of Douglas-fir, and mean height, mean diameter, mean volume and mean crown lengths of the 100 tallest trees/ha. Furthermore, the forest and its components on the best site seem to have developed faster towards a more mature phase of development (Kuiper 1988b). Their architecture begins to show characteristics typical of old-growth stands, whereas the trees and the architecture of the stand on the poorest site still show characteristics of second-growth stands.

The relatively wide age distribution suggests that in the *Tsuga heterophylla* zone Douglas-fir may successfully be used in multi-aged silvicultural systems. This indicates that Douglas-fir has a much wider "silvicultural amplitude" than the range of silvicultural systems commonly adopted.

## 5. SOCIAL TREE CLASSES IN SEMI-NATURAL SECOND-GROWTH DOUGLAS-FIR STANDS

#### Abstract

The architecture of semi-natural second-growth Douglas-fir stands in western Washington was studied to quantify the development of the tree population into social classes (Leibundgut 1959). Three plots were selected on sites of site class 2 (McArdle 1961) with a stand density of 160, 232 and 304 trees per ha respectively and three plots on relatively poor sites (site class 4), with a range in stand density of 512, 1080 and 1296 trees per ha. For each plot significant differences between social classes could be identified by the parameters h/d-ratio and tree volume. For the plots on good sites age distribution, total standing volume and distribution of the number of stems over the social classes closely resembled each other. This allowed an analysis of the influence of stand density. Very significant differences between the plots were found in dominant and codominant trees. Dominants and codominants numbered 68 percent of total number of stems on average, and their total crown projection area averaged 64 percent of the plot area, indicating for all 3 plots an utilisation of the resources very different from even-aged managed stands. For the three plots on poor sites much variation existed in the distribution of tree age and number of stems over the social classes, so that no comparisons between the plots were possible. Dominant and codominant trees accounted for 47 percent of the total number of stems and 48 percent of crown cover on average, indicating that in terms of timber production, semi-natural stands do not allocate all resources to timber logs. All plots were characterised by a very heterogeneous horizontal and vertical stand architecture. This has important silvicultural implications.

## 5.1 Introduction

The term semi-natural second growth stand refers to a special stage in secondary forest succession in the Pacific Northwest, following logging and (slash) burning of the previous generation of old-growth stands. Because many old-growth stands were cut during the so called railroad loggings at the beginning of the 20th century, the natural forest reestablishment that followed, frequently developed into well stocked second growth stands, in which a large number of Douglas-fir trees are present. Many of these trees now have reached marketable seizes, and logging of second growth stands is taking place at an alarmingly rate. Stands are called "semi-natural" because of their rather special developmental history, in which human interference was largely restricted to initial logging activities, after which the stands were left to themselves to develop naturally during a period of 50 or 60 years. Second growth Douglas-fir stands are essentially non-uniform with regards to tree sizes, tree composition, age structure and canopy development (Oliver et al. 1986b), especially when compared with the even-aged Douglas-fir plantations which are established all over the world. A large biodiversity thus seems to be a characteristic feature both of natural old-growth and of semi-natural second-growth stands (Franklin and Dyrness 1973; Waring 1979; Oliver et al. 1986; Franklin et al. 1986; Kuiper 1988a; Otto 1984; Olson and Martin 1981).

Three distinct stages of stand development can be identified for second growth stands, when focussing on the tree components mainly: an open growth stage (Oliver et al. 1986a), a stage of plastic response (Harper 1977) and a stagnation/mortality stage (Drew and Flewelling 1979). These stages would refer to stages of forest mosaic development; not to phases of eco-unit development (Oldeman 1990). Oliver and Larson (1990) distinguish a forest mosaic pattern of four stages of secondary succession following a major disturbance. The stand initiation and stem exclusion stages are most relevant for second-growth stands; the other two stages referring to mature and old-growth stands mainly.

- 1) stand initiation stage
- 2) stem exclusion stage
- 3) understory reinitiation stage
- 4) old-growth stage

Before the available growing space is reoccupied, trees are expanding in an "open growth" condition; the term referring to the typical architecture of long and relatively wide tree crowns of trees that have developed solitary, unhampered by neighbouring tree competition. Parts of a stand may be in the stem exclusion stage, with some trees dying from competition, while other, more open areas are still in the stem recruitment stage, because of spacing, species, and site irregularities. In fact, a given stand may take several decades before all parts make the transition from the stands initiation stage to the stem exclusion stage (Oliver and Larson 1990).

In the case of Douglas-fir, the open growth stage may be relatively short or may extend over several decades. This is often the case when the re-establishment of trees following logging and burning was delayed by heavy weed and shrub competition. Such tree-less development phases are common features in forest succession (Fanta 1985). The vegetation in these early stages of secondary succession of weeds and shrubs interspersed with solitary trees, is typically very heterogeneous (Franklin and Dyrness 1973). Much of this variability is attributable to site differences caused by biotic and abiotic remanence (Oldeman 1990), such as a wide range of types of logging disturbance and degrees of burning severity (Hemstrom and Franklin 1982). By the process of fusion, the initial high number of very small regeneration units (often as wide as the crown of a single solitary tree), merge into a limited number of larger units, which in the course of natural events, will develop into a closed forest canopy. The open growth phase ends, when neighbouring tree crowns start to touch each other. Note that in plantation forestry the open growth phase will be kept as short as possible, due to the practice of planting well rooted trees at regular spacings: usually within a period of 5 years time the trees close in and enter the next stage in stand development.

After the available growing space is reoccupied, those plants with a competitive advantage in size or growth strategy are able to expand into the growing space occupied by other plants, and reduce their growth rate or kill them. This stage is referred to as a stem exclusion stage (Oliver and Larson 1990), or sometimes as a stage of plastic response (Harper 1977).

As trees close in, they begin to compete with adjacent trees for light, water, nutrients, and other components of the \*available growing space. During competition trees adapt their shape by a plastic response, by which they adjust to the changing growth conditions, as the amount of respiring tissue increases relative to the amount of photosynthetic tissue of each tree (cf chapter 3). The more the respiring tissue increases, the more the allocation of photosynthates is influenced: firstly towards a reduction of diameter growth and in case of very strong competition, towards a reduction of height growth (Assmann 1961; Mitchell 1975). The plastic adjustment response enhances existing differences in growth rate between the trees.

If all trees in a stand were identical, none would have a competitive advantage which would allow it to expand by taking growing space away from a neighbour. Each tree than would eventually expand until all photosynthate was consumed by its own respiration to keep its increased size alive, and it would no longer grow. If all trees behaved uniformly in this manner, the stand would eventually quit growing and become a "stagnant stand". The uniform age and spacing of forest monoculture plantations may be creating stands which approach stagnation more commonly than do naturally grown forests.

Actually, some trees outgrow others in a stand because even monoculture plantations are rarely uniform in site, tree age, spacing or genetic potential. As some individuals outgrow others, they take away available growing space by shading foliage. The reduced growing space of the tree being outcompeted, forces it to put less of its reduced photosynthate into growth, and it declines in growth. The result is crown differentiation, with some trees becoming larger at the expense of others.

The degree of dominance and suppression within a canopy stratum has been described by classifying trees into crown classes: (Assmann 1961). Usually 4 categories of trees are distinguished, representing different growth potentials of trees: \*dominant trees, \*codominant trees, \*intermediate trees and \*suppressed trees. Each \*social class (crown class), may be characterised by specific distribution patterns of various tree parameters (Greggs 1981; Oliver and Murray 1983; Faber 1986).

During the subsequent stage of stagnation and mortality (Drew and Flewelling 1979), dominant and codominant trees are hampered in their growth due to neighbouring tree competition, whereas trees in the lower social classes will be suppressed and will gradually be eliminated from the stand by premature death. During this phase of stand development the initial heterogeneity and stratification levels out by converging development of neighbouring small regeneration units, forming a single canopy stratum of dominant and codominant trees, which gives the (wrong) impression of a uniform, evenaged stand. Current silvicultural practices in the Pacific Northwest are such, that most semi-natural Douglas-fir stands are already in a stagnation/mortality stage when scheduled for first thinning (Reukema 1975; Oliver et al. 1986b).

The development of social tree classes as described above, seems to be a key-factor in second-growth Douglas-fir stand dynamics (O'Hara 1988; Oliver and Larson 1990; Lassole 1979). According to Oliver et al. (1986b) little work has been done so far to quantify the distinction between social tree classes in Douglas-fir stands, which was the main objective of this chapter.

## 5.2 Material and methods

#### 5.2.1 Basic experiment design

It was recognised that trying to make a comparison between different semi-natural Douglas-fir stands, can be quite tricky, due to the large variation that exist between and within such stands. Nevertheless, an attempt was made for 6 different semi-natural second growth Douglas-fir stands to quantify the variability of their tree components in terms of their development into social tree classes.

Because it was assumed that tree competition largely depends on stand density, and that stand density therefore may influence the distribution of trees over the social classes, stands were selected with increasing density order. As site factors might influence the architecture and development of Douglas-fir stands too (Keyes and Grier 1981; Grier et al. 1986; Kuiper 1988b), two series of plots were established: one on productive sites (site class 2; McArdle 1961) and one on poor sites (site class 4).

Number of trees per ha and basal area per ha at a given age were used as an expression of stand density. This was considered convenient, although it was realised that their use as a stand density measure is limited, since a given number of trees or basal area per ha could represent very different stand histories, stand architectures, yield potentials and tree forms (Oliver and Murray 1983). Therefore the above stand density measures were compared with the real situation as represented by crown projection maps. Site quality was verified by the site index of dominant height at age 50 years and compared with site index curves of McArdle (1961). Note that such a site index is a measure of past forest growth and not of future forest productivity (Oliver and Murray 1983). All trees were assigned to a specific crown class in the field, by a relative classification of trees exposed to approximately the same light conditions. The social position of the tree crowns could be verified objectively with the vertical diagrams.

## 5.2.2 Sites

All plots were located within the *Tsuga heterophylla* zone (Franklin and Dyrness 1973) in western Washington (Fig 5.1). According to the classification by Franklin and Dyrness (1973) the site class 2 plots belonged to the *Tsuga heterophylla-Polystichum munitum* association (plot 1), which typically occupies moist sites, and to the *Tsuga heterophylla-Rhododendron macrophyllum-Berberis nervosa* association (plots 2 and 3), which is considered the climatic climax association for the *Tsuga heterophylla* zone (Franklin and Dyrness 1973).

Plot 1 was located near Cathlamet in southwest Washington, on a plateau overlooking the Columbia river. It is in fact a third-growth stand. Old growth stands were cut in this area around 1840. Eighty five years later the second growth stands were harvested and a natural third-growth Douglas-fir stand has developed. The very low tree density in this stand probably was due to a large deer population in the area, which reduced most of the natural regeneration. Plot 2 was located on Pillchuck Tree Farm, close to Arlington (WA). Here the old growth stands were cut around 1885, after which the area was regenerated mainly by red alder (*Alnus rubra* Donn). Thirty five years later the alder was largely cut and a natural Douglas-fir stand developed. The soil is a well drained, deep sandy loam with pebbles, developed in glacial outwash material.

Plot 3 had a similar developmental history and was located on the same site as plot 2. The only difference was that after removing the red around 1920, a very dense, Douglas-fir/western hemlock (*Tsuga heterophylla* (Raf.) Sarg) stand developed. About 1968 most of the western hemlock was precommercially thinned from below, so that a relatively dense and nearly pure Douglas-fir stand remained.



Figure 5.1: Plot location in western Washington. 1 = Cathlamet (South Fork Mill Creek); 2 = Arlington (Armstrong track 1); 3 = Arlington (Armstrong track 2); 4 = Carson (Trout Creek); 5 = Randle (High Bridge); 6 = Carson (Falls Creek).

The plots on the relatively poor sites (site class 3-4), belonged to the *Pseudotsuga* menziesii-Holodiscus discolor association, which is a community typical of dry forest sites in the *Tsuga heterophylla* zone and in which Douglas-fir is considered the potential climax species (Franklin and Dyrness 1973).

Plot 4 was situated in the Wind River Ranger District, near Carson, about 20 miles from the Oregon border. Most of the second growth forests in this area have developed naturally after the Yacolt Fire in 1902. The year of origin of the stand of plot 4 is probably 1925; age at breast height measured in 1984 was 59 years on average. The stand has never been thinned. The soil is a well drained loamy sand with 10-30 % gravel and is derived from andesite parent material; site class 4.

Plot 5 is located in the Randle Ranger District, a little south of Cispus river, on a hilltop 900 m above sea-level. The stand has developed after a wildfire in 1918 and has never been thinned. Mean age at breast height in 1984 was 50 years on average; site class is 3. The soil is a well drained, yellow-grey loamy sand from volcanic origin.

Plot 6, like plot 4, is located in the Wind River Ranger District. Data of U.S.D.A. Forest Service indicate 1937 as the year of establishment. Most trees, however, appeared to be younger. The stand is very dense with many suppressed trees and has never been thinned. The soil is a well drained loamy sand; site class 3.

#### 5.2.3 Measurements

In order to quantify the distinction between social classes by different tree parameters, in each stand a 50 by 50 m plot was laid out, in a more or less homogeneous area. Measurement of all trees in each plot included the exact location of the stem base, diameter at breast height (d.b.h.) and crown radius in at least four directions, on the basis of which a crown projection map was constructed. Topheight, height of the crown base and the point at which the crown was widest were measured and a sketch was drawn of the shape of the trees seen from the same direction, perpendicular to the baseline of the plot. With these data vertical diagrams were drawn to scale of forest strips 10 m wide (Fig. 5.2). All trees were assigned to one of the four social classes subjectively (dominants, codominants, intermediates and suppressed), based on the relative position of the crown in the forest canopy. Their estimated social position was verified with the newly constructed vertical diagrams. Most trees were cored for age determination at breast height. Stem volumes were taken from volume tables for Douglas-fir, western hemlock and red alder (McArdle 1961; USDA Forest Service 1955). Diagrams were constructed of the distribution of various parameters over the social classes for all plots to analyse possible trends.

## 5.2.4 Calculations

Mean values of age, h/d-ratio and tree volume were plotted with their 95 % confidence interval to detect possible significant differences between the social classes in and between plots in the mean parameter value of a particular social class (e.g. dominants or codominants). Possible trends could so be visualised. In case of slight overlap between the confidence intervals a Tukey-Kramer test proved to be the most discriminatory method to test significant differences. In the analyses it was assumed that all social classes had essentially the same distribution pattern to keep the statistics manageable.

## 5.3 Results

Stand ages ranged from 41 to 59 years at breast height and stand density ranged from 160 to 1296 trees per ha with basal areas between 31 and 58 m2 (Table 5.1).

Table 5.1: General plot information

no.	location	elev. (m)	age yrs	N/ha	hdom (m)	B.A. m2	V m3
1	Cathlamet	360	46	160	41.2	44	543
2	Arlington	100	48	232	41.2	38	543
3	Arlington	100	51	304	43.5	37	534
4	Carson	530	59	512	27.6	31	324
5	Randle	900	47	1080	31.0	56	619
6	Carson	480	41	1296	28.3	43	355

age = mean stand age at breast height; N/ha = number of stems per ha with dbh over 5 cm.

#### 5.3.1 Stands on productive sites

Vertical diagrams of the forest architecture are presented in Figure 5.2. On each diagram all trees in a 10 m wide strip are drawn to scale with different species coded by differences in shading. Each plot is represented by 2 vertical diagrams, illustrating the differences in stand architecture within each plot. Figure 5.2 visualizes the within-stand variation in architecture being almost as large as the variation between stands of varying density.





Figure 5.3: Projection of crown classes, as derived from crown projection maps. The lighter shades indicate dominance; the black holes represent gaps in the canopy.

Differences in stand density are very pronounced on the horizontal plane of crown projection maps. In Figure 5.3 a model showing the crown classes is presented, as derived from the crown projection maps. The lighter shades indicate dominance; black shades represent gaps in the canopy. It simulated the pattern of an aerial picture, taken approximately 50 m above the forest canopy. Compared with the other two plots, low density plot 1 clearly has much wider crowns in the crown classes of dominant and codominant trees. Planimetric analysis of the crown projection maps indicated that on average 15 % of the plot were occupied by gaps. The classical crown cover (crown projection area) of dominant and codominant trees together occupied 64 % of the plot area; the number of dominant and codominant trees calculated as a percentage of the total number of stems was 68 % (Table 5.2).

Table 5.2: Distribution of the number of stems over the social classes, in percentage of total number of stems per ha (N/ha).

plot	N/ha	D	С	I	S	(D+C)
1	160	33	35	18	14	68
2	232	40	31	20	9	71
3	304	36	30	26	8	66
4	512	28	36	34	2	64
5	1080	23	25	25	27	48
6	1296	9	18	26	47	27

Appreciable differences between the plots could also be noted in the distribution patterns of d.b.h., h/d-ratio and crown width respectively over the social classes (Figure 5.4), whereas a comparison of the age distribution between the plots suggests that the uneven tree-compartment might act as a complicating factor. For instance, when dominant trees are always found to be older than codominant, intermediate and suppressed trees, the value of other tree parameters will likely be influenced. If social classes are linked up with tree age, it is very difficult to distinguish between the social classes on the basis of single parameters. In Figure 5.5 (top-part) mean tree ages are given with a 95 % confidence interval for the different social classes in plots 2 and 3. For plot 1 insufficient tree age data were available per social class to allow the construction of confidence intervals. Although Fig. 5.5 suggests some trends in tree age between the social classes in plot 2 and 3, there were no significant differences. When plot 2 is compared with plot 3, tree ages of the dominants and codominants are significantly higher in plot 3, i.e. approximately 2 years.



Figure 5.4: Distribution pattern of tree age, d.b.h, H/d-ratio and crown width over the social classes for plot 1, 2 and 3.



Figure 5.5: Mean parameter values with their 95 % confidence intervals for the different social classes of trees for plot 1, 2 and 3. Top: tree age; middle: H/d-ratio; bottom: tree volume.

Figure 5.5 also shows the mean values of h/d-ratio and tree volumes for the different social classes in the three plots. H/d ratio seems a good parameter to detect differences between the social classes, as there is no overlap between the confidence intervals, with the one exception of suppressed trees in plot 3. Note that in all plots the suppressed trees have a fairly large confidence interval. This is due to the low number of trees sampled and probably also to their divergent sizes. To analyse the influence of stand density by

comparing the plots, dominant and codominant trees are most suitable. Tree volume also is a good parameter to distinguish between social classes in each plot. Here again, the dominant and codominant trees can best be used to calculate differences between plots (Figure 5.5).

A linear regression analysis confirmed that tree age was not linked to h/d-ratio or to tree volume to any significant degree. If these variables had proved to be mutually dependent, more complicated analyses of covariance would have been necessary, with tree age as the covariant. But apart from this practical aspect, the lack of correlation between tree age and h/d-ratio and tree age and between tree volume and tree age confirms numerically that big trees are not necessarily old trees (Oliver and Stephens 1977), and that the same strategic behaviour may occur at many different moments in a tree life (cf. Oldeman and Dijk 1991).

## 5.3.2 Stands on relatively poor sites

General plot information is presented in Table 5.1. Vertical diagrams of stand architecture are given in Figure 5.6. The forest canopy is very stratified and heterogeneous: plots 5 and 6 have the architecture of a "Plenterwald" (selection cutting system), which may be a characteristic development phase of Douglas-fir stands belonging to the *Pseudotsuga menziesii-Holodiscus discolor* association. The crown projection maps (30 x 30 m plots; Figure 5.7) show clear differences between the plots in crown size related to stand density. But age differences between the plots may also be involved as factors causing differences in crown widths.

Gaps occupy 17-29 % of plot area, which is quite substantial. Crown cover of the dominants and codominants taken together range from 45 to 53 % of plot area (Table 5.3). This means that a lot of space, shown on the horizontal and vertical maps, is not occupied by dominants and codominants. Potential site productivity thus is far from being fully utilised by trees in these natural stands; even less so than in the stands on better sites.

Table 5.3: Percentage of crown cover for the social classes taken together, as measured from crown projection maps.

plot	(D+C)	(S+I)	gaps
1	65	18	17
2	66	19	15
3	60	27	13
4	45	26	29
5	53	22	25
6	45	28	17



Figure 5.6: Vertical diagrams of the plots 4, 5 and 6.  $\square$  = Douglas-fir;  $\square$  = Tsuga heterophylla.



Figure 5.7: Crown projection maps for plot 4, 5 and 6 (30 x 30 m). The lighter shades indicate dominance; black holes represent canopy gaps.

The distribution of the number of stems over the social classes is much more variable compared with the plots on good sites (Table 5.2): especially plot 6 has a very large number of suppressed trees. This variability, and the differences in tree age and standing volume between the plots (Table 5.1), makes a direct comparison between the plots, to analyse the influence of increasing stand density, less meaningful.



Figure 5.8: Mean parameter values with their 95 % confidence intervals for the different social classes of trees for plot 4, 5 and 6. Top: tree age; middle: H/d-ratio; bottom: tree volume.

Mean tree ages plus their 95 % confidence intervals of the social classes in each plot are shown in Figure 5.8. For plot 5 and 6 some age trend might be imagined, but is not significant. Only the suppressed trees are significantly younger than the trees belonging to the other social classes. In plot 4 there are no age differences between the social classes.

H/d-ratio shows a clear shift towards the higher values, when making a comparison between the social classes in each plot: in plot 4 the differences are negligeable, but for plot 5 and 6 the differences are very significant (apart from the suppressed trees in plot 5).

Individual tree volumes (Figure 5.8; bottom part) in the social classes differ very significantly for all three plots. When examining the slight overlap in the volume intervals between intermediate and suppressed trees in plot 4 with the Tukey-Kramer test, the volume differences between these two classes are significant. Tree volume thus seems to be the best stem parameter to distinguish between the social classes in each plot, and not tree sizes or ages.

## 5.4 Discussion

In order to analyse differences between the social tree classes of dominant, codominant, intermediate and suppressed trees in second growth Douglas-fir stands, first of all an objective method of verification of the subjective classification of the social position of a tree crown in relation to those of neighbouring trees is required. The vertical diagram method used in this study is a good tool to meet this requirement.

The results indicate that, apart from crown parameters, tree volume and h/d-ratio are the best stem parameters to distinguish between social classes. This may seem quite obvious for even-aged Douglas-fir monocultures, but it is now established for multi-aged and highly diversified natural second growth stands as well.

The link between present canopy position and individual tree volume indicates that dominant trees apparently have been successful in securing a favourable competitive position for light, water and nutrients during an extended period of time. During the stand development stage of plastic response and the subsequent stage of stagnation and mortality, dominant and codominant trees expand their crown and root areas, increase their basal area and volume increments and occupy more and more growing space at the cost of intermediate and suppressed trees. Figure 5.9 shows this process as the development of canopy heights at 10 year interval for a group of Douglas-fir trees recently cut in a second growth stand on a relatively poor site (site class 4). The dominant tree becomes ever more dominant during the development of the stand, as indicated by the increasing steepness of the growth lines compared with neigbouring trees. This is an observation frequently made in natural Douglas-fir stands (Krueger 1967). Whenever a tree becomes dominant it usually maintains that dominant position from the seedling on. Moreover, dominance is established very early in life; often already in the open growth phase following stand establishment. On the basis of the present results of the architecture and age analyses we stand, although Figures 5.5 and 5.8 tend in that direction. But it certainly holds true that a few years advantage over neighbouring trees is helpful in attaining (and maintaining) dominance (Krueger 1967). Most of the dominant and codominant trees are confined to the higher age classes. In all the semi-natural second growth stands studied of approximately 50 years old, as a rule there is a range in tree ages of at least 10 years, in which the intermediate trees show the largest age range (Table 5.4).



Figure 5.9: Reconstruction of canopy development at a 10 years interval as derived from stem analysis, for a group of Douglas-fir trees recently cut in a second growth stand near Eatonville (Bethel Ridge plot; site class 4). Tree ages are indicated above tree tops.

On the one hand, it is commonly assumed that the growth conditions in even-aged plantations are in accordance with the silvicultural requirements of Douglas-fir, being a secondary pioneer species (Reukema 1975; Oswald and Pardé 1976; Smith 1986). On the other hand, the present study shows that biodiversity of the tree population, which includes genetic, architectural and spatial variability, is a characteristic of semi-natural second-growth Douglas-fir stands, in which they differ completely from the uniformity of even-aged Douglas-fir plantations (Field and Manuwal 1973; Archie and Baumgartner 1978; Hooven 1973). The typical development of social classes of trees, as analysed in the present study, leads to a concept of a forest community in which four sub-populations coexist, each with a specific age structure, h/d-ratio and volume growth potential, in the form of a mosaic of very small units. Gradually the units will merge together to form a single canopy stratum by the process of fusion, as described by Oldeman (1990), and the distinction between the sub-populations of trees becomes less relevant, as this stratum consists mostly of dominant and codominant trees; the intermediate and suppressed trees being gradually eliminated from the stand.

plot	n	D	С	I	S
1 Cathlamet	18	43-53	42-50	45-50	42-46
2 Arlington	75	47-55	45-55	45-61	45-50
3 Arlington	57	45-53	44-53	46-54	41-47
4 Carson	35	56-65	53-61	53-65	58-59
5 Randle	56	43-56	44-56	37-52	36-47
6 Carson F	119	41-50	41-48	31-45	28-44
7 Yellow J.	26	58-59	57-60	52-60	57-59
8 Humptulips	31	50-55	50-54	47-55	-
9 Stossel Cr	29	49-56	48-55	43-55	-
10 Bethel R	46	51-54	49-54	48-55	42-51

Table 5.4: Age variation of Douglas-fir trees of different social classes for 10 second growth stands in western Washington

n = number of trees per stand bored for age determination (total number = 492)

For all plots studied, at age 40-60 years a clear distinction between the social classes of trees is still very meaningfull, also in terms of silvicultural implications. On relatively poor sites the development seems to proceed at a slower pace and it even may take a hundred years or more before the stage of a seemingly uniform but fused canopy of dominant and codominant trees is entered. Usually, a silvicultural stand will be cut long before that time (Reukema 1975).

In semi-natural second-growth Douglas-fir stands there is a marked under-utilisation of the site productivity for timber-production by the tree population, as indicated by the limited crown cover of dominant and codominant trees (varying between 45 to 66 % of

plot area) and the relatively large proportion of gaps in the total area. From the point of view of timber production maximization, this is a negative consequence of the developmental history and the apparently substantial and long-lasting competition by intermediate and suppressed trees. From an ecological point of view, this implies that a relatively large proportion of site factors is allocated to non-tree components of the forest community, which is not necessarily bad and fits in with forms of multiple-use management without maximization of single functions (Hooven 1973; Twight 1973). With absolutely no human interference during stand development, semi-natural stands will produce less valuable timber than would be possible in a managed stand on the same site. If this is not acceptable from an economic point of view, the present study indicates some opportunities that exist for improving timber production in semi-natural stands, by stimulating and enhancing the growth of certain categories of trees by silvicultural measures such as selective thinnings, especially when applied early during stand development (Welch 1939; Stein 1955; Adlard and Smith 1981; Twight 1973).

The highly stratified canopy structure of the stands on relatively poor sites (Figure 5.7), resembling a "Plenterwaldaehnliche Entwicklungsphase" (Leibundgut 1982), is likely to be of transitory nature (see also Figure 2.1). It would be very interesting to investigate how to maintain this very interesting forest development phase by appropriate silvicultural measures. There are good opportunities to study and develop such a "Douglas-fir selection cutting system" on *Pseudotsuga menziesii-Holodiscus discolor* sites in western Washington. The similarity in growth conditions of these sites and sites in The Netherlands frequently used for Douglas-fir plantations, suggests that the small-scaled selective thinning regimes used in The Netherlands may be quite appropriate as a principle to manage natural second growth stands on poor sites on a sustained basis in western Washington as well (Franklin 1963; Hammond 1969; Caruso 1973; Lewis et al 1978; Wierman and Oliver 1979; DelRio and Berg 1979; Adlard and Smith 1981).

## 5.5 Conclusions

The new concept of a highly diversified architecture of semi-natural second-growth Douglas-fir stands, as presented in this chapter, may necessitate a revision of silvicultural regimes which consider Douglas-fir stands as monoculture crop; to be managed and harvested by large scaled and highly mechanized operations aiming at maximization of the timber production function. It seems obvious that thinning measures will be most effective when specified for and adjusted to the different social classes of trees (Assmann 1961; Leibundgut 1978; Faber 1986). But in Douglas-fir silviculture these ideas have not yet been implemented with precision or on a large scale (Oliver and Murray 1983; Oliver et al. 1986b; Oliver and Larson 1990).

## 6. DOUGLAS-FIR THINNING EXPERIMENT IN GERMANY

#### Abstract

The architecture of a 25 year old experimental thinning plot, in a 53 year old Douglasfir plantatation near Freiburg, southern Germany, was studied. Vertical diagrams were made and the distribution of various stem-, crown- and increment parameters, including tree height, d.b.h., h/d-ratio, crown width, crown length, crown surface area and basal area increment were analysed. This experiment included early and heavy thinning (plot 1), early and moderate thinning (plot 2), late and heavy thinning (plot 3) and no-thinning (plot 4). Main objective was to study the effects of the different treatments on stand architecture. The results indicated the following effect of early thinning on dominant trees: values for the stem parameters were 10-15 percent higher; crown parameters were 20-30 percent higher, but basal area increment was not significantly different, compared with no-thinning. Late thinning showed no significant differences compared with no-thinning. Early treatments had a greater overall effect on the codominant trees: stem parameters increased 15-20 percent on the average; crown parameters were 20-40 percent higher and basal area increment was 30-50 percent higher compared with no-thinning.

#### 6.1 Introduction

Observations of the architecture and development of semi-natural Douglas-fir forests can provide basic knowledge of stand dynamics, which is crucial to understand the influence of silvicultural measures, such as thinning, on stand development (Greggs 1981; Oliver and Larson 1990). Especially on sites where a minimum of human interference is desirable from an ecological or economical point of view, such studies on the development of stand architecture hardly influenced by man can be very helpful (chapter 5). Unmanaged Douglas-fir stands are very rare in Europe, but in the area of origin in the Pacific Northwest many examples of natural and semi-natural Douglas-fir stands can still be found. A complicating factor is that the site conditions in the Pacific Northwest in many ways do not resemble those in western Europe (Otto 1984; Kuiper 1988). Therefore one should be very weary with the "translation" of results derived from research in Douglas-fir forests in the Pacific Northwest to the European situation.

Natural stands have a disadvantage over carefully designed experimental plots, i.e. their variability is a characteristic feature, of which many sources are unknown or unquantifiable. They cannot yield such reliable information as could be derived from thinning experiments, in which:

- the developmental history is known;
- the initial situation of the experiment is well documented;
- the site is more or less homogeneous and at least is known;
- variation of tree age and its assessment are no extra complications.

For a better understanding of stand dynamics of Douglas-fir and the influence of thinning on it, in the ideal situation one should have access to data derived from many different thinning experiments, with different provenances, on different sites, at different ages at the beginning of the experiment, using different methods of thinning (high-, lowand selective thinning), different thinning intensities, as well as different timing of thinning. Although many long-term Douglas-fir yield plots and spacing studies have been established throughout Europe and the United States (Vries 1961; McArdle et al. 1971; Worthington and Staebler 1961; Spurr 1963; Bergel 1969; Reukema 1970; Oswald and Pardé 1976; Tuyll and Kramer 1981; Curtis et al. 1982; Harington and Reukema 1983; Rollinson 1987), which may provide important information about stand development on a hectare basis, being designed for traditional growth and yield studies, they usually give only limited information about individual tree growth and crown development. For a silvicultural analysis of the influence of thinning on tree and stand architecture additional tree-wise data are required (Kerr 1953; Krueger 1967; Curtis and Reukema 1970; Berg and Bell 1979; Schuetz 1984; Oliver et al. 1986a; Kuiper 1988; O'Hara 1988; Oliver and Larson 1990).

A long term thinning experiment in southern Germany, which has taken into consideration individual tree data, will be set out in this chapter. The good thing about this unique thinning experiment is, that the developmental history is largely known. The thinning method, a form of selective high-thinning which focusses on the release of "plus-trees" from neighbouring tree competition, in addition to the removal of dead and dying trees in the understory, was kept the same throughout the experiment. So was the method of periodic inventory and documentation over an extended period of time, including per tree data. All this is essential to evaluate the influence of a reduction of stand density on the social development of the tree population.

The main objective of this case-study was to analyse the influence of different treatments on tree and stand architecture in Douglas-fir thinning plots near Freiburg, southern Germany, with special attention to the effect on the different crown classes of dominant, codominant, intermediate and suppressed trees (cf. chapter 5 on social position of trees).

## 6.2 Materials and methods

## 6.2.1 Experiment design

In 1961 the Forest Research Station in Freiburg (Forstliche Versuchs- und Forschungsanstalt Baden-Wuerttemberg) established an experimental plot in a 28 year old Douglas-fir stand, to compare three different treatments:

- Plot 1: early and heavy thinning
- Plot 2: early and light thinning
- Plot 3: late and medium strong thinning

This corresponds with the current system of selective high-thinning in Douglas-fir in Baden-Wuerttemberg (plot 1): a silvicultural regime that was in common praxis a few decennia back (plot 3); and a method of stand treatment in between these two (plot 2). A base-line no-thinning plot (plot 4) was established in 1957 in a 25 year old untreated Douglas-fir stand to record the reduction of the number of stems by self-thinning and to follow the influence on the development of social tree classes and the development of h/d-ratio (as a parameter for tree stability). Initial spacing of this stand in 1932 was unknown, but most likely must have resembled that in common use with Norway spruce (Picea abies), with much over 3000 planted seedlings per ha. In the three thinning plots the initial number of stems at the beginning of the experiment (about 1500 trees per ha at a dominant height of 20 m) was the same for plot 1, 2 and 3 and also the anticipated stand density at the end of the rotation ("Zielstammzahl"; about 150 trees at a dominant height of 38 m) is supposed to be the same. Just the sequence of reducing the number of stems is different (Figure 6.1). In Figure 6.1 (below) it seems as if in the non-treated plot 4 basal area decreases stepwise, suggesting some form of thinning. But that was not the case: only standing dead trees have been removed periodically, accounting for sudden reductions in hasal area.

## 6.2.2 Site conditions

Experimental plots 1,2 and 3 (Stadtwald "Uhlberg" VII), north of Freiburg, are located on a 600 m hilltop overlooking the lowlands of the river Rhine and is freely exposed to the south, southwest and western winds coming down from the Vosges mountains in France. Its exposition is to the south with a 26 % slope. The soil is a rather dry, gravelly loamy sand; parent material is Gneiss. According to the meteorological station in Freiburg (270 m) the average temperature is 16.4 C and the precipitation is 520 mm (open field) in the vegetation period (5/1 - 11/1). More details about soil and climate are given in Mitscherlich and Moll (1970). Site class is 2 (according to Mauser 1968). Plot 4 (Kandern, Dgl 98) has similar site conditions, but is somewhat less exposed. The potential natural vegetation on this site is classified as an atlantic, submontaneous beech/oak/fir forest, on a medium dry, loamy, gravelly brown forest soil; the parent material of which is granite (more details: Kuiper, 1986).

#### 6.2.3 Developmental history

Four years before the beginning of the experiment in 1961 in the three thinning plots the stand had been thinned according to the principles of \*selective high-thinning, in which plus-trees were selected and were released from neighbouring tree competition. Thus at the beginning of the experiment at age 28 years the stand was fairly uniform, well stocked and was growing fast towards a single canopy stratum. There were no appreciable differences in (micro)site conditions or in tree ages and the plus-trees were evenly spaced in all three plots. At an age of 34 years plot 1 and 2 were thinned for the first time in the experiment. At an age of 39 years a second and quite intense thinning was considered necessary because of tree competition to the plus-trees by adjacent trees. Especially in plot

2, which had been exposed to a lower thinning intensity than plot 1, the plus-trees had suffered from competition and in the lower reaches many trees were suppressed. In plot 3 the stand was considered extremely and "unnaturally" dense (according to a note of the Forest Research Station). The effect of no-thinning was noticeable by the presence of trees with weak, short crowns in all social classes. At an age of 43 years plot 3 was thinned for the first time according to the principles of selective high-thinning. Number of trees per ha, standing volume, basal area but also crown suppression, were very high at that time. It was remarkable, that the plus-trees in plot 3 selected and released in 1957, which had kept pace with those in the other plots with reference to d.b.h. and crown size so far, now clearly showed signs of competition stress. A large proportion of intermediate and suppressed trees indeed was still alive, but showed no increment. Plot 2 gave the impression of greater vitality, and had a higher standing volume and a 40 % higher number of stems compared with plot 1. At an age of 49 years (by 1982) most plus trees appeared to be well crowned, but in plot 2, as 10 years had passed since the previous thinning, a release of the plus-trees was considered very necessary. By this time the original selection of a fairly large number of plus-trees often resulted in mutual competition of similarly sized dominant trees, necessitating a selection between plus-trees. The 1982 high- thinning consequently opened up the stand considerably. In 1982 in plot 3 a very pronounced tree differentiation was reported. Crown lengths of plus-trees averaged 45 %, versus 50 % and 47 % in plot 1 and 2 respectively. In plot 3, because of the high density, the lateral development of many plus-tree crowns was lagged behind according to all criteria.

#### 6.2.4 Methods

A ten m wide grid pattern was laid out over an area of 100 by 40 m, covering all three plots. The slope was measured and a slope correction was made, when conveying the measurement data to millimeter paper. All tree stump positions were mapped and for each tree the crown radius was measured in at least four directions. Asymmetric parts of the crown were measured additionally. A crown map was constructed and verified in the field. Tree heights and heights of the crown base were measured as well as irregularities in the crown and forks in the stem. The crown base was defined as the lowest whorl with at least three green branches. In case of an irregular crown base, which is characteristic of many trees in unthinned stands, the lowest living whorl was considered the crown base for the whole tree, when calculating crown lengths and crown surface area. A sketch was drawn of each tree seen from the southern direction. These sketches were used for a realistic representation of the shape of the trees in the vertical diagrams. All trees were assigned subjectively to a social class of dominant, codominant, intermediate or suppressed trees. These social classes (crown classes) were not determined by fixed parameter values, but instead the crown position of each tree was considered with reference to the crowns of adjacent trees. Thus it is a relative classification, made for the sake of comparing trees exposed to approximately the same growth conditions. Tree diameter data were derived from the periodic inventories by the Forest Research Station in Freiburg. Annual basal area increments for individual trees were deduced from the 1986 and 1982 data.



Figure 6.1: Number of stems related to dominant height (h 200) for the different thinning methods in the Baden-Wuerttemberg experiment (above), and the development of total basal area per ha (below).

#### 6.2.5 Calculations and presentation of results

Vertical diagrams and crown maps are presented to make visible the variation in stand architecture as a result of different thinning methods. On the crown maps the social positions of the trees are distinguished by different shadings. Assessment of the total crown projection area occupied by the different social classes of trees on the crown maps was made by planimeter.

The distribution of various tree parameters over the sample are presented by bar diagrams to provide a comprehensive picture of the variation of parameter values within the tree population, being considered more informative than stand mean values, especially in this case when data per tree are available. To provide some form of classification to summarize stand data, in this paper the IUFRO-classification introduced by Leibundgut (1959) is used to define parameter classes, e.g. in case of crown length classification. However, for many tree parameters no fixed classes have been defined in the literature, necessitating the use of locally valid classes, e.g. for crown width, crown surface area and basal area increment.

To identify the possible impact of a thinning method on the tree population, which was stratified into social classes of dominant, codominant, intermediate and suppressed trees, for different tree parameters mean values were plotted per social class along with their 95 % confidence interval. This is a simple method to detect significant differences between the social classes in each plot as well as differences between the plots in the mean parameter value of a particular social class. In case of a slight overlap between confidence intervals a statistical test is required, for which the Tukey-Kramer test was found to be most discriminative.

The relationship between crown surface area and annual basal area increment was studied by regression analysis, in which crown surface area was calculated after Assmann (1961).

#### 6.3 Results

Fieldwork was done in November 1986, so that the data correspond to the end of the 1986 vegetation period. The thinning plots 1, 2 and 3 cover an area of 0.1259 ha, 0.1585 ha and 0.1076 ha respectively, whereas baseline plot 4 is 0.1647 ha large. Total number of stems is 348 trees per ha in plot 1; 410 trees per ha in plot 2; 556 trees per ha in plot 3 and 771 trees per ha in plot 4. The slope is 25-30 % in southwestern direction and 2-3 % in northeastern direction.



Figure 6.2: Crown map, representing the horizontal distribution of the tree crowns divided into social classes of dominant (----), codominant (----), intermediate (----) and suppressed trees (-----).

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## 6.3.1. Stand architecture

On the crown map (Figure 6.2) the horizontal crown projection areas of the trees are distinguished according to their social position. In plot 1 large and regularly shaped tree crowns are noticeable, especially when compared with plots 3 and 4. In plot 2 a large variation exists in crown sizes: both very large and extremely small crowns are found. In general there are many canopy gaps in plots 1, 2 and 3, each approximately the size of one tree crown. There are less canopy gaps in plot 4. The horizontal distribution of trees over the social classes clearly reflects a significant increase in the number of stems of intermediate and suppressed trees from plot 1 to plot 4. Dominant trees usually have the largest crowns, and there are no appreciable differences in dominant tree crown size between the four plots. Codominant trees generally have smaller crowns and they seem to be distributed somewhat clustered in small groups, in comparison with the more individually spaced dominants. Intermediate and suppressed trees have a highly variable crown size and are distributed more or less randomly. Crown cover percentages for the social classes are given in Table 6.1. There appeared to be no significant differences between the four plots in crown cover of dominant and codominant trees taken together.

Plot	1	2	3	4
Plot area (ha)	0.13	0.16	0.11	0.16
N/ha	341	435	548	770
Crown cover (D+C)	71	7 <del>9</del>	65	70
Number of (D+C)	82	79	63	43

Table 6.1: Crown cover area as percentage of total plot area and number of stems as percentage of total number of stems per plot for dominant and codominant trees taken together.

Vertical diagrams of stand architecture are presented in Figure 6.3. Many trees in plot 1 and 2 look less stressed by competition than those in plot 3 and 4, as indicated by crown size and shape: in plot 1 and 2 crown widths are larger and average crown bases lie around 15 m above ground, whereas in plot 3 and 4 average crown bases lie around 20 m. Asymmetric crown bases are found in all plots. Tree heights vary between 22 and 35 m with no appreciable differences between the plots, although intermediate and suppressed trees clearly are more frequent in plot 3 and 4. The smallest crown sizes are found in plot 4.

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Figure 6.3: Vertical diagrams of the stand architecture and crown map in a 40 by 10 m strip of the 4 plots. The crown tops of smaller trees in the background are indicated with " $^{"}$ .

Distribution diagrams of tree height, d.b.h., H/d-ratio, crown width, crown percentage, crown surface area and basal area increment are presented in Fig 6.4. Each parameter is divided into classes of which the distribution over the sample is given as percentage of the total number of stems:

### Tree height (Figure 6.4 a)

Class width is 2.5 m. Most trees are between 27.5 and 32.5 m tall. In plot 1, 19 percent are taller than 32.5 m; in plot 2: 23 percent; in plot 3: 24 percent and in plot 4: 39 percent. This suggests that plot 4 may have a somewhat higher site class than the other plots. In plot 1, 2 and 3 fifty percent of the trees is lower than 30 m, and in plot 4 only 30 percent of the trees is lower than 30 m.

#### **D.b.h.** (Figure 6.4 b)

Class width is 5 cm. A trend in the distribution pattern from plot 1 to plot 4 is noticeable. Also the portion of higher d.b.h. values decreases in the same order: in plot 1 d.b.h. values of 52 percent of the trees are over 40 cm; in plot 2 this is 47 percent; in plot 3: 32 percent and in plot 4 only 12 percent of the trees are thicker than 40 cm.

#### H/d-ratio (Figure 6.4 c)

Class width is 10. A shift towards higher h/d-ratios is noticeable in the plot sequence 1 to 4. If an h/d-ratio smaller than 70 is considered indicative as a measure of tree stability and a value over 100 indicative of tree lability, than the distribution over the sample is as follows: in plot 1, 27 percent of the trees has an h/d-ratio value smaller than 70 and 2 percent larger than 100. In plot 2 these figures are 21 percent and 9 percent respectively; in plot 3: 3 percent and 16 percent respectively; and in plot 4: 3 percent and 63 percent respectively.

#### Basal area increment (Figure 6.4 d)

Class width is 10 cm2/year. For the period March 1982 - November 1986 the distribution of the mean annual basal area increment of individual trees show a shift in the sequence from plot 1 to 4. Basal area increment is considered large when values are over 50 cm2/y and small when these values drop below 20 cm2/y. These limits are arbitrarily, however, and can be fixed differently, being dependant, amongst others, on site quality and thinning regime. In plot 1: 28 percent of the trees have large basal area increment values and 14 percent have a small increment; in plot 2 these figures are 23 percent and 23 percent respectively; in plot 3: 16 percent and 49 percent respectively; and in plot 4: 6 percent and 58 percent respectively.




Figure 6.4 (a,b,c,d): Bar diagrams of the distribution of tree height, d.b.h., h/d-ratio, and annual basal area increment over the four sample plots, presented as a percentage of the total number of stems in each sample.

#### Architectural analysis of Douglas-fir forests

## Crown length percentage (Figure 6.4 e)

Class width is 5 % of total tree length. Distribution of crown percentage shifts from medium to long crowns in plot 1 to very short crowns in plot 4. Following the classification of Leibundgut (1959) crowns are considered long if the crown percentage is over 50 % of top height; medium sized if crown percentage is between 35 and 50 % and short if crown percentage is lower than 35 %. In plot 1: 27 % of the trees have long crowns and 2 % short crowns; in plot 2 these figures are 11 % and 13 % respectively; in plot 3 and plot 4 long crown are completely absent, whereas 39 % and 81 % of the trees have short crowns in plot 3 and 4 respectively.

#### Crown width (Figure 6.4 f)

Class width is 1 m. Here too, a shift in the median of the distributions is apparent. Satisfactory crown width is considered beyond a value of 6 m, being the hypothetical mean crown size in plot 1 in case of full stocking. In plot 1: 51 percent of the trees have a crown wider than 6 m; in plot 2 this is 26 percent; in plot 3: 12 percent and in plot 4: 16 percent.

If 4 m is considered to be an absolute mimimum value for crown width at this age, being the mean crown width in plot 3 in case of full stocking, in plot 1 only 2 percent of the trees have too narrow crowns; in plot 2 this number is 19 percent; in plot 3: 41 percent and in plot 4: 36 percent.

# Crown surface area (Figure 6.4 g)

Class width is 25 m2. Trees with an average crown length of 14 m and a crown width of 6 m or more, are considered to have a large crown area, which corresponds with a crown surface area over 125 m2. Similarly trees with a crown length under 10 m and a crown width smaller than 4 m are considered to have a small crown surface area, which corresponds with values lower than 75 m2. In plot 1: 67 percent of the trees have large crowns and 5 percent have small crowns. In plot 2: 47 percent large crowns and 19 percent small crowns. In plot 3: 25 percent large crowns and 51 percent small crowns; in plot 4: 19 percent large crowns and 53 percent small crowns.

## 6.3.2 Distribution over the social classes.

In Figure 6.5 the distribution of the number of stems over the social classes is given as a percentage of total number of stems for all four plots. Plots 1 and 2 are very similar in this respect. In plot 4 the limited number of dominant trees is remarkable, whereas almost 60 percent of the total number of trees consist of intermediate and suppressed trees. In plot 1, 2 and 3 in sequential order the most remarkable differences are found in a decrease in codominant trees and subsequent increase of intermediate trees; the percentage of dominant and suppressed trees remaining fairly constant. In absolute numbers there are 153, 151, 158 and 121 dominant trees per ha in plot 1 to 4 respectively, which seems to be a sufficient number to select plus-trees from to build a final crop stand.

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Figure 6.4 (e,f,g): Bar diagrams of the distribution of crown width, crown length percentage and crown surface area over the four sample plots, presented as a percentage of the total number of stems in each sample.

In Figure 6.6 the mean values of various tree parameters per social class and per plot are given along with their 95 % confidence intervals. Differences between the social classes in each plot as well as differences between the plots in parameter values for a particular social class can easily be distinguished. To summarize the influence of different thinning treatments on each social class, as reflected by mean parameter values, in Table 6.2 mean parameter values are compared with mean values from plot 4, which are set at 100 %. For both early treatments (plot 1 and 2) dominant trees on the average show a 10 % increase in d.b.h. values; 15 % decrease in h/d-ratio; 25 % increase in crown length percentage; and 20 % increase in crown surface area, when compared with dominants in plot 4. Although Table 6.2 suggests a 20 % increase in mean basal area increment, these basal area increment values are not significantly different from those of plot 4 due to overlap between both confidence intervals. Also note that crown width values of dominant trees are not different from those in plot 4.

The effects on codominant trees are similar to those on dominant trees, as can be read in Figure 6.6 and Table 6.2. Basal area increment values even show a 30-50 % increase compared with codominants in plot 4.



Figure 6.5: Distribution of the number of stems over the social classes in each plot.

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Figure 6.6: Mean values and their 95 % confidence intervals for d.b.h, H/d-ratio, crown length and crown width, distinguished per social class and per plot.



Figure 6.6 (continued): Mean values and their 95 % confidence intervals for crown surface area and basal area increment, distinguished per social class and per plot.

		Plot	
_	1	2	3
Dominants			
D.B.H.	112	113	106
H/D	80	82	85
C.L.	126	121	115
C.W.	97	93	86
C.S.A.	121	111	96
B.A.I.	121	116	103
Codominants			
D.B.H.	114	113	102
H/D	77	79	88
C.L.	125	120	106
C.W.	113	98	85
C.S.A.	140	117	89
B.A.I.	152	132	99
Intermediate	5		
D.B.H.	123	107	99
H/D	69	82	85
C.L.	132	126	107
C.W.	149	105	92
C.S.A.	203	131	99
B.A.I.	247	131	87
Suppressed			
D.B.H.	100	102	109
H/D	107	83	81
C.L.	122	102	105
C.W.	114	89	106
C.S.A.	145	89	112
B.A.I.	486	190	286

Table 6.2: Mean parameter values per social class and per plot, in percentage of parameter values of plot 4 (base line = 100 %).

D.B.H. = diameter at breast height; H/D = H/d-ratio; C.L. = crown length; C.W. = crown width; C.S.A. = crown surface area; B.A.I. = basal area increment.

## 6.3.3 Crown size and increment

The results of a regression analysis showing the relationship between annual basal area increment and crown size for all trees in each plot is given in Table 6.3. The differences between the plots are small, especially when considering correlation coefficient values between 0.85 and 0.91.

Cumulative basal area increment at age 53 years is approximately the same for plot 1, 2 and 3: they number 83.4, 83.2 and 83.7 m2/ha respectively. For plot 4 total basal area increment is somewhat smaller: 73.8 m2/ha (data: Forest Research Station Freiburg).

plot	1	2	3	4
a	0.03	0.01	0.01	0.02
b	1.45	1.64	1.77	1.53
r	0.91	0.88	0.86	0.85
n	43	69	59	60

Table 6.3: Regression and correlations coefficients of the relationship between crown surface area and annual basal area increment  $(Y = a X^b)$ 

a and b: regression coefficients

r: correlation coefficient

n: number of trees

X: crown surface area (m2)

Y: basal area increment (cm2/y)

## 6.4 Discussion

As was demonstrated in earlier chapters, the social position of trees seems to be a major factor in the dynamics of Douglas-fir forests (Krueger 1967; Oliver et al. 1986a; O'Hara 1988; Faber 1986; Oliver and Larson 1990). Already very early during stand development it is determined which trees will grow to dominance and which trees will become more and more suppressed and will gradually be eliminated from the stand (Oliver and Murray 1983; Reukema 1975; Kuiper 1988a; Schober 1969 and 1988). During the subsequent stages of stand development the social position largely determines to which trees the increment is allocated (Lassole 1979; Oliver et al. 1986a; Tuyll and Kramer 1981; Tappeiner et al. 1982). As mentioned before, one great advantage of the method of architectural analysis used, is the verifiable classification of trees into social groups. Vertical diagrams allow a judgement of the growth potential of each tree with regard to

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the position of adjacent trees. The possibility of repeated verification makes this method of architectural analysis scientific and unique.

The results of the present study indicate that most of the stem and crown parameters studied confirm the silvicultural advantages of early and heavy thinning over late thinning or no thinning, in terms of individual tree parameters.

The H/d-ratio is a measure of tree stability, not taking into consideration the dynamical aspects of windthrow. The trend towards increasingly higher H/d-values of plot 1 to 4 sequentially, is an indication of management risks involved in the various silvicultural systems. This result is consistent with theories which state that on sites with a high wind-throw risk early and heavy thinnings are to be preferred (Savill 1983; Bryndum 1986). Furthermore, when there is less need for additional thinnings later on in the rotation, this will enhance the stability of the crop against windthrow, because in the more vulnerable later phases of stand development the stand canopy remains closed. However, in such a silvicultural system there are some penalties in terms of decreased wood quality because of heavier branching of the trees (Kenk and Unfried 1980; Kenk 1981).

Thinnings later on in the rotation may be profitable in terms of marketable thinning logs (Worthington and Staebler 1961), but have the disadvantage that the reaction of extra growing space on individual tree growth is less (Schober 1969; Harrington and Reukema 1983; Oliver et al. 1986). Gaps in the canopy may result which do not close so easily and the trees will have higher h/d- ratio, which further decreases the stability of the crop (Oswald 1985)

For the important social class of dominant trees an early and heavy thinning in this study had a significant positive effect on the stem dimensions of 10-15 % and on the crown dimensions (with the exception of crown width) of approximately 25 %, when compared with no-thinning. There was no significant effect on basal area increment. Early but medium strong thinning had about the same effect on dominant trees. In late thinning the mean parameter values hardly differed from those in the non-thinned plot.

For the codominant trees larger effects were perceptible: both early treatments had a significant positive effect on the stem dimensions of 15-20 % on average; crown dimensions were 20-40 % larger and basal area increment was 30-50 % larger, compared with no-thinning. Apparently codominant trees had developed better and show higher increment rates in the two early thinning plots compared with the late and no-thinning plots. As was the case with dominant trees, late thinnings showed hardly any effect on codominant trees different from the non-thinned plot.

These observations are relevant to practical forest management and silvicultural research. For instance, the observation that trees with long crowns were absent in the late and no-thinning plots (plot 3 and 4) is important, given the current trend towards the development of mathematical growth models of individual trees. Crown length is directly related to the photosynthetic crown surface area and as such plays a major role in many competition indices, which have been developed in recent years (Assmann 1961; Curtis and

Reukema 1970; Bella 1971; Hatch et al. 1975; Lassole 1979). Another example is the total crown cover of dominants and codominants, which was found to be more or less the same in all plots. Thinning regime thus seems to have little influence on total crown cover. This is important to know when the management aim is maximum volume growth or maximum yield per ha. Similarly, many other results of this study can also be placed in a larger frame of reference of forest management and research related issues, which is the objective of chapter 9.

There is always this dilemma for forest managers to choose either for maximizing individual tree growth or for maximizing total stand yield (Drew and Flewelling 1979). In this paper only the silvicultural implications of different thinning methods on tree and stand architecture have been dealt with, focussing on individual tree size mainly. It will be very interesting to study in addition the outcome of the different thinning treatments on overall yield (Tuyll and Kramer 1981; Berg and Bell 1979; Warrack 1979; Reukema 1979; Tappeiner et al. 1982). This is one of the research aims of the Forest Research Station in Freiburg. Such a long term yield study should include an analysis of costs and benefits taking into account the number of stems and the respective stem dimensions which are being released by thinnings at different intervals during one rotation period (Tappeiner et al. 1982). It is anticipated that on the basis of such information one can make a well-founded decision in favor of one particular thinning regime.

## 7. DOUGLAS-FIR THINNING EXPERIMENT IN THE NETHERLANDS

#### Abstract

In connection with the discussions on the necessity of thinnings in Douglas-fir plantations, the architecture and social tree development of Douglas-fir was analysed in a thinning experiment, which included a low-thinned and a non-thinned plot. Results indicate that after 38 years of non-thinning, enough dominant and codominant trees with medium long crowns and good growth potential remained, to select the 100-150 final crop trees from, as advised in forestry practice. However, the high values for H/d-ratio may indicate some problems if crop trees are released too quickly.

### 7.1 Introduction

Thinning experiments with Douglas-fir, which include a non-thinning treatment, like the one presented in the previous chapter, are extremely rare in The Netherlands. A large number of traditional growth and yield plots have been established for Douglas-fir, (Veen 1951; Vries 1961; LaBastide and Faber 1972; Tol 1986), but unfortunately these experiments seldom include data per tree which allow to accurately predict the growth potential of individual trees or to study the development of crown classes (Faber 1983; Oliver et al. 1986a; Leersnijder 1992)

It would be interesting to analyse the consequences of a no-thinning regime versus various thinning regimes that are or have been common practice in Douglas-fir silviculture in The Netherlands, given the Governmental plans to expand (triple) the area of Douglas-fir plantations in the next decades (Meerjarenplan 1986). Because many of these future Douglas-fir stands will be planted on relatively poor sites, formerly occupied by Scots pine (*Pinus sylvestris*), an important management objective will be to seek ways to minimize costs of silvicultural practices, e.g. to avoid precommercial thinnings.

In 1975 a thinning demonstration plot was established in a 28 years old previously unthinned Douglas-fir stand near Apeldoorn, in the central parts of The Netherlands; the so called Grevenhout demonstration plot. Three different thinning treatments were applied: \*high-thinning, \*low-thinning, and no-thinning. However, when compared with a carefully designed thinning experiment, there are several disadvantages of the Grevenhout plot: there are differences in site quality between the plots; the different thinning methods have not always been applied correctly; the thinning intensity was not always consistent between the treatments; and too many crop trees have been selected. Thus, unfortunately, the Grevenhout demonstration plot is not suitable to study the effect of different thinning methods on forest architecture and on growth and yield (Kuiper and Schoenmakers 1990; Dik 1987). Developmental trends can not be deduced reliably from its data. Yet, the nothinning plot offers an unique opportunity for base-line research, which was the main objective of this case-study.



Figure 7.1: Vertical diagrams and crown maps of the low-thinning and no-thinning plots. In the no-thinned plot there are many intermediate and suppressed trees still alive. In spite of the narrow spacing there are as many well developed dominants as in the low-thinned plot.

### 7.2 Material and methods

Two sub-plots of the Grevenhout experiment were used to analyse stand architecture and the development of social tree classes: a no-thinned plot and a low-thinned plot, which lie next to each other and which occupy essentially the same site, as indicated by the site index  $h_{100}$  (Table 7.1). Initial spacings in 1947 were 1 x 1 m.

Table 7.1: Stand data of the sub-plots in 1985 (after Kuiper and Schoenmakers 1990).

size	N/ha	BA	Vtot	$\mathbf{h}_{100}$
0.31	1260	32.6	320*	21.3
	size	size N/ha 0.31 1260 0.22 1260	size N/ha BA	size N/ha BA Vtot   0.31 1260 32.6 320*   0.22 1260 42.2 380

\* in addition, in the low-thinned plot approximately 95 m3/ha has been removed from the stand by thinnings (which corresponds with a removed basal area of 13.6 m2).

#### 7.3 Results

Figure 7.1 gives an impression of stand architecture at age 38 years (1985). The nonthinned plot is very dense, with a lot of small, suppressed trees. Standing dead trees are not indicated on the vertical diagrams, but in the no-thinned plot over 3000 dead trees per ha were found (versus 1360 living trees). Figure 7.2 gives the distribution of the number of stems over the social classes, of the diameter, of H/d-ratio and of relative crown lengths for the 2 plots. The total number of dominant and codominant trees/ha in the nothinned plot is 244 and 285 trees respectively. For the low-thinned plots these figures are 50 and 403 trees respectively. The number of dominant and codominant trees over 20 cm in diameter in the no-thinned plot is very similar to that of the low-thinned plot: on the average there are 350 trees/ha over 20 cm in diameter. In common forestry practice in The Netherlands, Schuetz and Tol (1982) advise to select no more than 100-150 crop trees/ha for Douglas-fir. Thus, after 38 years of no-thinning there seem to be plenty of trees to make a selection of final crop trees from.

However, in the no-thinned plot only 43 trees/ha have an H/d-ratio smaller than 75. In the low-thinned plot there are 79 such trees/ha. Mind the risks of releasing crop trees ! There are many trees with an H/d-ratio over 125 in both plots.

Trees with medium long crowns (i.e. trees with relative crown lengths longer than 35 % of top height) amount to 130 trees/ha for the no-thinned plot and to 670 trees/ha for the low-thinned plot. Thus there are appreciable differences in crown length between the two treatments.



Figure 7.2: Distribution of various stand parameters over the low-thinned plot (above) and the no-thinned plot (below).

Mean values of dbh, height, H/d-ratio, relative crown length and current annual basal area increment for dominant trees are given in Table 7.2. Analysis of variance indicated that there were no significant differences in these parameters between the plots.

plot	n	dbh	hdom	H/d	cl	bai
Low	12	25.8 (2.0)	21.3 (0.8)	83 (6)	44 (4)	29.6 (6.8)
No	8	25.6 (3.9)	21.3 (1.8)	84 (8)	40 (4)	21.1 (6.4)

Table 7.2: Mean values (with standard deviation) of various tree parameters for dominant trees in the 2 plots (p = 0.025).

n = number of dominant trees sampled; dbh in cm; h in m; cl = crown length in percentage of top height; bai = current annual basal area increment in cm2/year.

## 7.4 Discussion

The analysis of the architecture and development of the no-thinned plot so far has made out some good cases in favor of more extensified silvicultural systems for Douglas-fir on relatively poor sites in The Netherlands. In spite of the very narrow initial spacing of  $1 \times 1$  m and consequently heavy tree competition, after 38 years of no-thinning there are sufficient large trees with medium long crowns and an acceptable basal area increment, which reflects a good growth potential, to provide a source for the selection of crop trees. Only the number of trees with an H/d-ratio lower than 75 is rather critical from a silvicultural point of view. These results suggest that silvicultural systems for Douglas-fir based on less human interference deserve more attention both in silvicultural research and in forestry practice.

## 8. SPATIAL DISPOSITION AND EXTENSION GROWTH OF THE STRUCTURAL ROOT SYSTEM OF DOUGLAS-FIR

Abstract

Kuiper, L.C. and Coutts, M.P., 1992. Spatial disposition and extension of the structural root system of Douglas-fir. For. Ecol. Manage. 47:111-125.

Root systems of Douglas-fir trees in The Netherlands were measured to study relationships between root system structure and size, and stem and crown diameter and growing space, all of which are aspects of tree stability. Twenty-one trees, planted between 12 and 37 years previously, were winched over and the structural portion of their root systems to a diameter of 0.5 cm and the crown perimeter were mapped. Retrospective measurements were made of the extension of major lateral roots. Size and shape of the crown projections were poorly correlated with root system width. Reconstruction of spatial development of the root systems revealed that root spread was very limited during the first 5 years after planting. Highly significant positive correlations were found between stem diameter at 1.3 m and root biomass, and with the cross sectional area of the structural roots.

#### 8.1 Introduction

A better understanding of the spatial disposition and extension growth of skeletal roots (terms used after Sutton and Tinus 1983) is required in many areas of forestry and is especially relevant to tree stability, where the structural root system functions for anchorage(Henderson et al. 1983; Deans 1983). The relationship between rooting and tree stability has been investigated for a number of conifer species to which windthrow is a major risk factor, e.g. for *Picea sitchensis* (Bong.) Carr (Fraser and Gardiner 1967; Coutts 1983b, 1986; Deans and Ford 1983; Blackburn et al. 1988), *Pinus contorta* Dougl. and *Picea abies* (L.) Karst. (Nielsen 1982), *Pinus radiata* (D.) Donn. (Sommerville 1979) and *Pseudotsuga menziesii* (Mirb.) Franco (Kuiper 1986).

Root anchorage can be considered in terms of a number of components which resist uprooting viz. the weight of the roots and soil which have to be levered out of the ground by wind action, the resistance of roots to being pulled out or bent on the windward and leeward sides of the tree respectively, and by the force required to break the soil (Coutts 1983b; 1986). The effectiveness of most of these components in anchorage increases with the overall size of the root system; for example, the force required to pull out a root of the soil has been found to increase linearly with diameter at the pulled end (Anderson et al. 1989). A mathematical model of the anchorage of shallowly rooted trees indicates that a 10 percent increase in the lee-side radius of the root-soil plate will give a 7 per cent increase in the force required for uprooting (Blackwell et al. 1989). Calculations on the relationships between size of the root system and strength of the anchorage are consistent with results of tree pulling experiments which showed that the resistance of trees to uprooting was linearly related to stem weight (Fraser and Gardiner 1967; Booth 1974).



Figure 8.1: Representative Douglas-fir root systems in plan view on a 1 m grid. Roots are shown to a diameter of 0.5 cm. Crown perimeter is shown by a dotted line, adjacent trees by black circles. The social position of the trees is indicated by D = dominant; C = codominant; I = intermediate; S = suppressed. Fig. 8.1.1 represents a dominant tree in plot 1; Fig. 8.1.2. a dominant tree in plot 2; Fig. 8.1.3 an intermediate tree in plot 3; Fig. 8.1.4. a codominant tree in plot 3; Fig. 8.1.5. a dominant tree in plot 4; Fig. 8.1.6. a dominant tree in plot 5.

Since stem weight is related to root weight (e.g. Albrecktson 1980), the size of the root system is a major factor in tree stability. It would be of some help to silviculturists to enhance tree stability, if a simple parameter could be identified by which the size and extension of the structural root system can be estimated in the field. After studying the structural root systems of 200 Douglas-fir trees 15-35 years old, Kuiper et al. (1990) found a positive correlation between diameter at 1.3 m (d.b.h.) and the cross sectional area (c.s.a.) of roots at a distance of 40 cm from the anatomical stem center.

The morphology of Douglas-fir root systems has been investigated extensively by Groth (1927), Hengst (1958), McMinn (1963), Koestler et al. (1968), Eis (1974) and Champs (1975). Most workers have found that Douglas-fir has a rather compact and densely branched root system permeating the soil in the immediate vincity of the stem, with some rope-like lateral roots penetrating long distance near the soil surface.

This paper presents observations to test the hypothesis that d.b.h. and the dry weight of the structural root system are closely correlated for Douglas-fir. In addition, root system spread is described in relation to that of the crown and to the presence of neighbouring trees. A knowledge of the growth rates of root systems is basic to understanding final root form, and as it is not known whether the rate of development of the root system influences final root form or the allocation of biomass between root and shoots, retrospective measurements of root extension were made in order to define the material better. Information on the rate of root development is also useful when deciding on the ages of crops suitable for root excavation in studies on tree stability.

#### 8.2 Material and methods

Coastal Douglas-fir of unknown provenance was used. The plots are located 3 km north of the city of Ede, in the central part of The Netherlands. Five plots were selected for study on the basis of similarity in site conditions and stand management history, ranging in age from 12 to 37 years (Table 8.1). Stand management was traditionally rather conservative (i.e. narrow spacings, light thinnings). Transplants 3-4 years old had been used for stand establishment.

Table 8.1: Stocking density and mean tree size in five Douglas-fir plots in The Netherlands.

Plot nr.	Ag (y)	e Stand establish- ment date	Initial spacing (m)	Present number of trees/ha	Mean height (m)	t d.b.h (cm)
1	12	1980	2.0 x 1.5	3000	5.7	7.0
2	17	1975	0.8 x 0.8	2450	8.9	15.0
3	27	1965	1.5 x 1.3	1825	14.9	15.6
4	33	1958	1.5 x 1.5	1525	16.8	19.1
5	37	1954	1.5 x 1.5	775*)	1 <b>9</b> .8	24.5

\*) plot 5 has recently been thinned

All plots had a well drained, dry, brown podzolic soil, with medium fine to medium coarse sandy texture and little loam. Maximum root penetration for the 27 to 37 year old trees was about 80 cm. Site class was IV, which corresponds with a dominant height of 25 m at age 50 years (LaBastide and Faber 1972).

Of the 21 trees selected for sampling 10 trees were dominant, 6 were co-dominant and 5 were intermediate. The sample trees had no visible damage to stem or crown. Distance and direction to neighbouring trees were measured. The north side of each tree was marked at ground level and the crown radius was measured in four directions. The main lateral roots were exposed at the base by excavation before winching the trees over. The size of the largest trees which could be sampled was d.b.h. 27 cm: it was limited by the capacity of the winch.

After winching, soil was removed from the exposed parts of the root system and the stem was cut off at the base. The root system was then pulled slowly out by a tractor. By this method the structural root system remained largely intact. Roots that were broken were excavated and tagged. All large and medium sized roots to a diameter of 0.5 cm (terms used after Boehm 1979) were thus recovered. Final cleaning was carried out with a jet of water. The clean root systems were weighed and laid on a wire screen with a grid of 0.5 m to be photographed. The relative positions of roots were mapped and their dimensions recorded until diameters were less than 0.5 cm. The radius of the root system was measured in four directions to a point where the roots tapered to 0.5 cm diameter.

Root extension was estimated from growth ring analysis (Fayle 1975a; Reynolds 1983). Disks were cut at 20 cm intervals measured from the stem centre, on 3 to 5 of the longest lateral roots per root system. These roots were usually also the largest in diameter. The disks were sanded with fine paper and growth rings were counted under a dissecting microscope. The difficulty of measuring growth increments of roots far away from the stem base, because of missing or incomplete growth rings, is well documented (Fayle 1975a). For each root, growth layers were traced out by width pattern to make sure they were not discontinuous. Each disk was examined by two different observers along three different radii.

On the scale drawings of the horizontal root plan the number of growth rings in the major lateral roots was indicated at 20 cm intervals along their lengths. Points with the same number of rings were connected by a line, forming more or less concentric ellipses to illustrate the spatial development of the root system in two-year intervals.

Total root c.s.a outside bark was calculated from measurements of the circumference of all roots at 40 cm from the anatomical stem centre. The use of a fixed measurement position, rather than one which varied with tree size, was adopted because of the difficulties presented by scaling and the interpretation of scaled measurements.

Root biomass (oven-dry weight) of roots thicker than 0.5 cm diameter was calculated from the weight of the fresh root system, after determining the moisture content of root samples taken from different parts of each root system. On the average 10 wood samples were taken per root system for moisture content, including parts of the heart of the root system, parts of major lateral roots and segments of finer roots.

Growing space and competition stress were calculated after Faber (1983). By this method the area of a plot is subdivided into small sub-plots of 1 dm<sup>2</sup>. For each sub-plot the distance factors to the surrounding trees are calculated using the following equation:

distance factor = volume  $e^{xp}$ . (distance) -2

For Douglas-fir the exponent of tree volume in the equation is 1.68, which is derived from emperical data of Faber. Each sub- plot is assigned to one of the surrounding trees, i.e. to the tree for which the distance factor is largest. When the whole plot area is thus assigned to the different trees in the plot, the sum of the sub-plot areas represents the potentially available \*growing space for each tree. Mean competition stress level for a particular tree is defined as the mean value of the distance factors at the perimeter of the potentially available growing space of that tree. Effective growing space is defined as the area potentially available minus the area for which distance factors have values lower than 50 dm<sup>3</sup>.m<sup>2</sup>. Empirical data by Faber suggested that at values lower than 50 a Douglas-fir tree suffers little from adjacent tree competition in terms of basal area increment reduction.



Figure 8.2: Relationship between mean root system width measured to where the roots taper to 0.5 cm diameter, and mean crown width for Douglas-fir. Regression line (solid) and 1:1 reference line (dotted) are shown.  $\Box$ , plot 1;  $\circ$ , plot 2;  $\star$ , plot 3;  $\bullet$ , plot 4 + 5.

### 8.3 Results

The spatial disposition of representative structural root systems of Douglas-fir, including all roots thicker than 0.5 cm is presented in Figure 8.1. On most root systems a few major lateral roots projected beyond the periphery of the crown. The major lateral roots were often unevenly distributed, making the root system asymmetrical. Symmetry was not related to the position of adjacent trees, nor to crown shape. The development of the woody root system showed no obvious influence which could be attributed to the roots of other trees; some lateral roots grew through and beyond root systems of adjacent trees (Figures 8.1.3, 8.1.4 and 8.1.5). The relationship between horizontal crown width and root system width to a diameter of 0.5 cm is shown in Figure 8.2: the diameter of some of the root systems was 1 m greater than that of their respective crowns.



Figure 8.3: Spatial development of the root systems. The more or less concentric circles or ellipses indicate the area occupied by lateral roots (to 0.5 cm diameter) at 2-year intervals; the numbers indicate the number of years taken to reach each boundary, beginning from the year of planting. A = plot 1; B = plot 2; C = plot 3; D = plot 4; E = plot 5.

The spatial development of the surface root systems is shown in Figure 8.3. Root systems of the older trees had grown more slowly in the early stages than those in more recent plantings. The ring counts showed that on average it took 9 years for roots of the trees in plot 3 to reach the 20 cm sampling point measured from the stem centre, whereas the other trees took 3 to 5 years. No root growth data are available for the period when extending to 20 cm, and since most roots had 6 to 8 growth rings at the final (0.5 cm diameter) sampling point, little information could be obtained about annual root growth over the last 6 to 8 years. The measured roots varied in length from 1.0 to 5.2 m. The overall mean root extension rate was 18 cm.y<sup>-1</sup> and the maximum root extension in any one year was 100 cm. Root extension rates were highly variable (Figure 8.4). The extension of individual roots (not shown) typically followed a variable pattern with periods of rapid and of very slow growth. High growth rates were not necessarily confined to a specific phase of root development. Curves of cumulative growth (not shown) for major roots of a single root system frequently crossed one another, so that the ranking of roots on a length basis changed during development.

Parameters		Coefficients			
x	у	а	b	$r^2$	п
dbh	root system fresh weight')	0.03	2.62	0.98	21
dbh	root system dry weight)	0.01	2.63	0.96	21
dbh	root c.s.a at 40 cm	0.07	3.09	0.98	21

Table 8.2: Regression and correlation coefficients of non-linear regressions of d.b.h. and three different root parameters for Douglas-fir, with the general equation:  $y = a x^{b}$ 

) All material between stem base and root diameter 0.5 cm

The relationships between d.b.h. and root parameters are given in Table 8.2: the correlations were positive and highly significant (p < 0.01). The best fitting non-linear regression curve representing the relationship between d.b.h and root biomass is given in Figure 8.5. For the limited d.b.h-range studied (5-27 cm) this is an exponential curve. In Figure 8.6 the relationship between stem basal area and root c.s.a. at 40 cm from the stem centre is shown. These parameters showed a 1:1 relationship for basal areas below 150 cm<sup>2</sup>, but root c.s.a. was much greater than stem basal area on the larger trees, probably because of the development of greater taper at, and extending through, the 40 cm measuring point with age. The relationship between effective growing space and root biomass is given in Figure 8.7. The trees in plot 1 and 2 were exposed to low competition stress levels, but the others suffered from medium to high competition stress, i.e. appreciable in terms of reduced basal area growth. For all categories of trees root biomass was related to growing space.



Figure 8.4: Mean rates of Douglas-fir extension from planting until the date of study, with 95 % confidence intervals (N = number of observations).



Figure 8.5: Relationship between d.b.h. and root biomass (oven-dry weight) for Douglas-fir.  $\Box$ , plot 1;  $\circ$ , plot 2;  $\star$ , plot 3;  $\bullet$ , plot 4 + 5.



Figure 8.6: Relationship between stem basal area at breast height, and total root c.s.a. 40 cm from the centre of the stump. The 1:1 (dotted) reference line is shown.  $\Box = 1$ ;  $\Theta = 2$ ;  $\bigstar = 3$ ;  $\bullet = 4$ .

## 8.4 Discussion

It has often been assumed that the area traversed by the Douglas-fir root system is proportional to the diameter of the crown (McMinn 1963; Smith 1964; Hengst 1958; Goehre 1958 and Koestler et al. 1968). However, in the examples shown in Figure 8.1 crown size and crown shape are weakly correlated with root spread to a terminal root diameter of 0.5 cm. This result is consistent with those of Eis (1974), who found that the direction in which an asymmetrical root system extended could not be predicted from stem or crown characteristics. In our study trees with asymmetric root systems often had symmetric crowns. On the well drained sandy soils of the present study large and medium sized roots frequently spread 1 m beyond the perimeter of the crown, and the area occupied by structural root area (for roots measured to 0.5 cm diameter) was 1.3 times larger on average than projected crown area. Roots with diameters of less than 0.5 cm may have extended several meters beyond that.

The number of major lateral roots may affect tree stability: where the number is small the stability of the structure becomes sensitive to its symmetry (Coutts 1983b). In the present study 5 to 10 major lateral roots were found per root system, and there was little variation with tree age. McMinn (1963) stated that the radial symmetry of Douglas-fir root systems was readily distorted by the proximity of other trees, whereas we found that the presence of adjacent trees had only small effects on the shape of the root systems. One difference between the two studies is that the stands investigated by McMinn originated from natural regeneration after clear felling, whereas the stands discussed here had been planted, but differences in site conditions may also have affected the results. The large proportion of asymmetric root systems might be partially due to bad planting; planting has been found to influence root system symmetry (Reynolds 1983).

Although Goehre (1958) and Hengst (1958) considered competition to be an important factor shaping the root system, overlapping and intermingling of the roots is more usual (McMinn 1963; Eis 1974). Assuming that the root systems of adjacent trees are distributed in a way similar to those of the sample trees (Figure 8.1), it is clear that significant intermingling of adjacent root systems occurred in the stands studied. Root contacts are frequent with Douglas-fir (Graham and Bormann 1966; Eis 1972; Reynolds and Bloomberg 1982), and McMinn (1963) found that even the most densely rooted central portions of Douglas-fir root systems were intersected by the roots of surrounding trees. The intermingling of the roots may assist tree stability by root interlocking and it emphasizes the potential risk of the spread of root diseases due to root contacts (Eis 1972; Hessburg and Hansen 1986) where the initial spacing has been too close, or where conservative thinning strategies have been practiced.

The low value for overall mean rate of root extension of  $18 \text{ cm.y}^{-1}$  was probably because more than 50 % of the root extension growth data was derived from the 33 and 37 year old trees (Figure 8.4). The roots of these trees made little growth in the early years after planting, and later growth was very variable. Such variable root extension has been attributed by Eis (1974) to an inherent pattern of growth reduction in the main laterals after a number of years of rapid growth, accompanied by increased growth of certain main branches of higher order. Such a pattern of growth can result in low mean values of root extension. In the trees we examined, mean growth rates ranged from 11 to 41 cm.y<sup>-1</sup> (Figure 8.4), rates appreciably slower than those reported for other species. Coutts (1983a) reported that with Sitka spruce the growth of the main laterals appeared to be slow in the first years after planting, but than proceeded to extend at a mean rate of about 60 cm.y<sup>-1</sup>, and Fayle (1975b) found a similar growth rate in red pine. In Douglas-fir Reynolds (1983) recorded extension of 55 cm.y<sup>-1</sup> in main roots. A possible explanation for the low mean growth rates in the present study can be found in the relatively poor quality of the site and in the intense within-stand competition due to the conservative silvicultural regime adopted. The thinning regimes used could have influenced the rates of root growth but details on the timing and intensity of many of the thinnings were not available.



Figure 8.7: Relationship between effective growing space (after Faber 1983) and root biomass. Competition stress levels to which the individual trees have been exposed:  $\diamondsuit$ , low;  $\Rightarrow$ , medium;  $\pm$ , high.

In our study the occurrence of a difference of 5 to 9 years between age of the stem at its base and the age of lateral roots at 20 cm from the stem base, indicates that the major roots were not necessarily the first to explore the soil immediately around the tree. This supports Eis's (1974) conclusions, based on naturally seeded trees, that the first-formed laterals do not necessarily develop into the major structural roots of the older tree. Apparently the decision which root will become a major structural root is not always made as early in life as Coutts (1983a) found in Sitka spruce. The slow start of root development found in the present study may be attributed to the use of 3 to 4 year old plants for stand establishment and the possibility of planting shock. After planting, new roots often develop while the old roots stagnate, a sequence which also occurs in other conifer species (Yeatman 1955).



Figure 8.8: Relationship between d.b.h and root biomass for Douglas-fir in the Pacific Northwest, compiled by Santantonio et al. (1977; open circles, n=36) and in the Netherlands (black circles, n=20).

All the root parameters studied showed significant positive correlations with d.b.h. The correlation coefficients are so high that one may confidently use d.b.h. to estimate dry weight, or c.s.a of the root system of Douglas-fir in The Netherlands where sites and stand ages are similar to those studied. Furthermore, data on the relationship between root biomass and d.b.h. in natural Douglas-fir stands in the Pacific Northwest (Santantonio et al. 1977) fit in with the data on Douglas-fir in The Netherlands (Figure 8.8), in spite of considerable differences in site conditions and management history between the two areas. The strong relationship between root biomass and d.b.h. did not appear to be influenced by the markedly different growth rates of the trees in the early years.

The results have implications for silviculture relating to the stability of the crop. Cremer et al. (1982) found that stocking density was an important factor in the stability of *Pinus radiata* D. Donn. subject to wind damage; at low stocking densities the stands were relatively stable. This was considered to result partly from the smaller height/diameter ratios which were found in the widely spaced crops, but also from the greater root development of trees with a large stem diameter. Our data show that d.b.h. can be used as a simple input variable to calculate woody root biomass for Douglas-fir. The effect of silvicultural treatments on d.b.h., which is readily measured, can be translated in terms of important root system variables.



Figure 8.9: Root system of a 27 years old intermediate Douglas-fir tree (plot 3) in plan view on a 50 cm grid.

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# 9. DISCUSSION AND CONCLUSIONS

#### Abstract

The results of various case-studies, presented in previous chapters, are discussed. Fortythree theorems concerning individual trees, eco-units and the forest mosaic are listed and used for approving or rejecting the hypotheses of the introductory chapter. Use and limitations of the architectural approach are evaluated and the impact of baseline research in natural forests for Douglas-fir plantation management is assessed. Elements for the design of new silvicultural systems for Douglas-fir are presented, particularly incorporating non-timber objectives in the design, among which the boosting of stand resistance against wind. Finally, scientific and practical conclusions are drawn.

## 9.1 Evaluation

So far the results of various case-studies have been presented. In this chapter these results will be discussed in the light of the objectives raised in chapter 1 and available information in the literature.

To recollect, this study focussed on the question: "What information is vital for silviculturists to enhance biodiversity of Douglas-fir forests in order to design silvicultural systems with higher levels of nature-conformity, adapted to future demands? "In this respect a higher level of conformity to nature refers to an overall extensification of and economy of management inputs and consequently more opportunities for spontaneous processes such as within stand competition, mortality and natural regeneration, decomposition of larger amounts of woody debris and increased rotation length in combination with lower investments.

It was anticipated that some of the information needed for the design of ecologically well balanced silvicultural systems could be derived from analysing the architecture of natural and semi-natural stands. A basic assumption was, that non-timber objectives, which will be an integral part of future forest management regimes, can best be realized when biodiversity is maintained or enhanced (Franklin et al. 1983; Oldeman 1990).

Obviously one has to limit oneself to a few well defined but essential objectives when dealing with such vast a subject as Douglas-fir ecology. In this paper only those aspects of silviculture have been studied, which are related to forest architecture. Let us summarize the most important results obtained so far, in the form of 43 \*theorems (proven propositions):

# THEOREMS ABOUT THE ECO-UNIT AND FOREST MOSAIC LEVEL:

1. The initial situation of natural Douglas-fir stand development usually is very heterogeneous, which can be deduced from age differences of the trees: at age 50 years dominant trees typically show an age range of 10 years (Ch.5).

2. The phase of natural stand establishment for Douglas-fir in the Pacific Northwest may extend over several decades. It is even possible that Douglas-fir forest regeneration extends over a period of more than 100 years (Ch.4).

3. Parts of natural stands may show a very complex age structure (Hugo Peak example; Ch.4).

4. At age 50 years on average 70 regeneration-units/ha can be distinguished (Ch.2;5).

5. The architecture of mature stands (at age 150 years) can be described by a mosaic of many very small regeneration-units, giving the impression of an individually mixed and very heterogeneous stand (Ch.2)

6. Fragmentation of the forest canopy into a number of newly-formed regeneration-units is very apparent from age 250 years onwards (Ch.2).

7. In old-growth Douglas-fir stands (age 450 years) within the *Tsuga heterophylla* zone in western Washington and western Oregon on average more than 100 different regenerationunits per ha can be identified (Ch.2).

8. Dense patches with extremely high values of basal area and total standing volume and large amounts of dead wood accumulated, should be considered representative for some of the mosaic structures characteristic of old-growth Douglas-fir stands (Ch.2).

9. Even during the biostatic phase of stand development tree volume and diameter of individual Douglas-fir trees keep on increasing, resulting in a steady increase in total standing volume. However, large fluctuations in total standing volume may occur, due to the fact that standing volume is significantly reduced when a single giant Douglas-fir tree dies. During the subsequent years this loss will be more or less compensated by increment of the remaining trees, until another giant fir dies, etc. This fluctuation may extend over a period of many centuries in natural Douglas-fir stands (Ch.2).

# THEOREMS ABOUT INDIVIDUAL TREE PARAMETERS

10. In natural stands mean crown length percentage of Douglas-fir shows a normal distribution at age 50 years (Ch.2).

11. Crown length percentages at age 250 years follow a normal distribution, which is skewed towards higher values (Ch.2).

12. In semi-natural stands the crown bases of Douglas-fir trees are often asymmetrical Ch 5).

13. In no-thinning plots in Germany trees with one-sided crowns were relatively numerous. However, asymmetrical crowns were found in all plots (Ch.6).

14. Like in natural stands the crown widths in experimental stands in Germany varied highly. About 85 % of the trees had crown diameters smaller than 6 m. Crown lengths varied from medium to long crowns in the early thinning treatments to very short in the late thinning treatments, whereas the smallest overall crown sizes were found in no-thinning plots (Ch.6).

15. There are appreciable differences between silvicultural treatments in Dutch experiments with regards to crown lengths: trees with crown length percentages over 35 % number 130/ha in a no-thinning plot versus 670 trees/ha in a low-thinned plot (Ch.7).

16. The vertical diagrams show that in intensely thinned plots in Germany, the crown base of Douglas-fir trees was 5 m lower on average compared with lightly thinned and non-thinned plots (Ch.6)

17. Crown widths of dominant trees in natural forest stands remain fairly constant at 8-10 m in diameter as a function of stand density, irrespective of tree age, as hypothesized earlier by Kuiper (1980). (Ch.2)

18. Lateral crown development of dominant trees in German experimental plots is not much influenced by differences in stand density: no significant effect of different thinning treatments was found on the size of crown widths of dominant Douglas-fir trees (Ch.6)

19. There appeared to be no significant differences between thinning treatments in German experimental plots in total crown cover of dominants and codominants taken together. Crown cover of dominants and codominants together ranged from 65 to 79 % of total plot area (i.e. somewhat higher values than for natural stands (Ch.6).

20. In semi-natural second-growth stands on productive sites crown cover of dominant and codominant trees together on average number 65 % of the plot area, whereas 15 % consist of gaps in the canopy (Ch.5).

21. In semi-natural second-growth stands on relatively poor sites crown cover of dominant and codominant Douglas-fir trees together ranged from 45-53 % of the plot area, and gaps in the canopy accounted for 17-29 % of the plot area, which is quite substantial (Ch.5).

22. In second-growth stands in the Pacific Northwest at age 50 years canopy gaps usually are restricted in size 1 to 3 times the mean crown diameter (Ch.5).

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23. In German experimental plots many canopy gaps were found approximately the size of 1 crown width. In no-thinning plots the number of canopy gaps was much lower than in the other thinning treatments (Ch.6).

24. In Dutch experiments there are no significant differences in mean stem and crown parameter values between the no-thinning and low-thinning treatments for dominant Douglas-fir trees (Ch.7)

25. In Dutch experiments no-thinning plots contain 43 trees/ha with H/d-ratio lower than 75; in low-thinning plots they number 79 trees/ha. In both plots there are many trees with H/d-values over 125 (Ch.7)

26. In German experimental plots the distribution of H/d-ratio shows a rather small proportion of trees with h/d-values lower than 70: 21 to 27 percent of the total number of trees in intensely thinned plots versus 3 percent in light and no-thinning plots (Ch.6).

27. For dominant trees in German experiments the effect of early and heavy thinnings resulted in a 10 to 15 percent increase in stem dimensions and a 25 percent increase in crown dimensions, compared with dominant trees in a no-thinning treatment. For dominant trees no significant correlation was found between the thinning treatments and basal area increment (Ch.6)

28. The effects on codominant trees in the German experiments were larger than on dominants: i.e. the early thinnings resulted in a 15 to 20 percent increase in stem dimensions; a 20 to 40 percent increase in crown size, and basal area increment was 30 to 50 % larger compared with codominant trees in no-thinning treatments (Ch.6).

29. In the German experiment stem and crown parameter values for dominant and codominant trees exposed to late thinnings hardly differed from those without thinning (Ch.6)

30. In the German experiment a significant increase in the number of intermediate and suppressed trees was apparent when comparing early thinnings with late or no-thinnings. Intermediate and suppressed trees in no-thinning plots numbered 60 percent of the total number of stems (Ch.6).

31. In absolute numbers there are 153, 151, 158 and 121 dominant trees/ha in German experimental thinning plots respectively, which is a sufficient number to select final crop trees (Ch.6).

32. Stand density in Dutch experimental plots without thinning is much higher than in experimental plots exposed to low-thinning. Total number of dominant and codominant trees per ha is 244 and 285 respectively in the case of no-thinning; and 103 and 211 respectively in case of low-thinning (Ch.7).

33. In spite of narrow spacings in no-thinning plots in the Dutch experiment there seem to be at least as many well developed dominant trees as in plots exposed to low-thinning (Ch.7).

34. In the Dutch experiment after 40 years without thinning there are plenty of potential crop trees (Ch.7).

35. Whenever during its \*life-span a Douglas-fir tree becomes dominant, it usually maintains that dominant position. A few years advantage in age over neighbouring trees is helpful in attaining dominance (Ch.5).

# THEOREMS ABOUT THE INFLUENCE OF SITE:

36. Higher site indices are linked to faster development towards a more mature stage of stand development (Ch.4).

37. Parameters linked to a gradient in soil texture and moisture availability are: number of Douglas-fir trees per ha; total standing volume; diameter distribution; tree height distribution; distribution of relative crown lengths and the mean height, d.b.h., volume and crown length of dominant trees (Ch.4)

38. On relatively poor sites the diversification of the tree population into distinct crown classes proceeds at a slower pace than on more productive sites (Ch.5)

# THEOREMS ABOUT DOUGLAS-FIR ROOT SYSTEMS:

39. Crown size and shape were only weakly correlated with root spread (Ch.8).

40. The development of the woody root system showed no obvious features which could be attributed to the influence of roots of adjacent trees (Ch.8).

41. Root extension rates were highly variable, with an overall mean rate of 18 cm/y and a maximum root extension in any one year of 100 cm (Ch.8).

42. A highly significant positive relationship was found between d.b.h and root biomass (Ch.8).

43. For all categories of trees root biomass was positively related to available \*growing space (Ch.8).

With reference to the hypotheses formulated in chapter 1, it can be concluded that the above mentioned results (theorems 1, 2, 3, 4) contradict the traditional point of view that Douglas-fir is a secondary pioneer species, which thrives best on large scale clearcut areas (hypothesis 1 approved). On the contrary, natural Douglas-fir forests do possess architectural features clearly distinct from plantations (theorems 5, 6, 7, 8, 9, 14, 16, 19, 20, 21, 22, 23,): hypotheses 2 and 3 approved. There is a very strong tree competition which leads to the development of distinct tree classes (hypothesis 4 approved), which can easily be verified by analysing vertical diagrams of the stand architecture (theorems 1, 10, 17, 27, 28, 30, 31, 32) and by the distribution pattern of H/d-ratio (theorems 25, 26) and tree volume (hypothesis 6 approved). The development of crown classes is a key factor to better understand Douglas-fir stand dynamics (theorems 19, 21, 28, 29, 30, 31, 32, 35, 42, 43): hypothesis 5 approved. This deserves a new definition of Douglas-fir stands as a forest community in which four sub-populations coexist in the form of a mosaic of small eco-units, each of which showing a distinct architecture and growth potential (theorems 15, 17, 18, 19, 20, 21, 25, 26, 27, 30, 35). This tree development strategy leads to a large biodiversity, in which site productivity is not always fully allocated to the production of stem wood only, but to other forest components as well (theorems 19, 20, 21). This suggests that new silvicultural systems for Douglas-fir aiming at maintaining a large biodiversity, do impose some penalties in terms of wood production: hypothesis 7 approved. Similarities between certain stand development phases of natural Douglas-fir stands and non-thinned plots in Europe (hypothesis 8 approved), suggest that small-scaled silvicultural systems for Douglas-fir based on individual tree selection (theorems 30, 31, 32, 33, 34) could successfully be applied both within and outside its area of origin.

Most of the above-mentioned information could be obtained only because the trees were studied and mapped according to their actual position relative to neighbouring trees. This is a major advantage of the architectural approach: it gives a realistic picture of the actual situation. For some statistical analyses it may be a disadvantage that the trees studied are not randomly distributed and thus some bias may occur due to interdependence (linkage) of the trees. Yet interdependence of neighbouring trees reflects the actual situation in Douglas-fir stands. By the application of certain statistical techniques to quantify tree and stand data this reality is largely disregarded.

It is a very limited concept to think of a tree as a "frozen sculpture". A river seems to be a much more realistic analogy, because each tree represents a constantly changing, flowing pattern of orderliness and information. Although its structure appears to be the same outwardly, it is like a building whose bricks are constantly being replaced by new ones. In the example of the human body, each cell is made of atoms that literally fly through it: it takes only a few thousands of a second to exchange oxygen and carbon dioxide in the lungs; sodium and potassium ions are pumped in and out of brain cells three hundred times per second. We acquire a new stomach lining every five days. Our skin is new every five weeks. Our skeleton, seemingly solid and rigid, is entirely new every three months. Every year, fully 98 percent of the total number of atoms in our body are replaced. Surprisingly this endless swirl of activity does not dissolve our shape or our identity. Although the material of the human body comes and goes, we are much more permanent at the genetic level (Chopra 1990).
#### Discussion and conclusions

When nature is infinitely dynamic and flexible, what is the use of an architectural analysis of forest stands with vertical diagrams, which are mere records of the shape of the trees and their relative position to each other and their place in the forest canopy at a fixed moment in their development? How can one pretend to study a living system, when one does hardly pay attention to its ecophysiological functioning? And when site influences are largely unknown or unquantified, how can one take into consideration genotype-environment interactions, which certainly have influenced the phenotypic variation found in Douglas-fir forests ?

In the architectural approach a systems hierarchy is used which accurately places a system in an environmental "field", so that both its position to lower hierarchical levels and its place within more complex higher hierarchical levels is clearly defined. By indicating the organizational level of a non-linear system with reference to the different environmental scales, complex reality becomes more comprehensive and can be communicated to others. If e.g. a tree is exposed to direct influences from its \*close environment, a whole set of growth conditions is altered in a way that is quantifiable and sometimes even predictable. But if the same tree is perceived in an undefined field of more or less random influences from a \*far environment (e.g caused by a storm), thereby skipping several hierarchical levels, the ensuing picture becomes chaotic. It is not that higher levels in the systems hierarchy are more chaotic by nature, but if in our perception the distance between one level and another becomes too large, chaos seems to prevail (Horgan 1993). Direct interaction between a tree and its close environment is orderly; the interaction between the \*far environment (e.g. climate) and a tree usually is a random phenomenon. Skipping hierarchical levels the other way around (from large to small) may create a similar chaotic effect in our understanding of complex non-linear systems (Prigogine and Stengers 1984). For example, this occurs when dealing with the spread of virus infections and other diseases (Hessburg and Hansen 1986; Reynolds and Bloomberg 1982).

The genotype of a tree describes its set of inherited genes, whereas the phenotype represents many aspects of morphology, physiology, behavior and ecological relations. In natural tree populations a continuous phenotypically distribution can be found for many characteristics, such as height and diameter growth, seed production, etc. This is partly caused by genetic differences within the population and partly by different environmental factors (Leersnijder 1992). The environment determines, directly or indirectly, which aspects of the genetic structure will be expressed: environmental factors influence the development rate of trees, the timing of flowering and regeneration and the biological \*life span of trees. If one plants a Bristlecone pine on a downtown lot in a polluted city, it may live for fifty years; planted in the country, its life span may increase to two hundred or three hundred years; on the wind swept ridges of the Rocky Mountains it might survive more than two thousand years. Which life span should be considered the natural one ? That depends entirely on the interplay between the organism and the prevailing environmental conditions. The resulting phenotype is largely impredictable, because the expression of its inherent genotype is influenced by complex, chaotic factors from different integration levels.

Trying to compare the results of baseline research in the area of origin of Douglas-fir in the Pacific Northwest of the U.S.A. and of architectural analyses of Douglas-fir plantations in western Europe thus can be very tricky because of ecological differences in growth conditions between the two areas. Historically, this has given rise to a lot of misunderstanding about the most suitable provenances of Douglas-fir for sites in Europe (Kuiper 1988). To understand site characteristics, one has to distinguish between primary site factors related to the \*far environment such as climate, topography, geomorphology, parent material and ground water level, and between secondary site factors, related to the \*close environment, which include the forest climate, micro-relief, soil-type, humus-form and water availability. The secondary site factors result from interactions between biotic and abiotic components of the forest ecosystem (Fanta 1985; Leersnijder 1992). Let us first consider the climatic factors:

Schenck (1936) advocated that the temperature distribution in the area of origin and on the potential planting site in Europe should match as closely as possible. This would guarantee a high level of adaptation to the new growth conditions. Hence if one had the intention to plant Douglas-fir in the vincity of the town of Utrecht in the central parts of The Netherlands, the best adapted provenance should be looked for near Port Alberni on Vancouver Island; the best provenance for Vlissingen, situated in the south western parts of The Netherlands, would be from the area around Lake Quinault on the Olympic Peninsula in western Washington; and for Maastricht in the far south of The Netherlands one should go for a provenance near Portland in Oregon. The climate diagrams of Figure 9.1 indeed show a marked similarity in the monthly distribution of the temperature between Portland and Maastricht.



Figure 9.1: Climate diagrams of Portland (Oregon, USA) and Maastricht (Netherlands). Temperature distribution is very similar between the two areas, but the distribution of precipitation is very different (after Walther and Lieth 1960).

### Discussion and conclusions

When considering the distribution of the precipitation, differences between the two areas are very apparent. In The Netherlands a peak in the precipitation occurs in mid winter and has a maximum in the summer period, whereas in the Pacific Northwest of the U.S.A. there is a maximum in precipitation in winter (75 % of total precipitation falls in the period between october and april), followed by a very dry summer. The winters in the Pacific Northwest generally are mild and wet, so that the process of photosynthesis usually continuous throughout the winter period. On the other hand early spring in The Netherlands can be characterized by severe cold and dry weather. When combined with some sunshine this frequently gives rise to the phenomenon of "uncompensated respiration" of Douglas-fir saplings (Goor 1958), causing considerable losses. To diminish these losses due to early spring frosts and uncompensated respiration some very sophisticated and complicated silvicultural systems have developed empirically in The Netherlands, like the "curtain cutting system" ("coulissenkap") and other small-scaled regeneration systems (Schuetz and Tol 1982). In the Pacific Northwest spring usually is very clouded and there are few problems with either frostbite or uncompensated respiration in Douglas-fir plantations, which usually extend over tremendously large areas, following large scale clearcuts.

The latitude is another difference between the Pacific Northwest and The Netherlands: 48 versus 52 degrees respectively, which causes a difference in direct solar radiation (Otto 1984) but also in photoperiodicity, which influences, among others, the day-length reaction in Douglas-fir (Wiersma 1978). The presence of a cold current along the coast in the Pacific Northwest versus a relatively warm one along the coast in western Europe, has an influence on the climate as well. In the Pacific Northwest, for instance, the isotherms are parallel to the coast, whereas in The Netherlands the isotherms are perpendicular to it. And of course there is the dominant influence of the topography on the local climate in the Pacific Northwest area, which is virtually absent The Netherlands. All these differences in climate make it very difficult to identify areas with similar climatic conditions in both areas.



Figure 9.2: Review of the best provenance areas of Douglas-fir in western Washington proposed for plantation sites in The Netherlands. A = ideas by Schenck (1936); B = proposition by Contactgroep (1950); C = by Kriek (1974); D = by Ruetz and Nather (1987). For explanation: see text.

Secondly, growth conditions are strongly influenced by the quality of the soil. Historically it was the dutch working party for boosting the productivity (Contactgroep Opvoering Productiviteit 1950) which looked at similarities in topography and soil conditions, when trying to identify the most suitable Douglas-fir provenances for The Netherlands. They also considered the amount of precipitation in the growing season as a determining factor to select the best provenance areas in the state of Washington. This working party recommended the flatlands bordering the foothills of the Olympic Peninsula and around the Pudget Sound as the potentially best areas to select provenances from (Figure 9.2b). Geologically these flatlands are of pleistocene origin, and thus similar to large areas in northwestern Europe. The humus-iron podsolic soils that have developed there, have a very coarse structure, a light texture and thus a very high water draining capacity. Frequently deep in the profile a consolidated glacial till can be found. The area lies in the rainshadow of the Olympic mountains, with an annual precipitation of 600 to 800 mm.

These site conditions thus seem to be as similar as can be found to many potential Douglas-fir sites in western Europe. However, from empirical provenance research (Kriek 1974 and 1979) it appeared that these areas around the Pudget Sound definitely do not yield the most adapted provenance for the sites in The Netherlands. Instead, Kriek (1979) recommends the foothill of the Cascade mountains, an area around the Olympic Peninsula and an area north of the Columbia river as the potentially best provenance sites (Fig. 9.2 c). These IUFRO-provenance trials clearly indicate that the most suitable sites are well drained, fertile, loamy soils of fluvio-glacial origin developed in granite parent material. Surprisingly these best adapted provenances (IUFRO-Douglas-fir seed collection series 1967/1968) seem to perform outstandingly throughout western Europe, in spite of considerable differences between original and exotic site conditions. No matter where they are planted, in France, Germany, Belgium, the Netherlands, Austria, Denmark or Switzerland, the provenances from the area indicated in Figure 9.2 d seem to be the best adapted (Ruetz and Nather 1987). Apparently these fast growing and genetically superior provenances have a wide ecological amplitude, adapted to a wide range of growth conditions.

Yet is difficult to explain why the best adapted provenances for the situation in The Netherlands do not come from relatively poor, dry sites which are most similar to the site conditions in The Netherlands, covered by the *Pseudotsuga menziesii/Holodiscus discolor* association (Franklin and Dyrness 1973), but instead they belong to the *Tsuga heterophyl-la/Polystichym munitum/Oxalis oregana* association, characteristic of very productive sites. More research on the influence of site conditions on the natural selection of Douglas-fir provenances will be needed to solve this problem.

Kuiper (1988b) gives a description of the soil characteristics of sites in the *Tsuga heterophylla* zone in western Washington and compares these with Douglas-fir planting sites in The Netherlands. Generally speaking the soils in the area of origin of Douglas-fir are less acid, more loamy, more fertile and have a higher water holding capacity. Under those conditions soil fertility rarely is a limiting factor to tree growth. But water availability is. The moister the site, the faster the forest community will develop and the higher will be total wood production (see the Hugo peak example in chapter 4). Yet there is a

limit to the amount of precipitation Douglas-fir can tolerate: above a total of 450 mm during the months of May, June, July and August (or an annual precipitation over 4500 mm) Douglas-fir disappears from the forest community and is replaced by *Picea sitchensis, Thuja plicata, Tsuga heterophylla* and hardwoods like *Alnus rubra* and *Acer macrophyllum* (Otto 1984).



Figure 9.3: Vertical diagram of the oldest Douglas-fir stand in The Netherlands in Park het Loo (106 years old) and of a 55 years old second growth Douglas-fir stand near Duvall, Washington (Stossel Creek plot).

It will be interesting to see how the oldest Douglas-fir stand in The Netherlands is going to fit in later into the natural forest development sequence as described in chapter 2.

The oldest Douglas-fir stand in The Netherlands was planted in 1881 and was 106 years old at the time of the measurements (Figure 9.3). It was established at a wide initial spacing of 5.5 x 5.5 m with rows of Douglas-fir alternating with rows of Pinus strobus. The Pinus strobus somehow soon disappeared from the stand, so that at least during the past 65 years the trees were spaced  $5.5 \times 8 \text{ m}$  (which corresponds to 227 trees/ha). Soil conditions are rich for dutch circumstances: a brown podsolic soil, rich in N and P, developed in loamy sand with a lot of organic matter in the upper 80 cm of the profile and a water holding capacity of 170 mm at field-capacity (Mohren 1987). However, in spite of the above mentioned favorable growth conditions, the trees already show alarming signs of ageing: they lack vitality and they have short crowns which show profuse adaptive reiteration. Note that many trees have their top blown out or bent (Figure 9.3) as a results of the prevailing winds, which is very characteristic of older Douglas-fir trees in The Netherlands, as soon as they expose their crowns above the surrounding forest (Burg 1986). The canopy of the stand consists of a single stratum and stand development should be classified as belonging to the young second-growth phase (see chapter 2). Annual volume increment was only 3 m<sup>3</sup>/ha in 1985. When compared with a natural Douglas-fir stand in western Washington in the same development phase, the differences in tree and stand architecture are very apparent (Figure 9.3 b). This demonstrates once and again that it is very tricky indeed to try to "translate" the findings of baseline research in the area of origin of Douglas-fir to planting sites in western Europe.

### 9.2 Designing new silvicultural systems for Douglas-fir

# 9.2.1 Theoretical framework (after Mollison 1988)

All \*designs that involve natural systems will undergo a long-term process of change, because designing is a continuous process, guided in its evolution by information and skills derived from earlier observation of that process. The evolution of the design is a matter of observation, and acting on the information so obtained. In the end it comes down to flexibility; to steering a path based on the results of trials, to acting on new information, and to continuing to monitor and to be open and non-discriminatory in our techniques.

Observation is too often regarded as being largely subjective and unscientific. However, anyone with practical experience with refining field observations as a design tool, will be convinced of the relevance and dependability of field observations.

Apart from studying the architecture of natural systems, we need to study process. In nature, events are ordered or spaced in discrete units. Even a partial understanding of the underlying patterns that link all phenomena creates a powerful tool for designers. It is in the application of harmonic patterns that we demonstrate our comprehension of the meaning of nature and life (Mollison 1988).

A good way to implement a new design is starting with a nucleus and expanding outward. Break up the job into small, easily achieved, basic stages and complete these once at a time. At the end of each stage both past performance and future stage of evolution should be assessed, so that a guide to future adjustments, additions or extensions is assembled as a process (Mollison 1988).

# 9.2.2 Objectives and design

There is a number of strategies that can be followed to convert management of commercial timberland into management with multiple objectives. These strategies are based on the following ecological observations in natural forests, assuming that they may provide lessons which can be profitably applied to forest plantation management (Franklin et al. 1986):

Many organisms are linked to the early stages of forest succession, i.e. the period prior to canopy closure. This is the stage of succession during which species diversity for mammals, birds, herbs, nitrogen-fixing plants, terrestrial invertebrates is highest (Deyrup 1975, Forsman et al. 1977, Maser and Trappe 1984, Dietrich 1993). It is easy to design silvicultural systems in which measures are adopted that will delay full canopy closure: e.g. by the use of much wider initial spacings. There is growing evidence (Reukema and Bruce 1977; Oliver et al. 1986; Oswald 1984; Schutz 1984; Cremer et al 1982, Mc Ardle et al. 1971, O'Harra 1988; Tol 1986; Tuyll and Kramer 1981) that economic yields will suffer very little from early wide spacings, especially when combined with selective pruning (Smit 1936, Welch 1939, Stein 1955, Breteler 1959, Eckstein 1970, Kenk and Unfried 1980; Kenk 1981, Bruenig et al. 1986, Oliver and Larson 1990).

Another important feature of natural forests which could easily be incorporated in management regimes, is the existence of a sufficient amount of dead wood, both standing (snags) and lying on the forest floor (logs). Dead wood is an important forest compartment in nutrient and energy cycling, it is a site for nitrogen-fixation, it is a source of soil organic matter and is very important for wildlife (Meslow 1978; Turner and Long 1975; Sollins et al. 1980; Graham and Cromack 1982, Maser and Trappe 1984). However, it should be noted that dead wood is a transitory feature: it must be continuously produced. It is a challenge to develop management strategies to provide a continuing source of coarse woody debris. To fulfill all functions it must also be renewed in large sizes. Guidelines for the amounts, sizes and decay stages of woody debris to fulfill various objectives are urgently needed (Franklin et al. 1986).

New snags can be created by retaining a number of selected trees from the previous generation into the next rotation as shelterwood on cut-over areas. Trees with crown and upper bole defects could be selected for this purpose. These trees than can be converted to

snags by girdling: preferably a few trees per year or per decade (depending on the specific site conditions) to provide a continuing source of snags.

Including hardwoods in Douglas-fir stands (Hattemer 1957) may be an appropriate option for a variety of management objectives, with potential positive effects on soil nutrients (Fogel and Cromack 1977; Fredriksen 1976), on the decomposition of organic matter (Turner and Long 1975; Trappe and Maser 1977), on the response of vertebrate and invertebrate populations to increased sunlight on the forest floor for part of the year (Voegtlin 1982; Mispagel and Rose 1978; Grier and McColl 1971), and by providing a very different habitat for epiphytes, invertebrates and some kinds of predators (Anderson 1970; Black and Taber 1977; Bowman and Harris 1980).

Thus it seems possible to create ecologically more diversified forest ecosystems. The enhancement of biodiversity will automatically have a stimulating effect on the biological activity of the soil, on the composition of mycorrhizae and other forms of symbiosis, which will be very helpful to boost a solid sustainability of economic production by the forest ecosystem in the long run.



Clearcutting over large areas near Matlock on the Olympic Peninsula, Pacific Northwest (photo R. v.d. Burg).

# Discussion and conclusions

Growing insights into the complexity of forest ecosystem functioning in the Pacific Northwest has lead to the development of ideas about New Forestry or New Perspectives for a more environmental approach to forest management. The basic \*paradigm in forestry used to be: "let's simplify the forest". New Forestry wants complexity to make a comeback. It should be recognized that Douglas-fir forests are in constant transition. Their average \*life span, before natural disturbances intervene, is about seven to eight centuries. Logging can be seen as one more interruption. But logging that takes every tree, burns the remaining wood waste and replaces a complex forest with a simple man-made stand is an unnatural interruption. The whole approach of forest management in the Pacific Northwest was backward: clearcutting over large areas, its pattern, the massive road network, the burning of leftover slash. It ran counter to how the forest evolved naturally (Dietrich 1993). In Franklins's theory of New Forestry, foresters should consider logging an area intensively for a brief period but then to pull out, closing the roads to let the land recover. In clearcuttings about 10 percent of the dead snags and green conifers of what was an oldgrowth stand should be left on the cutting site. The trees that are left become homes for insects, reptiles, birds and mammals. Such a "dirty clearcut" comes closer to mimicking what nature accomplishes with fire or windstorms. In New Forestry trees are replanted further apart to delay the closure of the evergreen canopy that chokes off light and life underneath; leave green trees in a clearcut; provide different ages and species of trees; and leave standing dead snags.

What is being proposed by Franklin and other scientists is not mere species protection or wildlife preservation but ecosystem management across the human landscape. A complex landscape planning scheme is envisioned. Its backbone would be the park and wilderness areas; its veins would be the riparian zones along rivers, which are the richest biologically. Urban areas should be given some geographic limit, and the surviving forest would be managed in a variety of ways: some of it set aside as permanent old-growth stands, some of it managed as tree farms for timber production, and some of it managed on much longer rotations that allow second-growth stands enough time to become a diversified wildlife habitat. These ideas are very similar to what e.g. Oldeman (1992) proposes by his "nested multiple-use" concept of forest resource utilization.

It seems that it is time we start to ask what kind of a forest we really need: what kind of overall ecosystem and landscape and production forest do we really want to pass to future generations? How much for wood production, how much for habitation, how much for developed recreation, how much for wildlife conservation, and how much for contemplation?

Nowhere else in the United States were the timber volumes so high and the public profits so great as in the old-growth Douglas-fir forests in the Pacific Northwest. For decades, cutting timber was the right thing to do: the nation needed the wood and there was little alternative use of the forest. The old-growth forests had enormous economic value and zero net growth, and the timber industry was anxious to get it cut and replanted. Now that has changed dramatically. In the past years there has been a true battle for the preservation of biodiversity in the Pacific Northwest, to save one of the grandest forest ecosystems on earth. Except for some old-growth remnants, the annihilation of ancient

forest on lower elevation lands was virtually complete by the end of the 1980's. The overharvesting of the old-growth forests became more and more apparent to most people. As a consequence the timber industry was making concessions in response to public pressure: in Washington State, it was leaving uncut per year trees worth about \$ 60 million that could otherwise be harvested, in order to satisfy environmental concerns. Since the 1970's the proposed harvest on the Olympic national Forest has fallen an incredible 90 percent by 1990. Never before, forest resource protection had become such an important political issue and the scope of the total area of forest land finally designated as critical habitat for the northern spotted owl was unprecedented (Dietrich 1993).

# 9.2.3 Designing more windfirm Douglas-fir stands

Designing more windfirm Douglas-fir stands seems especially important in areas where windthrow is a major risk factor, as is the case in many parts of western Europe (Kuiper 1986b, Kuiper and Schooten 1985a; Savill 1989; Ford 1980).



Endemic windthrow is a constant risk factor for Douglas-fir plantation management (picture of a mixed Douglas-fir/japanese larch stand, Leenderbos, The Netherlands)

Because results of tree pulling experiments with Douglas-fir on dry sandy soils in The Netherlands (Kuiper 1986b; Kuiper and Schooten 1985b) are very similar to the results of other tree pulling experiments on different sites and with different species (Fraser and Gardiner 1963; Coutts 1983; Nielsen 1986; Sommerville 1979), it seems justified to try to draw conclusions from observations of tree pulling experiments with respect to the design of silvicultural systems aiming at the enhancement of tree stability against windthrow. The following observations, derived from tree pulling experiments, could be helpful as tools of design:

Tree size: beyond a certain level (12 to 15 m) tree size becomes critical to windthrow. Measures to enhance tree stability should be taken before this critical height level is reached, i.e. during the early stages of stand development.

Tree crowns: to some degree it seems possible to enhance favorable tree crown properties such as a low branch mass, a long and preferably narrow shape and a low crown density, by initial spacing and by thinning: wide spacing and heavy and early thinning can increase crown length significantly, but unfortunately by the same measures branch mass increases too. The positive effect of lowering the center of pressure by increasing the crown length seems to be greater than the negative effect of an increase in branch mass. From the point of view of energy uptake from the wind by individual trees, the net-effect of wide spacings and heavy, early thinnings is assumed to be positive. But this assumption has to be checked by windtunnel experiments.

Lateral rooting: as has been demonstrated by Coutts (1986) lateral rooting is a major component in the anchorage of conifer trees. Eis (1974) showed marked differences in root development between dominant trees compared with trees of the other social classes. These differences were apparent already when the trees were only 10 years old and they became even more pronounced with increasing age (Eis, 1974). The study by Kuiper (1986b) confirms that there are significant differences in anchorage between dominant trees and trees of other social classes in stands of 33, 43 and 66 years old. The results of Douglas-fir root studies, as presented in Chapter 8, clearly indicate that stem diameter at 1.3 m and woody root biomass are strongly correlated for Douglas-fir. When analysing the diameter distribution of a Douglas-fir stand, as a rule dominant trees occupy the highest diameter classes, as has many times been demonstrated in the previous chapters. This certainly is an element of explanation of the observed fact that Douglas-fir trees are less sensitive to windthrow at H/d ratio smaller than 60 (Faber 1979); i.e. short, massive trees with strong diameter growth are firmly anchored.

Because of the inherent natural tendency of Douglas-fir trees towards early crown stratification (Krueger 1967; Oliver et al. 1986a), the enhancement of the growth of the dominants by means of a positive \*selective thinning could provide a way to increase the anchorage. Dominant trees should be selected as crop trees very early (e.g. when they are 4 m tall), and should be released from neigbouring tree competition regularly from then onwards. By systematically increasing the available growing space it seems possible to enhance lateral root development for a selected number of trees and thereby to increase their anchorage significantly.

The number of crop trees required in a silvicultural system, depends on its objectives. In silvicultural systems frequently used in The Netherlands final timber crop trees number between 100 and 150/ha (Schuetz and Tol 1982). When confining the tending and thinning measures to crop trees only, costs for silvicultural treatments are kept low. Thus from the point of view of individual tree anchorage a relative wide initial spacing and early selective thinning should be considered very helpful.

Such a thinning regime, in which a limited number of trees is given the opportunity to develop long crowns, thick stems, low h/d-ratio and strong lateral rooting will enhance the anchorage of the entire stand too, in the sense that a sufficient number of "stability trees" provides a backbone for the entire stand. A sufficient number in this respect could be more than 150 trees/ha.

Our observations (Chapters 6 and 7) show that in Douglas-fir stands, which, after planting, are left to themselves, a sufficient number of stability trees can be identified, even at an early stage of stand development.

Many foresters agree that the best way to reduce windthrow is to gradually accustom the trees to windstress by adopting a wide initial spacing regime combined with precommercial thinnings (Cremer et al. 1982; Booth 1974; Bryndum 1986). This has a positive effect on both the energy-uptake component and on the anchorage component of individual tree stability.

However, from the point of view of the stability of the entire stand, a closed canopy with plenty of neighbouring crown contact is very helpful to dissipate wind energy harmlessly. It has been demonstrated many times that no-thinning plots are very stable. In most wind-exposed areas in Great Britain, especially on sites where rooting conditions are not optimal, no-thinning regimes are widely adopted (Savill, 1983). These arguments are in favor of narrow spacings and leaving a stand unthinned. What could be a solution to these seemingly contradicting ideas? Perhaps a good option to enhance stability is to incorporate both aspects into one silvicultural system, i.e. provide ample growing space during early stand development, and keep the stand as dense as possible once a critical tree height of 15 m is reached (Mitscherlich 1973; Bryndum 1986). The required measures would include a relatively wide initial spacing followed by two to three precommercial thinnings, to reduce the number of stems, to select and release 100-150 candidates for the final crop and to further stimulate the growth and quality of these crop trees, including pruning to a height of 6 m, when the trees are 12 m tall (Welch 1939, Stein 1955, Eckstein 1970, Kenk 1981).

Depending on the objectives and the anticipated wood quality, it is conceivable that within one stand timber trees and so called "stability trees" are to be two different objectives. Timber trees are to yield the most valuable dimensions and wood quality. The economic value of the entire stand is most often concentrated upon them. For stability trees the production of high quality wood is not necessarily the main function. Their primary function is to become most stable and windfirm, so they should be allowed to develop under optimal growth conditions, including fertilization, if necessary. When the critical stand height is reached, such a multi-function stand could consist of a few hundred stability trees together with 100 crop trees.

Commercial thinnings in later years of the rotation period should be light and selective. On sites with a high windthrow risk it may often be better not to thin at all, because of the neighbouring crown contact and because a closed canopy causes less turbulence compared with a more open irregular canopy. Reduction of canopy roughness therefore also is recommended for reducing interception of polluted air and rain. Thinned crops are especially susceptible to wind damage during the 2 to 5 year period when the canopy is re-closing (Savill 1983).

Attention should be paid to stand edges. On very exposed sites a shelterbelt of Douglas-fir interplanted with deciduous trees like birch, beech and oak can be created, with a gradual transition towards the pure conifer stand core. When mixtures are not desired, an alternative is to thin Douglas-fir early and heavily in a belt of about 50 m from the edge to provide a zone which the wind can penetrate. Topping or high pruning the edge zone can be very effective to stabilize internal edges (Huette 1986). Half of the crown of the trees in the edge zone can be removed, provided that they have crown lengths of at least 30 percent of total tree height. The best results are gained when some additional fertilizer is applied after topping or pruning (Huette 1986), although this diminishes the multipleuse potential of such stands because fertilizers may cause shifts in soil fauna and flora to occur.

A silvicultural system aiming at maximum stability, like the one suggested above, is different from the systems commonly used in forestry practice. To reduce costs precommercial thinnings are avoided and commercial thinnings later in the rotation period are preferred, when the trees have marketable sizes.

# 9.3 Conclusions

1. Natural Douglas-fir stands on poor sites, belonging to the *Pseudotsuga menziesii-Holodiscus discolor* association (PSME-HODI), show some characteristics of a "Plenter-waldaehnliche Entwicklungsphase" at age 50 years (Ch.5).

2. The similarity in growth conditions between relatively poor sites belonging to the PSME-HODI association in western Washington, and sites in The Netherlands frequently used for Douglas-fir plantations, show the small-scaled selective thinning regimes used in the Netherlands, to be quite appropriate to manage second-growth stands on poor sites in the U.S.A. on a sustained basis too.

3. Tree genera that occupy ecological niches in natural Douglas-fir stands in the U.S.A. are similar to those in coniferous forests in western Europe and include: *Taxus, Acer, Alnus* and *Populus*. In the shrub layer *Acer, Cornus* and *Vaccinium* are present frequently in both areas. The understory vegetation in natural Douglas-fir stands much resembles that

of montane and boreal conifer stands in Europe too, at least on the level of the genus (e.g. Linnea, Oxalis, Vaccinium, Polystichum, and various mosses). (Ch.2).

4. Douglas-fir is able to develop successfully in multi-aged stands. This suggests a much wider "silvicultural amplitude" for Douglas-fir than is commonly admitted.

5. Diversification of the forest canopy and continuous initiation and development of a large number of regeneration-units built by shade-tolerant species, demonstrate the importance of small-scale "disturbances" in the dynamics of natural Douglas-fir stands.

6. A new concept of the development of semi-natural second-growth Douglas-fir stands may be that of "a forest community in which 4 sub-populations of *Pseudotsuga menziesii* coexist, each with a specific age structure, H/d-ratio distribution and volume growth potential, in the form of a mosaic of very small units" (Ch.5).

7. The Carbon River case-study (1000 + year stand), in which serial species Douglas-fir outlived at least two generations of western hemlock, makes a climax theory for Douglas-fir forests hypothetical at best (Ch.2).

8. The results of the architectural analysis of the German thinning experiment confirm the silvicultural advantages of early and heavy thinning over thinning late or never in terms of individual tree parameter values (Ch.6).

9. The results of an evaluation of tree development in a never thinned plot in The Netherlands show advantages of more extensified silvicultural systems for Douglas-fir on relatively poor sites. Only the effects on H/d-ratio seem critical; the effects of no-thinning on all other stem and crown parameters studied are to be judged positively (Ch.7).

10. The H/d-ratio and tree volume seem to be the best objective parameters to detect differences between social crown classes (Ch.5).

11. D.b.h. can be used as a simple input variable to calculate woody root biomass for Douglas-fir. Hence, the effect of silvicultural treatments on d.b.h., can be estimated in terms of root systems variables (Ch.8).

12. By making better use of the natural tendency of Douglas-fir trees to develop different social classes, root anchorage can be enhanced (Kuiper 1986b). When dominants are selected and tended early during 2 to 3 successive precommercial thinnings, optimal opportunities are created for the development of deep crowns, thick stems, low h/d-ratio and firm rooting. By the time the stand enters the critical phases of development the crop trees are most stable. From that moment onwards radical changes in the canopy are to be avoided, and maximum advantage is to be taken of the resistance offered by neigbouring tree crowns. From the viewpoint of stand stability it is better to stop thinning once a tree height of 15 m is reached (Ch.9).

# SUMMARY

In chapter 1 a review of the literature shows that both in its area of origin and in Europe, Douglas-fir is a highly successful tree species, that grows fast, on a wide range of sites, and that is appreciated for its excellent wood. In this paper it is postulated that an architectural analysis of natural Douglas-fir forest ecosystems yields vital information, by comparing codified basic tree and forest characteristics, needed for the design of sustainable silvicultural systems with a high level of biodiversity and consequently low-management inputs ("do less and accomplish more"). This can serve the management of multiple-use Douglas-fir forest plantations. Several assumptions and hypotheses are formulated, to be tested by the case-studies in the following chapters.

The architecture of 5 natural Douglas-fir stands, located on high-yielding sites in the *Tsuga heterophylla* zone in western Washington and western Oregon was analysed in chapter 2. Stand ages ranged from 50 to 1000 + years. Vertical diagrams and crown projection maps were used to identify developmental phases. The results show the spatial coherence between forest components by describing the characteristics of trees, eco-units and the forest mosaic for each plot in detail. From the results, general developmental trends were deduced. The architecture of natural Douglas-fir forests was shown to be very diversified in all developmental phases.

In chapter 3 developmental aspects of Douglas-fir ecosystem functioning are related to the complex structural and spatial variability of old-growth stands, described earlier in this paper. The biodiversity of the forest canopy and the continuous innovation and development of numerous regeneration-units built by shade tolerant species, and their comparison with other studies on non-tree components of such stands, demonstrate the importance of small-scale dynamics of old-growth Douglas-fir forests.

In chapter 4 architecture, age distribution and genetic variability of Douglas-fir in a 500 m long elevational transect on a slope in a mature Douglas-fir stand was analysed, using stand architecture diagrams. The transect was divided in four sub-plots, corresponding to different elevational classes. A total of 200 trees were cored at breast height for age determination; for 100 Douglas-fir trees the genetic variation of ten isozyme loci was related statistically to variation in tree height and diameter at breast height. The proportion of variation between elevational classes was significantly higher for the quantitative parameters than for the isozyme variation and was related to the site gradient. The relatively wide age distribution in all four sub-plots indicates that Douglas-fir develops successfully in multi-aged stands, so that it has a wide "silvicultural amplitude".

The architecture of semi-natural second-growth Douglas-fir stands in western Washington was studied in **chapter 5** to quantify the development of the tree population into social classes (Leibundgut 1959). Three plots were selected on sites of site class 2 (McArdle 1961) with a stand density of 160, 232 and 304 trees per ha respectively and three plots on relatively poor sites (site class 4), with a range in stand density of 512, 1080 and 1296 trees per ha. For each plot significant differences between social classes could be identified by the parameters h/d-ratio and tree volume. For the plots on good sites age distribution, total standing volume and distribution of the number of stems over the social classes closely resembled each other. This allowed an analysis of the influence of stand density. Very significant differences between the plots were found in dominant and codominant trees. Dominants and codominants numbered 68 percent of total number of stems on average, and their total crown projection area averaged 64 percent of the plot area, indicating for all 3 plots an utilization of the resources very different from even-aged managed stands. For the three plots on poor sites much variation existed in the distribution of tree age and number of stems over the social classes, so that no comparisons between the plots were possible. Dominant and codominant trees accounted for 47 percent of the total number of stems and 48 percent of crown cover on average, indicating that in terms of timber production, semi-natural stands do not allocate all resources to timber logs. All plots were characterised by a very heterogeneous horizontal and vertical stand architecture. This has important silvicultural implications.

In chapter 6 the architecture of a 25 year old experimental thinning plot, in a 53 year old Douglas-fir plantation near Freiburg, southern Germany, was studied. Vertical diagrams were made and the distribution of various stem-, crown- and increment parameters, including tree height, d.b.h., H/d-ratio, crown width, crown length, crown surface area and basal area increment were analysed. This experiment included early and heavy thinning (plot 1), early and moderate thinning (plot 2), late and heavy thinning (plot 3) and no-thinning (plot 4). Main objective was to study the effects of the different treatments on stand architecture. The results indicated the following effect of early thinning on dominant trees: values for the stem parameters were 10 to 15 percent higher; crown parameters were 20 to 30 percent higher, but basal area increment was not significantly different, compared with no-thinning. Late thinning showed no significant differences compared with no-thinning. Early treatments had a greater overall effect on the codominant trees: stem parameters increased 15 to 20 percent on the average; crown parameters were 20 to 40 percent higher and basal area increment was 30 to 50 percent higher compared with no-thinning.

In view of the discussions on the need for thinning Douglas-fir plantations, in **chapter 7** architecture and social tree development of Douglas-fir were analysed in a Dutch thinning experiment, including a low-thinned and a no-thinned plot. Results indicate that after 38 years of no-thinning, enough dominant and codominant trees with medium long crowns and good growth potential remained to select the 100 to 150 final crop trees, as advised in forestry practice (Schuetz and Tol 1982). However, the high values for H/d-ratio may announce problems when crop trees are to be released.

In chapter 8 root systems of Douglas-fir trees in The Netherlands were measured to study relationships between root system structure and size, and stem and crown diameter and growing space, all of which are aspects of tree stability. Twenty-one trees, planted between 12 and 37 years previously, were winched over and the structural portion of their root systems to a diameter of 0.5 cm and the crown perimeter were mapped. Retrospective measurements were made on the extension of major lateral roots. Size and shape of the

#### Summary

crown projections were poorly correlated with root system width. Reconstruction of spatial development of the root systems revealed that root spread was very limited during the first 5 years after planting. Highly significant positive correlations were found between stem diameter at 1.3 m and root biomass, and with the cross sectional area of the structural roots.

Finally in chapter 9 the results of various case-studies, presented in previous chapters, are discussed. Forty-three theorems concerning individual trees, eco-units and the forest mosaic are listed and used for approving or rejecting the hypotheses of the introductory chapter. Use and limitations of the architectural approach are evaluated and the impact of baseline research in natural forests for Douglas-fir plantation management is assessed. Elements for the design of new silvicultural systems for Douglas-fir are presented, particularly incorporating non-timber objectives in the design, among which the boosting of stand resistance against wind. Finally, scientific and practical conclusions are drawn.

# SAMENVATTING

In hoofdstuk 1 toont een literatuuroverzicht over de Douglas duidelijk aan, dat zowel in zijn oorsprongsgebied als in Europa, de Douglas een zeer succesvolle, snelgroeiende boomsoort is, die op een heel scala van groeiplaatsen zich thuisvoelt en die bijzonder gewaardeerd wordt vanwege zijn houtkwaliteit. In deze studie wordt gesteld dat een architectuur-analyse van natuurlijke douglasbos-ecosystemen belangrijke informatie kan opleveren, die nodig is voor het ontwerpen van duurzame en biologisch gevarieerde bosteeltsystemen met een geringe management-input ("doe minder en bereik meer"). Dit is van belang voor het beheer van multiple-use douglasbossen. Verscheidene veronderstellingen en hypothesen zijn geformuleerd, die vervolgens zullen worden getoetst aan de hand van case-studies, die in de volgende hoofdstukken aan de orde komen.

De architectuur van 5 natuurlijke douglasbossen op produktieve groeiplaatsen in west Washington en west Oregon wordt geanalyseerd in **hoofdstuk 2**. De leeftijd van de opstanden varieert van 50 to 1000 jaar. Schaaltekeningen van zijaanzicht en kroonprojekties werden gebruikt om verschillende bosontwikkelingsfasen te identificeren. De resultaten tonen de onderlinge samenhang tussen de verschillende boscomponenten. De kenmerken van bomen, eco-units en het bosmozaiek worden voor elk proefveld in detail beschreven. Van de resultaten worden algemene ontwikkelings-trends afgeleid. De architectuur van natuurlijke douglasbossen blijkt zeer gevarieerd te zijn in alle ontwikkelingsfasen.

In hoofdstuk 3 worden enkele aspekten gepresenteerd van het funktioneren van bosecosystemen die samenhangen met de complexe architectuur en ruimtelijke variatie van oude bossen, zoals die al eerder in dit rapport ter sprake kwam. De grote biodiversiteit van het kronendak en de voortdurende initiatie en ontwikkeling van talrijke verjongingseenheden van schaduwverdragende boomsoorten, toont het belang aan van kleinschalige dynamiek binnen oude douglasbossen, hetgeen bevestigd wordt door studies in dergelijke bossen naar ándere boscomponenten dan bomen.

In hoofdstuk 4 wordt de architectuur, de leeftijdsverdeling en de genetische variatie van de Douglas geanalyseerd voor een volwassen bos op een 500 m lange groeiplaatsgradient. Het transect is opgedeeld in 4 sub-plots, die overeenkomen met verschillende groeiplaatsomstandigheden. In totaal zijn er 200 bomen aangeboord om hun leeftijd te kunnen bepalen en van 100 bomen is de genetische variatie vastgesteld van 10 iso-enzym systemen, die vervolgens statistisch in verband is gebracht met de variatie in boomhoogte en diameter op borsthoogte van de betrokken bomen. Boomhoogte en stamdiameter waren duidelijk gecorreleerd met de groeiplaatsgradient. Het aandeel van de variatie tussen de sub-plots was aanzienlijk groter voor de stamparameters dan voor de vastgestelde iso-enzym variatie. De relatief brede leeftijdsspreiding in alle vier de sub-plots geeft aan dat de Douglas op succesvolle wijze in staat is om zich in meerjarige opstanden te ontwikkelen. Dit vormt een aanwijzing voor een brede "teeltkundige amplitude" voor de Douglas.

#### Summary

Een analyse van de architectuur van half-natuurlijke jonge douglasopstanden in west Washington wordt behandeld in hoofdstuk 5, met speciale aandacht voor de ontwikkeling van sociale boomklassen (naar Leibundgut 1959). Drie plots werden geselecteerd op relatief rijke groeiplaatsen met een stamtal varierend van 160, 232 en 304 bomen per ha. En er werden drie plots geselecteerd op arme groeiplaatsen met een stamtal varierend van 512, 1080 en 1296 bomen per ha. Voor alle plots kon er een samenhang worden aangetoond tussen de sociale positie van een boom en zijn h/d-verhouding en stamvolume. Voor de plots op rijke groeiplaats kon de invloed van de opstandsdichtheid worden bestudeerd, omdat de leeftijdsverdeling, de staande houtvoorraad en de stamtalverdeling over de sociale klassen min of meer vergelijkbaar was. Voor dominante en codominante bomen konden er zeer signifikante verschillen tussen de plots worden aangetoond. Beide boomklassen tesamen genomen, maakten gemiddeld 68 % van het totale stamtal uit en 64 % van de totale kroonbedekking, hetgeen wijst op een benutting van de aanwezige groeiplaatsfactoren die afwijkt ten op zichte van gelijkjarige beheerde opstanden. Voor de plots op arme groeiplaatsen maakten dominante en codominante bomen gemiddeld 47 % van het totale stamtal uit, en 48 % van de kroonbedekking, hetgeen nogmaals onderstreept dat in half-natuurlijke jonge douglasbossen het groeiplaatspotentieel niet optimaal wordt benut voor de produktie van hout. Alle plots worden gekenmerkt door een zeer heterogene horizontale en vertikale architectuur, hetgeen belangrijke teeltkundige consequenties heeft.

In hoofdstuk 6 wordt de bosarchitectuur geanalyseerd van een 25 jaar oude dunningsproef, nabij Freiburg, in zuid-Duitsland. Het experiment omvatte een vroege en zware dunning (plot 1); een vroege en lichte dunning (plot 2); een late en zware dunning (plot 3) en een ongedunde opstand ter controle (plot 4). Doel van deze case-study was het bestuderen van het effekt van de diverse opstandsbehandelingen op de bosarchitectuur, waartoe schaaltekeningen werden vervaardigd en de verdeling van verschillende opstandsparameters werden geanalyseerd, waaronder boomhoogte, dbh, grondvlakbijgroei, kroonbreedte, kroonlengte en kroonmanteloppervlak. De resultaten tonen aan dat vroege dunning op dominante bomen het effekt had, dat de waarden van de stamparameters gemiddeld 10-15 % hoger waren; dat de kroonparameters gemiddeld 20-30 % hoger lagen; maar dat de grondvlakbijgroei niet significant verschilde ten op zichte van niet dunnen. Late dunning had geen noemenswaardig effekt ten opzichte van niet dunnen. Vroege dunningen hadden op de ontwikkeling van codominante bomen een groter effekt dan op dominante bomen: stamparameters namen gemiddeld met 15-20 % toe; kroonparameters met 20-40 %; en de bijgroei lag 30-50 % hoger vergeleken met ongedunde codominante homen.

In verband met de diskussies over de noodzaak van dunningen in Douglasopstanden, wordt in **hoofdstuk 7** de architectuur en de ontwikkeling van sociale boomklassen geanalyseerd binnen een Douglas-dunningsproef in Nederland. Een plot waarin uitsluitend laagdunning heeft plaatsgevonden en een ongedunde plot werden met elkaar vergeleken. De resultaten tonen aan, dat na 38 jaar van niet-dunnen, er genoeg dominante en codominante bomen aanwezig zijn met een behoorlijke groeipotentie, zoals aangegeven door kroonontwikkeling en lopende bijgroei, om de 100 tot 150 toekomstbomen te kunnen selecteren, zoals wordt geadviseerd binnen de gangbare teelt van de Douglas (Schuetz and Tol 1982). Alleen de hoge waarden van de h/d-verhouding baart zorgen, als toekomstbomen in een dergelijk teeltsysteem worden vrijgesteld.

In hoofdstuk 8 worden de resultaten gepresenteerd van een onderzoek naar de beworteling van de Douglas in relatie tot de ontwikkeling van de stam, kroon en groeiruimte. Een en twintig bomen, aangeplant tussen de 12 en 37 jaar geleden, werden omgetrokken om de architectuur van het grove wortelstelsel (alle wortels tot 0.5 cm dikte) te kunnen analyseren. De kroondiameters werden eveneens vastgelegd. De laterale uitbreiding van grote zijwortels werd gerecontrueerd aan de hand van groeiring-analysen. De grootte en vorm van de kroonprojekties bleken nauwelijks gecorreleerd te zijn met de breedte van het wortelstelsel. Reconstructie van de ruimtelijke ontwikkeling van de wortelstelsels toonde aan dat laterale wortelontwikkeling zeer beperkt was gedurende de eerste 5 jaar na aanplant. Zeer signifikatieve positieve correlaties werden er gevonden tussen de stamdiameter op borsthoogte en de totale wortelbiomassa.

In hoofdstuk 9 tenslotte, worden de resultaten van de case-studies uit de voorafgaande hoofdstukken, besproken. De hypothesen uit het inleidende hoofdstuk worden getoest aan een lijst met 43 theorema's over individuele bomen, eco-units en het bosmozaiek. De voor- en nadelen van de architectuurbenadering worden geevalueerd, en de impact van nullijn-onderzoek in natuurbossen voor het beheer van aangeplante Douglasopstanden wordt geanalyseerd. Elementen worden aangedragen voor het ontwerpen van nieuwe teeltsystemen voor de Douglas, met speciale aandacht voor de integratie van andere beheersdoelstellingen dan alleen houtproductie, en voor het ontwerpen van stormvaste Douglasopstanden. Tenslotte worden er een aantal wetenschappelijke en praktische conclusies getrokken.

Glossary

# GLOSSARY

Terms and concepts marked with an asterisk \*, when occurring for the first time in the text, will be explained in this glossary in alphabetical order. Definitions without source are specific for this book.

\*Aggradation phase: a phase in eco-unit development, starting as soon as the canopy closes and ending when trees generally can no longer close gaps in the canopy.

\*Alters- und Zerfallsphase (german): forest development stage following the "\*Optimalphase" in which the canopy opens up by the process of \*fragmentation. Characterised by a gradually declining total basal area until forest degradation is replaced by forest regeneration in the absence of major catastrophes (Leibundgut 1978).

\*Architecture: generally speaking, architecture is the design and construction of an object. In this paper the term architecture is used as spatio-temporal \*structure linked to a well-defined hierarchical level (Oldeman 1990).

\*Architectural tree model: the growth program which determines the successive architectural phases of a tree. Hence it gives rise to a differentiation sequence from seed to maturity (Hallé et al. 1978).

\*Biostatic phase: a stage in \*eco-unit development succeeding the \*aggradation phase, and ending by the breaking up (\*fragmentation) of the original stand (large eco-unit) into a mosaic of smaller patches, due to natural mortality of large trees over time. When they die they leave a gap in which a young eco-unit may develop (similar to the steady state shifting mosaic, after Borman and Likens 1979).

\*Canopy closure: sum of crown projection areas as a percentage of the total plot area.

\*Canopy gap: the openings in the canopy between tall trees-of-present (Peters 1992).

\*Close environment: depending on the scale on which a system is observed, its environment can either be close (micro environment) or far (mesa, macro and mega environment). The microenvironment of a system will have a direct influence on its functioning, in terms of modifying the system's inputs and outputs. Micro-environmental influences usually are quantifiable and, to a certain degree, predictable, which is often not the case with the \*far environment.

\*Codominant tree: a tree whose crown is exposed to full light from above, but to comparatively little light from the sides, which is positioned in the general level of the crown cover, and usually is more or less crowded on the sides (Munns 1950; Ford-Robertson 1971).

\*Compartment: set of abiotic or biotic components in a living system, that is delimited as a recognizable functional ensemble (Oldeman 1990).

\*Competition: interaction between living systems, by which one system profits at the costs of the other (Leersnijder 1993).

\*Crown class: functional ensemble (\*compartment) of trees in a stand based on their crown development and crown position in the forest canopy, relative to the crowns of adjacent trees (Ford-Robertson 1971).

\*Descriptive model: a model that gives only the properties of a system as seen from the outside (Leersnijder 1993).

\*Design: a beneficial assembly of components in their proper relationships, with a unified purpose. Designing is the gathering, selecting and weighing of information in order to process it into a step-by-step development plan (Oldeman 1990). The purpose of an initial design is to evolve some sort of plan to get one started in an otherwise confusing and complex situation. Any design is composed of concepts, materials, techniques and strategies (Mollison 1988).

\*Dominant height: (top height) mean height of the hundred tallest trees per ha (Schuetz and Tol 1982).

\*Dominant tree: a tree whose crown extends above the general canopy and receives full light from above and partly from the sides. Usually with a well-developed crown, larger than the average trees in a stand (Munns 1950; Ford-Robertson 1971).

\*Eco-unit: a distinct hierarchical level between forest components and forest mosaics: the smallest category of an ecosystem, of which the limits and \*lifespan have been defined as a surface of ground on which at one moment in time, a vegetation development has begun, of which the \*architecture, ecophysiological functioning and species composition are ordained by one set of trees until the end (Oldeman 1990).

\*Eco-unit development: a subprocess in forest succession, in which an \*innovation phase, an \*aggradation phase, a \*biostatic phase and a \*degradation phase are distinguished (Oldeman 1990). The presence of trees in different developmental stages is symptomatic for eco-unit development.

\*Explanatory model: a model which explains a system in terms of its sub-systems (Oldeman 1990).

\*Far environment: the meso, macro and even mega environment of a system. The influence by the far environment on non-linear systems, governed by simple rules, through feedback and related effects, is difficult to predict accurately and frequently gives rise to complexity, diversity and almost random and chaotic phenomena (Prigogine and Stengers 1984; Horgan 1993).

\*Forest architecture: the morphological expression of a forest stand, both created and modified by the \*architecture and functioning of its components (Kuiper, this book).

\*Forest components: organisms in forest stands (e.g. trees), which form the building blocks of \*eco-units, and of which their \*architecture and functioning can be explained by their organs as sub-systems at a lower hierarchical level (Kuiper 1988a; Oldeman 1990).

\*Fusion is the formation of larger eco-unit-like mosaics by converging development of neighbouring smaller eco-units.

## Glossary

\*Genotype: complete set of inherited genes of an organism.

\*Growing space: the space available to a tree, in which it is more competitive than its neighbours (constraints for competition are not defined).

\*Heterogeneous stand: a stand with a high level of biodiversity, as expressed by a diversified stand architecture, species composition and tree size spectrum.

\*High thinning: thinning method involving the cutting of dominant and codominant trees mainly, to release crop trees from neighbouring tree \*competition.

\*Innovation phase: a phase in eco-unit development following the degradation phase, in which trees re-establish in canopy gaps (new eco-units).

\*Intermediate tree: tree shorter than dominant and codominant trees, but with its crown either below or extending into the forest canopy, receiving a little direct light from above, but none from the sides. Its rather small crown is typically crowded on the sides (Munns 1950; Ford-Robertson 1971).

\*Jungwaldphase (german): forest development stage following forest regeneration, in which the initial large number of regeneration units develop into a smaller number of aggrading eco-units, which merge into a closed canopy by the process of \*fusion. Characterized by a strong height growth and the development of different \*social classes of trees.

\*Life cycle: sequential development of forms or functions of an organism during its \*life span.

\*Life span: to speak accurately about life span, one must refer to the many life spans represented within a living physical structure. E.g. in the human body a cell in the lining of the stomach lives only a few days; a typical skin cell only two weeks; a red blood cell two or three months; whereas the neurons in the brain seem to last a lifetime. Yet exactly the same DNA controls all these life spans: skin cells and brain cells are genetically identical. Through a process we do not yet understand, our DNA is able to create all kinds of specialized cells: brain, skin, heart, liver and so on; each with its own allotted life span. Hence, its definition depends on scale and complexity of the system.

\*Low thinning: method of thinning from below, by which the smallest trees are removed from the stand.

\*Optimalphase (german): forest development stage following "Jungwuchsphase" and developing into an "Alters- und Zerfallsphase". Characterized by closed stands, from the moment of height growth culmination to the stage of culmination of basal area. Forest regeneration is usually absent (Leibundgut 1978).

\*Paradigm: any pattern or example.

\*Phenotype: all aspects of morphology, physiology, behavior and ecological relations of an organism, which can be visually observed, resulting from its genotype-environment interaction.

\*Plenterwaldaehnliche Entwicklungsphase (german): forest development phase following a rather stable "\*Alters- und Zerfallsphase" in which forest degradation is slow and forest regeneration is taking place over an extended period of time and in very small eco-units, resulting in a very heterogeneous forest architecture. Usually this phase develops into an "\*Optimalphase".

\*Potential tree: stage in tree development in which the final size and expansion of the tree has not yet been reached, which may be interrupted by premature death or suppression (Hallé et al. 1978).

\*Regeneration-unit: \*eco-unit in a more limited sense, dealing with tree components mainly; a group of trees with similar ages that has become established essentially at the same moment and is evolving as a distinguishable age group towards later stages of \*stand development.

\*Reiteration: the duplication of the original model of a tree from a meristem not contained in the embryo. Reiteration is at the base of any modification of the \*tree's architecture not inherent in its model (Oldeman 1990).

\*Rotation: the time-span between sowing or planting and harvesting a crop; the number of years between the regeneration of a stand and its final harvest at a specified stage of development.

\*Rules of nature: channels through which creative intelligence flows. At a quantum mechanical level, matter and energy become interchangeable. Any physical structure first takes form as quantum fluctuations, as virtual energy, before it proceeds to condense into impulses of energy and particles of matter; a process which, ultimately, is guided by intelligence; by rules of nature (Chopra 1990).

\* Selective thinning: thinning method in which crop trees are released from neighbouring tree competition selectively (in contrast with systematic thinning).

\* Silvatic mosaic: a forest area subjected to the same regime of climate and soil, which shows the same complex of silvigenetic dynamics, resulting in an \*eco-unit composition that oscillates around a specific state and determining the architecture and ecological functioning as long as the resource regime remains essentially unchanged (Oldeman 1990).

\*Silviculture: the science and art of guiding the natural development of trees and other forest components in such a way that management objectives are met with on a sustained basis, preferably with the least possible effort.

\*Silvicultural system: biological management system for forest stands, aiming at a "target forest type", by favoring certain forest architectures and development phases in which the growth of certain tree species can be enhanced or retarded, to meet management objectives. This may include a regime of measures of site preparation, of plant propagation, of selective thinning, of wood harvesting techniques, and of maintaining a high level of biodiversity, adapted to the ecological requirements of the site and tree species.

\*Silvidiagram: a graphical representation of the architecture of an individual tree (usually a stand mean tree) during its life cycle. A list of tree size data and data concerning ecological interactions with other forest components is usually included (Kuiper 1988a).

## Glossary

\*Social position: position of a tree in relation to its neighbours (see \*crown class).

\*Stand architecture: the visible, morphological expression of a stand, as indicated to scale on vertical diagrams and crown projection maps, resulting from the sequential development of the phenotype and spatial arrangement of its component organisms.

\*Stand development: sequential growth and competition of a stand; forest components other than trees usually being ignored. Stand development in this restricted sense can be characterised by different tree development stages, such as an open growth stage (Oliver et al. 1986a), a stage of plastic response (Harper 1977) and a stagnation and mortality stage (Drew and Flewelling 1979).

\*Stand structure: pattern of horizontal and vertical distributions of trees in a stand.

\*Structure: arrangement of data in time and space which are not directly derived from living systems but indirectly from models of these systems (Oldeman 1990). In a more strict sense, structures are processes which repeat themselves in accordance with rules of nature. And rules of nature are like channels which give direction to the flow of creative intelligence. In this sense, structures can be regarded as patterns of channeled intelligence (Chopra 1990).

\*Strategy: refers to the process of planning to achieve a future goal; it adds the dimension of long-term planning to technique.

\*Suppressed tree: a tree whose crown is located entirely below the general level of the canopy, receiving no direct light from above or from the sides. Trees that are suffering from neighbouring \*tree competition.

\*System: arrangement of functional units. Systems may be chosen arbitrarily, but they are considered biologically equivalent if they show both identical architecture and identical ecophysiological or genetical regulation processes.

\*Theorem: a proposition that has been proved or assumed to be true; proposition demonstrably true or acknowledged as such

\*Tree architecture: the morphological expression of the genetic blueprint of tree growth and development (Hallé et al. 1978).

\*Tree competition: interaction between adjacent trees for the allocation of available \*growing space (competing for the available resources of light, water and nutrients).

\*Tree-of-present: tree which has reached its final expansion into the canopy (or at a lower level), often by \*reiteration (Hallé et al. 1978), symptomatic for eco-units in the \*biostatic phase of stand development (Peters 1992).

\*Tree-of-past: tree in a senescent phase of development (Peters 1992).

\*Understory reinitiation stage: as the overstory grows older, new herbs, shrubs and trees appear in the forest floor. These are usually species capable of living under high shade. In a literal sense, the stand would no longer be a single cohort after the forest floor stratum develops. The understory reinitiation stage generally contains more animal species than does the stem exclusion stage, but fewer than the stand initiation stage (Oliver and Larson 1990).

\*Verjungungsphase (german): forest regeneration phase.

\*Yield table: mathematical growth model showing the anticipated development pattern of managed stands (usually of even-aged pure stands), for a particular silvicultural system and for different sites.



Schematic profile of an old-growth Douglas-fir tree illustrating its individualistic nature and its deep asymmetric crown. Several fan-shaped branch clusters are identifiable on the lower bole of the tree (Franklin et al. 1981).

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Architectural analysis of Douglas-fir forests

## **CURRICULUM VITAE**

Leen Kuiper werd geboren op 19 juni 1956 te Geldrop. Na het behalen van het diploma Atheneum-B aan het Lorentz Lyceum in Eindhoven, begon hij in 1974 aan zijn studie Bosbouw aan de toenmalige Landbouwhogeschool te Wageningen. Na zijn kandidaatsexamen in 1977, werden stages doorgebracht aan de E.T.H in Zuerich, Zwitserland (gebergtebosbouw), en aan het Ecologisch Instituut van de Poolse Academie voor Wetenschappen in Warschau, Polen, waarbij met name europese oerwoud-restanten werden bezocht.

De doctoraalstudie omvatte de vakken Bosteelt en Bosoecologie, Natuurbeheer en Vegetatiekunde. Gedurende deze tijd verrichtte hij onderzoek naar kleinschalige bosverjonging op het landgoed Schovenhorst; naar de invloed van begrazing op struweelontwikkeling langs de Overijsselse Vecht; en naar enige toekomstverkenningen voor het landschapsbeheer van een zwitsers bergdorp, in het kader van landschapsoecologisch projekt Vals. In 1981 werd het doctoraalexamen gehaald en sindsdien is hij te werk gesteld als (aanvankelijk pro-Deo) medewerker bij de vakgroep Bosteelt en Bosoecologie, belast met de voorbereiding en uitvoering van een onderzoeksprojekt naar de architectuur en ontwikkeling van de Douglasspar.

In 1982 werd er experimenteel onderzoek verricht naar de windworp-problematiek bij de Douglas, waartoe bomen werden omgetrokken door middel van een handlier, om de verankering te kunnen bestuderen. In 1983 vond er een verkennende studiereis plaats naar het westen van de Verenigde Staten, gevolgd door 6 maanden veldonderzoek in natuurlijke Douglasbossen in Washington en Oregon in 1984. Daarna is hij vanaf 1985 als (part-time) onderzoeksassistent in dienst gekomen van de Stichting BION van de Nederlandse Organisatie voor Wetenschappelijk Onderzoek NWO, gedetacheerd bij de vakgroep Bosbouw van de L.U.W., om het douglasprojekt verder uit te werken.

Daarna is hij in 1991 vertrokken naar Kameroen, om als ontwikkelingswerker bij de Nederlandse Organisatie voor Ontwikkelingssamenwerking SNV, zich bezig te houden met toegepast agroforestry onderzoek in de droge savanne-zone van noord-Kameroen, in samenwerking met het Institut de la Recherche Agronomique te Maroua. Tevens heeft hij daar een projekt geleid voor aangepaste technologie (touw-pompen).

Na terugkeer in Nederland werd hij in 1994 aangesteld als bosbouwdeskundige bij een bedrijf dat de haalbaarheid van beleggingen in milieuvriendelijke projekten onderzoekt. Als hoofd van de bosbouw-afdeling is hij verantwoordelijk voor het ontwikkelen van een investeringsbeleid voor plantages van tropische hardhoutsoorten, alsmede voor het voorbereiden van management-plannen gericht op het herstel en duurzaam beheer van secundaire tropische regenbossen in Papua New Guinea, India, Malaysia en de Solomon eilanden. Het uitvoeren van projektidentificatie-missies in bovengenoemde landen behoort eveneens tot zijn taken.