Continuous-cover forestry with Douglas-fir

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Report No. 51, July 2006

CONTINUOUS-COVER FORESTRY WITH DOUGLAS-FIR

A literature review and a modelling attempt

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ABSTRACT

There are very few examples of Continuous Cover Forestry with Douglas-fir in either experimental plots throughout the world or in wild "natural" stands. Indeed, if the purist definition of Continuous Cover Forestry is taken to mean that stands exhibit diameter and age distributions resembling a smooth "inverse J" curve, there may be *no* real-life examples!

Douglas-fir is not a very shade-tolerant species and it requires substantial light to grow and to thrive. Good seedling growth should not be taken as a good indicator of subsequent sapling growth. North American researchers have concluded that understorey saplings require at least 30-45% of full sunlight to achieve sufficient vigour that would enable them to eventually form part of the canopy. Expressed differently, recruitment from the understorey requires a maximum Stand Density Index of 370-670 (metric units) of the overstorey or less than 30-55% full site occupancy. To achieve this, it is necessary to maintain stands with extremely low stockings of canopy trees, or else stands must have "clearfell patches" of at least 0.25 ha, or with a diameter of 1-2 times the height of surrounding trees. Such large clearfell sizes stretch the definition of Continuous Cover.

To create a mathematical model, a simple two-stage stand structure was compared with a typical even-aged regime. Under a range of assumptions, a comparison of profitability (using NPV, LEV and IRR as criteria) indicated that the continuous-cover regime was less profitable, due to the 60-year "transition period" required for converting a non-forested site (the Kyoto rule) into continuous cover.

Continuous Cover Forestry might be an expensive way to grow Douglas-fir, but it is theoretically possible provided that canopy stockings are maintained at very low figures or else the definition is relaxed to allow harvesting coupes of at least 0.25 ha.

Project code: EO1-55. Funded by the Ministry of Agriculture and Forestry.
Practising continuous-cover forestry with Douglas-fir in New Zealand.
Contracting Organisation: The NZ Douglas-fir Research Cooperative.

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METHODOLOGY

Depending on the country of origin, there are a number of phrases that describe "Continuous Cover Forestry" (CCF). The search can be restricted to those references that include Douglas-fir (*Pseudotsuga menziesii* Mirb.) but even so, there are too many sources to examine them all, in this report. An Internet search with Google for 'continuous cover' (the British term) AND 'Douglas' yielded 13,800 hits. One with 'uneven-aged' (the American term) AND 'Douglas' yielded 54,200 hits.[3] The German word 'Dauerwald' was also popular (14,100 hits), although not in combination with Douglas or *Pseudotsuga* (only 67 hits).

In view of the enormity of the task, the search concentrated on the questions listed as title headings below. In addition to the Internet search, likely journals were browsed and international experts consulted. By a process of iteration, it was possible to focus on the most fundamental and important references, and to identify the key investigators in this specialist field.

WHAT IS CONTINUOUS-COVER FORESTRY (CCF)?

There are a large number of definitions of CCF, and equivalent terms, not all of which are necessarily compatible. Pommerening and Murphy (2004) say, "Broadly speaking CCF includes those silvicultural systems which involve continuous and uninterrupted maintenance of forest cover and which avoid clearcutting". They provide a table giving 24 semi-synonyms from the associated literature.

Möller, writing in 1922, saw 'Dauerwald' (permanent forest) as a system for increasing the standing volume of a forest, with higher sustained revenues, while maintaining ecological benefits including soil quality (Platt 2002). The French term is 'jardinage', with a similar distinguished pedigree.

According to the British Forestry Commission, 'continuous cover forestry' is "a general term covering several silvicultural systems which conserve the local forest canopy/ environment during the regeneration phase". It avoids the cutting of contiguous areas more than two tree heights wide, whereas 'clearfelling' is defined as the cutting-down of all trees on an area more than 0.25 ha (Mason et al. 1999).

Pommerening and Murphy summarise the various concepts into the following main components:

- Continuity of woodland conditions (no clearfelling > 0.25 ha).
- Emphasis on vertical and horizontal structure.
- Mixed age classes and tree species.
- Attention to site limitations.
- Selective individual tree silviculture.
- Conservation of old trees, deadwood and protection of endangered plants and animals.
- Promotion of native tree species (and provenances) and broadleaves in particular.
- Ecologically sensitive forest protection, thinning and harvesting operations.

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[3] Other terms include: ecological silviculture, near-natural forestry, close-to-nature forestry, pro silva, green-tree retention, multiaged and multicohort forestry, and selection silviculture (also known as the German word *Plenterwald*).

- Ecologically sensitive wildlife management.
- Establishment of forest margins and a network of protected woodlands.

Some authors also include natural regeneration as being a pre-requisite, but this is discussed later.

HOW IMPORTANT IS SHADE-TOLERANCE?

A common belief of foresters is that pioneer or light-demanding species such as radiata pine are best grown in even-aged stands. This is said to mimic the “natural” situation that occurs after a fire, which releases trees from competition, fertilises the site and melts the resin in the serotinous cones. In contrast, shade-tolerant species such as redwood (*Sequoia sempervirens*), western hemlock (*Tsuga heterophylla*) or miro (*Prumnopitys ferruginea*) are believed to be able to recruit from understorey seedlings and are therefore more conducive to CCF.

In New Zealand, Douglas-fir is considered shade tolerant. This is certainly true, if radiata pine is the only yardstick. On an international scale, however, Douglas-fir is deemed at best only of intermediate tolerance (Mason et al 1999; various websites). Indeed, some sources rank the species as being “intolerant” (O’Hara 2002; various websites). One definition that distinguishes between tolerant and intolerant species is that the former can be expected grow in small gaps (0.05 ha) (Mason et al 1999). With this definition, Douglas-fir can be considered intolerant because minimum recommended gap size is 0.25-0.5 ha (Ketchum 1994; Mailly and Kimmins 1997).

More fundamentally, one can question the basic assumption that CCF is suitable only for shade-tolerant species that can survive in an understorey. The reality may be that, although shade-tolerant species can survive and prosper under a less tolerant species (and not vice versa), it is difficult and perhaps impossible for most species to survive for long in their own shade (O’Hara 1998a). In other words, the concept of CCF using a single species, whereby replacement trees are recruited from vertically beneath the canopy of the same species, may be erroneous – for any species!

To emphasise this potentially important observation: if the above “rule” is correct, it may be biologically impossible to grow a single species under CCF without adapting some sort of patch or mini clearfell system, whereby replacement trees are distanced horizontally from their larger neighbours but not vertically beneath them. Conversely, if this type of patchwork forestry is accepted as being a valid form of CCF, then it should be possible for *all* species to be grown this way. The difference is merely one of coupe size. Radiata pine, for example, could easily be grown as “continuous cover” if replacement trees were allowed patches of one hectare or more. To state emphatically that Kaingaroa Forest, for example, is not managed on a continuous cover basis, it would be necessary to assert that the clearfelling coupes are too large to qualify.

Having said this, there seems to be no consensus on this matter, even among specialist foresters. For example, such a conclusion is challenged by the website of Selkirk College, British Columbia, which states that “the moderate shade tolerance of Douglas-fir …makes it suitable for regeneration under its own canopy” (selkirk.ca/rr/bec/zones/IDF.html). In this context, it is important to distinguish successful gemination and growth of *seedlings* (less than 1.4 m height) from that of *saplings*, because the former may be prolific but not persist (Churchill, 2005).

There are certainly very few New Zealand examples of Douglas-fir regenerating vertically under its own canopy – unless there is side-light entering from an adjacent edge or clearing. One exception was Compartment 64 in Golden Downs, Nelson, where a stocking of 1600 stems/ha was reduced to 300 stems/ha for the purposes of a trial (NN256). The thinning coincided with a seed year, and the resultant regeneration (on a forest floor that was devoid of weed competition) was prolific. It is not known, however, if any of the young seedlings survived when the overstorey closed canopy. Similar regeneration did not persist in a seed-orchard stand in Rotoehu Forest, Bay of Plenty (Compartment 55). (Charlie Low, pers. comm.). There is plenty of anecdotal evidence about "carpets" of young (1-3 m) Douglas-fir invading canopy gaps in native forests, but these do not survive (Nick Ledgard, pers. comm.).

The example of Redwood (*Sequoia sempervirens*) is often used in New Zealand discussions to illustrate the point that shade-tolerant species can be grown under continuous cover – even if the canopy consists of the same species. There are good examples of Redwood's potential to grow under its own canopy in prominent tourist destinations, such as in stands around Rotorua. Redwood, however, is quite different to Douglas-fir: it readily coppices from cut stumps, and may also more actively root-graft. Whereas, in other species the young seedlings cannot compete against mature trees, and will die during a drought, this does not apply in Redwoods – the coppiced stems receive their water and nutrients through root-grafting with their giant neighbours. To a lesser extent, Douglas-fir also exhibits root-grafting, although coppicing does not occur.

WHAT ARE THE PERCEIVED BENEFITS OF CCF?

The word "perceived" is used to describe the benefits and disadvantages of CCF because this literature review has identified that most of the attributes of this type of forestry appear to be guesswork, derived from theory, rather than based on evidence from robust trials or surveys.

In parts of the United States, there is a growing perception that forestry as currently practised [ie clearfelling] is not socially acceptable (Emmingham 1998). Platt (2001) reports that "all over Europe" there is a trend towards a greater mixture of species and ages because of a heightened awareness of the multiple functions of forests, including biodiversity. According to some British authors (Mason et al 1999), CCF has less visual impact; there is greater species diversity (at least at a small scale); there are lower restocking costs; greater resilience against windthrow; and lastly CCF can produce large diameter, high quality sawlogs. The general, forest-loving public seek a situation where there are always large trees to admire and where there is never any catastrophic disturbance.

A major driving factor behind the trend to CCF appears to be that stands of mixed age and species are more "natural". Because "Nature Knows Best" and natural stands provide obvious environmental benefits, it follows (or so the argument goes) that humans should try to emulate those systems.

One difficulty appears to be that authors think at different scales. A *stand* of multi-aged trees may be more species-diverse than a similar stand of even-aged trees, but the same may not apply to *forests* that occupy land on a larger scale: a forest that comprises only stands of "balanced" age classes may be less diverse that one that is a patchwork of different-aged but even-aged stands. Kaingaroa *Forest* has considerable species diversity because it is managed under continuous cover on a landscape scale, although at a compartment scale it is managed on a single-rotation, clearfelling system.

With regard to the ability of a forest to sequester and retain atmospheric carbon, it is very important not to be confused by the issue of scale. There is a gain in carbon in the biosphere – with an implied decrease in the atmosphere – that is commensurate with the standing volume of the forest, measured across all stands within that forest. Similarly, forest removals imply a loss to the atmosphere regardless of whether the loss occurs in the form of numerous individual trees that are widely separated or whether the harvested trees are clustered in a clearfelling coupe. Certainly in the absence of reliable yield information, there would seem to be no inherent benefit from CCF as far as carbon sequestration is concerned.

WHAT ARE THE PERCEIVED DISADVANTAGES OF CCF?

According to Mason et al (1999), the disadvantages of CCF include: it is more complex to manage, requiring skilled personnel; it is more difficult to predict and regulate yields; there is more site damage on heavy soils ("because of less brash to provide brash-mats"); it is not cost effective unless natural regeneration is employed (which is not possible where there is weed competition, heavy browsing pressure, or a requirement to utilise improved seed sources); and it takes a long time to determine the ultimate success of the system. Moreover, the almost continuous presence of understorey slash in some systems of CCF may increase the risk of fire (Curtis, 1998).

One could add the obvious disadvantage: CCF may be less profitable than clearfelling systems. Clearfelling may often be the most cost-effective means of producing timber, environmental considerations aside, for the following reasons: the piece size is greater; a larger volume of wood is harvested per coupe (ie economies of scale); a substantial volume is often obtained from a smaller area of land (thus minimising skid-sites, logging tracks and other set-up costs); the least number of visits per rotation are incurred for the purpose of harvest; trees can be felled towards open areas, thereby ensuring no expensive and dangerous "hang ups"; no care needs to be taken to protect the remaining crop from damage by machines, ropes or falling trees; and lastly, opening up a stand can make it vulnerable to costly wind events.

For similar reasons, even production thinning is not profitable over most of New Zealand with radiata pine. With Douglas-fir, the operation barely breaks even. The arguments for CCF rest on the fact that there may be environmental, social and aesthetic benefits that outweigh the cost-efficiency factor.

WHERE CAN ONE FIND PRACTICAL EXAMPLES OF CCF WITH DOUGLAS-FIR?

The huge quantity of literature relating to continuous-cover indicates a great degree of public interest, but contrasts strongly with the paucity of field trials or observations of practical examples of CCF. If a prime reason for the push towards CCF is its "naturalness", it should be readily apparent in natural stands. Douglas-fir occurs naturally in the West of Canada, and the North-West of the United States, and this is the logical place to search for such stands. Yet Emmingham (2002) states "most foresters, forestry scientists, forestry professors and researchers in the Pacific Northwest have never seen a functioning uneven-aged forest". He continues: "there is widespread scepticism…that it would work in the Pacific Northwest's summer drought conditions with such species as Douglas-fir". Partial cutting methods, he averred, were more likely to be accepted in Interior forests, including interior Douglas-fir (where weed competition is not as severe).

Germany and France may have led the way in developing the philosophy of CCF but, in those countries, Douglas-fir is often regarded as an unfortunate exotic introduction rather than a forest type to be cherished[4]. For this reason, there may not be the same pressure to investigate CCF with Douglas-fir in those parts of Europe.

There is sometimes a perception in New Zealand that CCF in Europe is the ordinary situation and that clearfelling is the exception. But even in shade-tolerant species like beech, "plenter-like" structures (ie stands made by selection logging rather than natural or artificial clearfellings) account for "as little as 0-15%" of the forest area in Central European forests (Schütz 2002). In Britain, 90% of managed forests employ a system of patch clearfelling, with an average size clearfelled coupe of 5-10 hectares (Mason et al 1999). Forests under CCF management "were probably less than 5000 ha" in extent at the beginning of the 1990s (Mason et al 2004). Needless to say, there are no examples in New Zealand of Douglas-fir grown under CCF, and precious few of any exotic trees grown this way.

The idealised "reverse-J" curve of diameter classes has been observed in forests for centuries, and is widely documented. Note, however, that the word *forest* is used advisedly, rather than the word *stand*. In other words, the negative exponential shape has always been most closely associated with large areas – at a smaller scale, the forests represent even-aged stands, or the equivalent of small clearfell patches (O'Hara 1998a). The slope of the curve varies, but is defined mathematically by the *q factor*. The q factor is the number of stems in a given size class divided by the number in the next larger size class. In a "balanced" stand, the q factor is frequently said to be constant across the full range of size classes, although it seems this definition may be mathematically convenient but has little ecological foundation (O'Hara 1998a).

It appears that the classic "reverse-J" curve is so rare in wild Douglas-fir stands that it is questionable if it exists at all. Where examples have been found that approach such a structure, it is debateable whether the trees vary in *age* as well as *size*. The distinction is important: if a mixture of tree sizes is the result of suppression or poor growth of some stand elements, then it is arguable that these may not be suitable quality to replace the canopy trees and form a sustainable crop. For example, thinning studies in Douglas-fir show that intermediate, suppressed or overtopped trees in even-aged stands with highly differentiated crowns often do not respond well to heavy thinning (Emmingham 1998). In less extreme cases, however, Douglas-fir will respond very well to release.

It is true that many natural stands of Douglas-fir comprise a mixture of age-classes, albeit not in a smooth inverse-J fashion but perhaps only in two or three age cohorts. The predominance of even age classes is linked to frequent perturbations, including wind, snow or pathogen attack (such as the Douglas-fir beetle *Dendroctonus pseudotsugae*). Wildfire, caused by lightning strike, or deliberately lit– a tradition that may go back 15,000 years in North America – tends to create a patchwork of even ages (Frankin et al 2002). Alternatively, if the fire is confined to the forest floor and does not reach the canopy, it has the property of destroying seedlings and saplings and leaving larger trees.

One informal experiment in CCF with Douglas-fir was conducted at Darfield in Central Canterbury by Bill Studholme of the Selwyn Plantation Board. He successfully used single-tree selection on a mature stand (aged 70-75 years), allowing the natural regeneration to flourish.

[4] It seems that Douglas-fir may indeed be native to Europe but died out only 10,000 years ago in the last ice age (Platt 2002).

This seemed to work until there was a periodic drought, where the young trees were out-competed by their neighbours and died. But Darfield is a particularly dry part of New Zealand (rainfall c. 650 mm/yr), and it would be interesting to observe how this experiment would have fared in a high-rainfall area, or one with more water-retentive soils. Bill also intended to convert many other Douglas-fir forests to a *Femelschlag* (or expanding gap) system, by mechanically thinning at age 40. Unfortunately, the market for Douglas-fir collapsed during this period, and he did not have the resources to continue the experiment.

IS IT IMPORTANT TO ENSURE NATURAL REGENERATION?

One tenet of CCF is that "regeneration is the first indicator of sustainability" (Guldin and Baker, 1998). But it is not at all clear why this should be so. There may be situations where natural regeneration does not work, but planted seedlings will grow adequately. Such an arrangement may have several advantages.

Natural regeneration depends on fortuitous high-seed years and does not allow for genetic improvement or for controlled spacing of trees. Random siting and clustering makes it difficult to locate seedlings for fertiliser and weed control; complicates pest control with young trees; and merely postpones the costs of silviculture from time of planting to time of thinning. Natural regeneration was a popular option in early NZ Forest Service days, but fell into disrepute for the above reasons. In summary: the authors of this report dispute that natural regeneration is necessarily the most profitable option, and therefore is an essential ingredient of CCF.

WHAT ARE THE MOST SUITABLE WAYS OF QUANTIFYING CCF?

To produce mathematical models of CCF, it is necessary to describe stands adequately, yet in a way that can easily be measured. Some metric must be used that expresses the ability of younger or smaller trees to survive the competition. The following proposals have been encountered in the literature:

Number of trees in canopy

This is obviously a simplistic approach, as it does not take into account the size of the trees in the canopy (for example, Wilson 1979, Wampler 1993, Bailey 1996).

BA of canopy

Basal area per hectare is the multiple of the number of trees and the size of those trees. It is clearly an advance on the above, but is only of general guidance, because the shade will depend on how basal area is distributed among the age cohorts. A few, larger trees will transmit more radiation than a less mature stand with many more stems (ie with the same Basal Area) – in larger trees, there are larger gaps between the crowns and the crowns themselves are themselves sparser (Mason et al 2004). The vigour and health of the crowns must also be important. Mason et al (2004) provided a figure of 35 m^2/ha for the maximum BA of the canopy, under which Douglas-fir seedlings will achieve 50% of the growth that would be attained in full light.

Light intensity

Churchill (2005) concluded that light was the primary factor in determining growth of Douglas-fir understorey, at least for low light levels.

The evidence (poor as it is) from the British researchers is that Douglas-fir requires a light intensity of at least 16% for seedlings to survive. Meanwhile, using data from Vancouver Island, Drever (1999) in his masterate thesis devised regression equations for height, basal area and volume growth of Douglas-fir saplings (NB saplings, not seedlings) as a function of light intensity. Drever and Lertzman (2001) stated "our data suggest that partial-cutting treatments need to create light environments greater than about 40% full sunlight". Even more light than this was indicated by Canadian studies (York et al 2002, 2004) using different-sized circular openings (0.1ha to 1.0 ha). See Table 1.

Table 1

Total transmitted light (%)	Extension growth (cm)
50.2	20
62.9	24
77.5	35

The conflicting evidence can be reconciled by the fact that the British researchers assumed that it was adequate for understorey seedlings to attain as little as half the growth of full canopy plants, whereas the others considered that such suppressed trees may survive but they do not prosper.

Churchill (2005) (in stands at Fort Lewis, Washington State) concluded that Douglas-fir required an average of 45% full sunlight to achieve vigour levels where recruitment into the overstorey without further release is likely. Under 10-35% full sunlight regeneration was growing slowly but was likely to respond to release and regain full growth rates (especially if less than 5m in height). Below 10% full sunlight, regeneration was scarce and of very poor vigour.

Stand Density Index

In an even-aged stand, SDI is a simple function of mean DBH and trees per hectare: $SDI = SPH*(Dq/25)^{1.6}$, where Dq is the quadratic diameter (Long 1995)[5]. For example, a stand with 200 trees per hectare and a quadratic diameter of 50 cm would have an SDI of $200*2^{1.6}$ or 606. It measures sapwood area, which is a surrogate for leaf area index – a metric which is harder to measure directly.

Many New Zealand foresters would better understand Stand Density Index if it was expressed in a different way, namely as a value on a scale that relates to the potential maximum value of basal area on that site. The maximum SDI could be described as "the maximum number of trees of a given size that can grow within a certain area". It is based on the "self-thinning rule" which states that if the logarithm of the mean plant mass is graphed against the logarithm of stand density (ie stocking) then the slope will be –3/2. If there are any more trees, or if the trees are larger, they will die by natural suppression.

SDI can be used to regulate stocking in uneven-aged stands by a three-step process (Long 1995). The first is to estimate the maximum SDI that the site will support, and the (lesser) number that will be obtained after every thinning operation. Then the proportion of this that will be contributed by the overstorey is deducted. Finally the residue is allocated among the understorey elements.

[5] $SDI = \text{Trees per Acre} * (D/10)^{1.6}$, where D is quadratic mean diameter in inches (Long 1998). In metric units, the function is given as: $SDI = sph * (D/25)^{1.6}$ where D is in centimetres (Woodall et al 2006). SDI can be converted from English units to metric units by multiplying by 0.42.

From Churchill's study we can expect full growth at less than SDI of 370 (30% full site occupancy); restricted growth at 370-670 (30-55% full site occupancy) and little or no growth if the SDI exceeds 670 (55% full site occupancy). Long (1985) gives the maximum SDI (for Douglas-fir) as 1450 stems/ha of 25 cm trees – which corresponds to about 71 m^2 BA. This has been exceeded in New Zealand, but perhaps not if we consider only sapwood BA and not the dead heartwood (which can continue to accumulate indefinitely).

But why would we want to use overseas estimates of basal area potential, when we have a good model in New Zealand (namely, the DF_NAT growth model that is contained in the Douglas-fir Calculator, Knowles 2003) that can provide such a figure for New Zealand own unique biotic and abiotic conditions?

BD*q* method
This creates a unique after-cut structure based on three stand parameters: B, the residual basal area; D, the maximum diameter retained in the residual stand; and the *q* factor (the slope of the inverse J curve). The BD*q* computation produces a target residual stand structure. An inventory is taken in the stand being managed and the existing stand inventory is compared with the BD*q* target. Invariably, some diameter classes in the stand being managed will contain more trees than the target, and some fewer (Guldin and Baker, 1998). Redistributing the basal area deficits in those classes below the target to the surpluses in other classes (and so violating the q parameter) ensures that the residual stand has sufficient basal area. Thus, at least in the Southern United States, BD*q* represent the priorities of tree marking.

Although the BDq method of tree marking is widely used in the United States, it is not suitable for prescribing stockings in stands with two or more distinct age classes, and therefore has been largely superseded by the SDI system (O'Hara and Valappil 1995).

Diameter-Limit Cut
A natural alternative of the BDq method is the diameter-limit cut. In its simplest form, it states that all and only the trees larger than a specific diameter limit may be cut (Buongiorno et al 2000). This method has fallen into disrepute in the United States probably because of its confusion with "high-grading". But the latter implies removal of only those trees that have commercial value, whereas the Diameter-Limit Cut is removal of all trees above a certain diameter. Also by ignoring age, it introduces the problem of the more vigorous trees being removed in any thinning. This dilemma of selectively removing more vigorous trees and thus reducing the genetic fitness of a stand sits at the crux of any introduction of CCF.

SUMMARY OF STUDIES, GIVING LEVELS OF OVERSTOREY DENSITY

The following table is reproduced from Churchill (2005) (with permission). It provides levels at which understorey vigour can be maintained in Douglas-fir stands.

Table 2: Levels at which understorey vigour can be maintained in the PNW of the USA and Canada.

Author	Overstorey Density or light level	Region
Bailey (1996)	<= 16 sph max to grow[a]	W.Oregon
Brandeis et al (2001)	<20m^2/ha to grow[a]	W.Cascades, OR
Carter & Klinka (1992)	30-40% PACL: other factors have greater influence on relative height growth than light	Coastal B.C.
Deisenhofer (2000)	7% indirect light: lowest level to maintain D-fir	W. Oregon
Del Rio & Berg (1979)	27-41 m^2/ha BA; 5-12% full sun to maintain[b]	E.Coast Range, OR
Drever & Letrzman (2001)	40% full sun to grow[a]	Coastal B.C.
Emmingham & Waring (1973)	7% RL: No D-fir advanced regen survival under this level	Southwest OR
Mailly & Kimmins (1997)	>40% RLI to grow[a]; 20-40% RLI to survive	Coastal B.C.
Miller & Emmingham (2001)	18-28 m^2/ha to grow[a]	Willamette Valley, OR
Wampler (1993)	<= 12 sph to grow[a]	W.Washington
Williams et al. (1999)	5% of PPFD to survive 50 years and reach 3 m	Interior B.C.

Note:

[a] : Grow [in this table] is defined as achieving growth rates for trees to be able to recruit into the mid and upper canopy without further overstorey removal

[b] : Maintain is defined as achieving sufficient growth rates, live crown, and stem stability to maintain release potential for future overstorey removal.

BA is basal area; RLI is relative light intensity; PACL is percent above canopy light; PPFD is photosynthetic photon flux density; RL is relative light.

WHAT FIGURES OF OVERSTOREY DENSITY ARE APPROPRIATE FOR NEW ZEALAND CONDITIONS?

The growing conditions in New Zealand are unique, and values obtained overseas may be inappropriate. For example, there are many **soil** organisms such as laminated root rot (*Phellinus weirii*) that have not yet reached our shores. **Leaf**-area index varies greatly with the presence or absence of Swiss Needle-Cast disease (present in some areas of New Zealand but not in others). In the relatively pollution-free Southern hemisphere, the **sunlight** is more intense but may not penetrate the canopy to the same extent as diffuse Northern hemisphere light. The incidence and distribution (diurnal, seasonal) of **rainfall** and **temperature** extremes may differ greatly in an island nation compared with continental climates elsewhere.

There is good evidence that New Zealand does indeed differ from overseas studies, in that our sites are capable of supporting much higher basal area and volume levels. In an unpublished study, all suitable PSP data plots were analysed by Knowles (pers comm.) to calculate RD (relative density) and SDI. Levels substantially higher than indicated by Curtis (1982) for the Pacific Northwest were discovered. Curtis said there was “some biological maximum which appears to [have a Relative Density of] about 14 for small plot observations”, whereas Knowles produced RD figures as high as 22. Similarly, Knowles gives a maximum SDI for New Zealand of over 2400, whereas the maximum in North America appears to be about 1450 (Long 1985).

For all these reasons, overseas studies can be little more than a guide. Unfortunately, we have no New Zealand data that relates to Douglas-fir growth of seedlings and saplings in a partly shaded situation. Applications to investigate CCF have hitherto been declined for government funding, and there has been little historic interest from the large-scale private sector.

HOW CAN CCF BE APPLIED IN PRACTICAL TERMS IN NEW ZEALAND?

York et al (2003, 2004) planted Douglas-fir in canopy gaps of different sizes (0.1, 0.3, 0.6, 1.0 ha) and found that the seedlings grew in all cases although, or course, least with decreasing gap size. There was a noticeable difference even between the larger gaps. They fitted a quadratic function to explain the drop off in height growth but it would have been useful if they had also recorded stem diameters, as these would have showed an even clearer picture than height alone (which is less affected by competition). The major failure of this study, for the purposes of this report, was the implication that seedling growth is indicative of future growth.

Churchill (2005) stated, "to maintain adequate vigour and recruit into the mid- and upper-canopy, understorey Douglas-fir saplings require a substantial amount of growing space. For single tree selection to work, it is recommended that the overstorey be heavily thinned early in a stand's development and then kept open through successive light thinnings". He went on to say, "a very general conclusion can be drawn that a maximum of 40% of full stocking or [a minimum of] 30-40% of full sunlight is necessary to maintain adequate vigour". Given that the maximum BA of Douglas-fir sapwood in North America is about 71 m^2/ha, stands must be maintained below about 28 m^2/ha to enable growth of saplings. This is a very low figure! But note that three other authors in Table 2 support or provide numbers lower than this, with one (Brandeis *et al.* 2001) suggesting that overstorey BA should be less than 20 m^2/ha.

With group selection, Churchill suggested a minimum gap size of 0.25-0.5 ha or a gap diameter of 1.5 times the height of the surrounding overstorey. Malcolm et al (2001) essentially supports Churchill's summary, giving an identical minimum gap-size for Douglas-fir. One problem of such a system is that it may not be classified as CCF, at least if the British definition of minimum gap size is used.

If one accepts that a continuous curving "reverse J" distribution of age classes in a single stand is an ideal, appealing to mathematicians and those with a purely theoretical idea of natural forests (not demonstrated in real-life examples of Douglas-fir) we must consider simpler stand structures. O'Hara (1998a) states that "stand structures with only two or three age classes or canopy strata may provide a simple means of meeting most, if not all, objectives of more traditional and complex uneven-aged stands". Seidel (1983) investigated this approach, but the data do not extend past the seedling stage, whereas Tesch and Korpela (1993) assessed more mature regeneration and identified the critical factors that led to growth response.

If one also accepts that clearfelling is the most profitable option, then two-tier forestry would be the form of CCF that comes closest to that. We can envisage small patches of trees 60-years old and ready for harvest alongside small patches that are half that age. The patch diameters would be one and a half times the height of the canopy trees (circa 40 m, leaving clearings of 60 m diameter – or about 0.25 hectare).

AVAILABLE MODELS FOR ANALYSING CCF

WestProPlus

This model is based on data from coastal D-fir/Hemlock forests in Oregon and Washington. The inland Californian version of this model is called CalPro, and other relatives are NorthPro and SouthPro, depending on the region of the U.S. being examined. It divides a stand into softwoods and hardwoods, broken down into the stockings in each diameter-class, using a BDq distribution. The selection of trees can be done using either the BDq or the diameter-limit system.

A “BDq distribution” can be used to describe existing stands, or stands after intervention or harvest. The letter ‘B’ is the total basal area of all trees. ‘D’ is the maximum and minimum diameter of trees. Presumably, if trees are too small they are not counted, and they are harvested if they become too large. The ratio of the number of trees in a given diameter class to the number of trees in the next larger class is ‘q’, which varies according to the size of the intervals between diameter-classes.

Having input the initial and the target conditions, the model then “grows” the stand, and the range of outputs includes a physical description of the target stand; the log-grades it produces; the species and size diversity; and the financial results.

Problems with using WestProPlus under New Zealand conditions include:

- Simulation of a regime starting with bare ground, rather than an existing mixed-size stand.
- Unnecessary complications (mixtures of hardwoods and softwoods, species diversity indices, too many age-classes).
- Verifying that the built-in growth models work adequately under NZ conditions.
- Use of site index as the only indicator of site productivity and only driver of the models.
- Selecting appropriate values of B, D and q to adequately describe a stand distribution.

There is good basal area data for New Zealand stands, so B should not be a problem. The range of diameter classes (D), and the ratio of stocking between them (q), seems to be an arbitrary judgement. As such, there are an infinite number of combinations, and a tedious iterative process would be necessary to narrow down the options to a feasible range.

The model which drives WestProPlus and relatives is described in Liang et al (2005). Practical applications of the model are described in Buongiorno (2001) and Buongiorno et al (2000).

MASAM (Multi-Aged Stocking Assessment Model)

This could be a useful alternative to WestProPlus, because it is built to deal with simple stand structures, such as a three-strata stand of a single species (O’Hara 1996, 1998b). Given a description of stand structure, the model predicts average diameters, stand density [ie stocking] parameters, and volume increment for each stand component and for the total stand. It may be more relevant to ponderosa pine than to Douglas-fir.

The Forestry Commission’s model

The (U.K.) Forestry Commission have produced software to support their Information Note 45 (Kerr et al 2002). This is a system of monitoring (permanent or temporary plots) located on a systematic grid over the whole area being transformed from even-aged management to CCF, and provides the species, number and diameter of trees. It is not a simulation system, and therefore is not very useful for the purposes of this study.

Churchill’s model

Churchill summarised his research by producing a regression equation of relative volume growth. This took into account those factors which proved to be of statistical significance but omitted those that were not important. Churchill’s equation is:

$$\text{Predicted RVG} = 1.337 + 0.076\text{LCR}^2\text{CDR} - 0.008\text{Ht} - 0.028\ln(\text{HDRatio}) + 0.003\text{HG}$$

Where RVG is the relative volume growth in cubic metres per year; LCR is the Live Crown Ratio; CDR is the visually assessed crown density rating; Ht is height in metres; HD ratio is the ratio of height to diameter; HG is the previous 5-yearly mean annual increment of height growth in centimetres.

As definitive as Churchill's study may be, it would need to be carefully validated for New Zealand because the variables (eg crown density rating) cannot easily be derived from the PSP system, and because the environment is probably different.

The D-fir Calculator
This provides the most suitable software for simulating even-aged Douglas-fir stands in New Zealand. For a more complex structure such as two-tiered forestry it is somewhat problematic to use because a) the overstorey will grow differently with "followers" that are half the age, compared to same-aged followers (which can be modelled without difficulty), and b) the understorey will exhibit relatively poorer growth, which cannot be calibrated easily for New Zealand conditions.

MODELLING A SIMPLE STAND STRUCTURE UNDER CCF

It was attempted to model the simplest possible system that could be called "continuous cover forestry". This is the system that most closely resembles traditional rotation forestry: a two-stage structure, whereby understorey trees are half the age of canopy trees. If the profitability of this simple structure is too low, and the feasibility too remote, then there is little hope for more complex and more expensive structures.

The modelled stand consisted of a single hectare, divided into four quarters. Two of the quarters (for example, diagonally opposite eachother) were clearfelled and replanted every 30 years, and the other two quarters were production thinned.

The modelling was done using the Douglas-fir Calculator (Knowles 2003), which has the advantage of being calibrated for New Zealand conditions – even though it was designed for even-aged forestry. A continuous-cover regime was simulated by dividing the stand into two growth phases: early and later. The **later** growth phase generated the clearfelling volume, but was constrained to a basal area of 35 m^2/ha – this being the amount of canopy that is believed from overseas studies (Mason et al 2004) to permit understorey growth of 50% of that under full sunlight. The **early** growth phase generated the production thinning volume at age 30. Productivity (ie the 500 Index, Knowles 2005) was halved for this run.

The two components were added together (see the Profitability Comparison spreadsheet) to create a continuous cover regime that yielded both production thinnings and clearfell volumes every 30 years.

Assumptions
In the CCF regime, we have assumed that the suppressed understorey has grown at 50% of the maximum growth rate during the first 30 years. This is an oversimplification, as the growth in very early years is likely to be largely unaffected by the overstorey – particularly in the centre of the 0.25 ha clearfell patches. As the surrounding trees grow, it is likely that the edge trees would be totally suppressed, whereas the central trees would gain a dominant state.

Following removal of the canopy trees, we have assumed that the growth catches up with trees grown under even-aged stand conditions, so that tree size at harvest is identical. It could be argued that this would not be case, as there would be some residual handicap from the first 30 years of suppression. On the other hand, it could be argued that the extensive side-lighting provided by the removal of the overstorey is tantamount to a heavy thinning, and trees would respond to that.

The 500-Index for the canopy trees was assumed to be 18.0 m^3/ha/yr – a fairly typical figure – and for the understorey trees was half that amount. Site Index remained unchanged for both growth phases at 32.0 m. Other inputs, including costs and prices, were the default assumptions originally obtained through telephone interviews during October 2005 aimed at modelling Douglas-fir in the Taupo catchment (Knowles and Hansen, 2005).

For economic comparison, two further simulations were constructed:

1. A 45-year old clearfell regime, typical of current practice.
2. A "permanent forest" regime, involving a 60-year transition to CCF, and then followed by an infinite series of CCF regimes.

Results and discussion

Clearfell forestry as currently practised on a 45-year rotation gives a (real) return of 7.43% IRR, a NPV of $1985/ha or a Land Expectation Value of $2140/ha for a 6% discount rate. Depending on the source of economic wisdom, it could be argued that such a return averaged over 45 years is very reasonable. Other commentators would argue that the return is insufficient compared with alternative investments.

Whatever the case regarding this particular argument may be, the CCF regime yields an Internal Rate of Return of only 5.89%, with a NPV and LEV of -$105.40. This compares unfavourably with the typical situation. A "subsidy" can easily be added to the spreadsheet to calculate that it would require an additional $80/ha/yr for the next 30 years to compensate for the imbalance in profitability.

RESEARCH NEEDS

This paper uses overseas findings to draw some conclusions that might be contested and need to be confirmed for New Zealand conditions. As previously mentioned, New Zealand differs from North America or Europe in its soils; in the presence of symbiotic and pathogenic organisms; and in the distribution and intensity of water, temperature and sunlight. Therefore, if CCF with Douglas-fir is to be pursued as a goal in New Zealand, a necessary first step is to undertake some local research.

Ideally, large-scale trials would be established that include practical treatments that could serve as demonstration plots but which yield data that could easily be expanded to an operational scale. These would, however, require considerable resources and take several decades to complete. A more modest research programme could focus on addressing the following questions:

- What is the maximum sapwood basal area that can be achieved for different mixtures of ages, and how does this vary across the range of possible sites?
- What is the reduction in basal area and height growth of seedlings and saplings with different levels of overstorey?
- Is it true that Douglas-fir cannot grow vertically beneath its own canopy?
- What size canopy gaps in a mature stand will have unimpeded growth of seedlings in the centre of the clearings, and how does this decline with increasing proximity to the perimeter?
- At what overstorey levels does natural regeneration occur, and at what levels does it allow ongoing survival and recruitment into the canopy?
- Does the growth in planted trees differ from naturally regenerated seedlings, and can planted trees thrive where no natural regeneration occurs?
- How is the growth of an overstorey impeded by the presence of a younger age cohort, as opposed to the well-understood interaction with same-aged "followers"?
- How can the wood quality from a CCF forest be expected to differ from that of even-aged stands?
- What are the costs of a CCF harvest likely to be, using currently available New Zealand technology and operators?

Some of these questions can be answered by assessing behaviour in existing stands, without the necessity of a formal trial, but others will require controlled conditions and replicated plots.

CONCLUSIONS

The most practical, or perhaps the only practical, method of CCF with Douglas-fir in New Zealand might be to adjust traditional "clearfell, rotational" forestry by reducing coupe size to its lowest biological limits. This is probably about 0.25 ha, because coupes smaller than this would probably result in sapling morbidity, and possible suppression by weeds. Unless this simple two-stage structure can be shown to work, there is little hope for more complicated structures.

A simple CCF regime was modelled as follows: at each harvest, one half of the stand was felled and replanted. Harvest occurred when the oldest trees were 60, with half of the stand already 30 years old at that stage.

Because of data and model limitations, it is not possible to definitively quantify growth rates of Douglas-fir in New Zealand when grown under any sort of continuous cover. The attempt to do so in this report is based on several key assumptions derived from overseas literature, and there is a compelling need to collect data from New Zealand plots (if available) or to establish trials to test both modelling and operational feasibility.

Although there is a perception that CCF has aesthetic and recreational appeal, and perhaps some other environmental benefits, it is very difficult to appreciate any useful physical or financial purpose that would be obtained by imposing legislative approval to the type of regime modelled here, utilising Douglas-fir. It produces a lower rate of return, and yet – on a landscape scale – provides similar benefits in terms of atmospheric carbon mitigation.

REFERENCES

Bailey, J.D., 1996. Effect of stand density reductions on structural development in Western Oregon Douglas-fir forests – a reconstruction study. PhD dissertation. Oregon State University, Corvallis, OR.

Brandeis, T.J; Newton, M.; Cole, E.C., 2001. A comparison of overstory density measures for describing understory conifer growth. For.Ecol. Man. **152**: 149-157.

Buongiorno, J.; Kolbe, A.; Vasievich, M., 2000. Economic and ecological effects of diameter-limit and BDq management regimes: simulation results for northern hardwoods. Silva fennica **34**(3): 223-235.

Buongiorno, J., 2001. Quantifying the implications of transformation from even to uneven-aged forest stands. Forest Ecology and Management **151**: 121-132.

Carter, R.E., and Klinka, K.,1992.Variation in shade tolerance of Douglas fir, western hemlock, and western redcedar in coastal British Columbia. For. Ecol. Man. **55**: 87-105.

Churchill, D.J., 2005. Factors influencing understory vigor in multi-cohort prairie colonization stands at Fort Lewis, Washington. Masters thesis, University of Washington, Seattle.

Curtis, R.O., 1982. A simple index of stand density for Douglas-fir. Forest Science **28**(1): 92-94.

Curtis, R.O., 1998. “Selective cutting” in Douglas-fir – history revisited. (U.S.) Journal of Forestry **96** (7): 40-46.

Del Rio, E., and Berg, A., 1979. Specific leaf area of Douglas-fir reproduction as affected by light and needle age. For. Sci. **25**: 183-186.

Diesenhofer, F.U., 2000. Influence of light on the growth of advance regeneration in the understorey of Douglas-fir dominated forests in western Oregon. Masters thesis. Oregon State University, Corvallis.

Drever, C.R., 1999. Made in the shade: regenerating coastal Douglas-fir and western redcedar under partial cutting treatments. Research project submitted in partial fulfilment of the requirements for the degree of Master of Natural Resource Management in the School of Resource and Environmental Management, Simon Fraser University. Report No. 249.

Drever, C.R., and Lertzman, K.P., 2001. Light-growth responses of coastal Douglas-fir and western redcedar saplings under different regimes of soil moisture and nutrients. Can.J.For.Rese./Rev.Can.Rech.For **31**(12): 2124-2133.

Emmingham, W.H., and Waring, R.H.,1973. Conifer growth under different light environments in the Siskiyou mountains of southwestern Oregon. Northwest Sci. **47**: 88-99.
Emmingham, B., 1998. Uneven-aged management in the Pacific Northwest. (U.S.) Journal of Forestry **96** (7): 37-39. (U.K.) Forestry **75**(4): 433-436.

Emmingham, B., 2002. Status of uneven-aged management in the Pacific Northwest.

Franklin, J.F.; Spies, T.A.; Van Pelt, R.; Carey, A.B.; Thornburgh, D.A.; Berg, D.R.; Lindenmayer, D.B.; Harmon, M.E.; Keeton, W.S.; Shaw, D.C.; Bible, K.; Chen, J., 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest Ecology and Management **155**: 399-423.

Guldin, J.M., and Baker, J.B., 1998.Uneven-aged silviculture, Southern style. (U.S.) Journal of Forestry **96** (7): 22-26.

Kerr, G.; Mason, B.; Boswell, R.; Pommerening, A., 2002. Monitoring the transformation of even-aged stands to continuous cover management. (U.K.) Forestry Commission Information Note 45.

Ketchum, S.J., 1994. Douglas-fir, grand fir and plant community regeneration in three silvicultural systems in Western Oregon. Masters thesis. Oregon State University, Corvallis.

Knowles, R.L., 2003. Farm forestry for economic and environmental sustainability – a new decision support system for farm foresters. In Charlton J.F.L. (ed) Proceedings of a workshop organised by the New Zealand Grasslands Association (inc) and the New Zealand Farm Forestry Association (Inc) held at the Palmerston North Convention Centre, 17th October 2003. Grassland Research and Practice Series No 10, 2003 pp 85-90.

Knowles, R L, and Hansen, L W., 2004. Profitability of converting pastoral farmland to production forestry in the Taupo basin. Primary Industry Management, **7**(2): 25-28, June 2004.

Knowles, R.L., 2005. Development of a productivity index for Douglas-fir. Douglas-fir research cooperative, unpublished report no. 44. February 2005.

Liang, J.; Buongiorno, J.; Monserud, R.A., 2005. Growth and yield of all-aged Douglas-fir – western hemlock forest stands: a matrix model with stand diversity effects. Can.J.For.Res. **35**: 2638-2381.

Long J.N., 1985. A practical approach to density management. Forestry Chronicle **61**: 23-27.

Long, J.N., 1998. Multiaged systems in the Central and Southern Rockies. (U.S.) Journal of Forestry **96**(7): 34-36.

Mailly, D., and Kimmins, K.P., 1997. Growth of *Pseudotsuga menziesii* and *Tsuga heterophylla* along a light gradient: resource allocation and morphological acclimation. Canadian Journal of Botany **75**: 1424-1435.

Malcolm, D.C.; Mason, W.L.; Clarke, G.C., 2001. The transformation of conifer forests in Britain – regeneration, gap size and silvicultural systems. Forest Ecology and Management **151**(1-3): 7-23.

Mason, B.; Kerr, G.; Simpson, J., 1999. What is continuous cover forestry? Forestry Commission Information Note, October 1999.

Mason, B.; Kerr, G.; Pommerening, A.; Edwards, C.; Hale, S.; Ireland, D.: Moore, R., 2004. Continuous cover forestry in British conifer forests. Forest Research annual report and accounts 2003-2004.

Miller, M. and B. Emmingham 2001. Can selection thinning convert even-age Douglas-fir stands to uneven-aged structures? Western J. of Applied Forestry **16**: 35-43.

O'Hara, K.L., 1996. Dynamics and stocking-level relationships of multi-aged ponderosa pine stands. Forest Science 42, monograph 33.

O'Hara, K.L., 1998a. Silviculture for structural diversity: a new look at multiaged systems. (U.S.) Journal of Forestry **96**(7): 4-10.

O'Hara, K.L., 1998b. Leaf area allocation – how does it work? (U.S.) Journal of Forestry **96**(7): 11.

O'Hara, K.L., and Valappil, N.I., 1995. Age class division of growing space to regulate stocking in uneven aged stands. In O'Hara, K.L. (editor) Uneven-aged management: opportunities, constraints and methodologies. Montana Forest and Conservation Experiment Station Publication no 56.

O'Hara, K.L., 2002. The historical development of uneven-aged silviculture in North America. (U.K.) Forestry **75**(4): 339-346.

Platt, I., 2002. Sustainable forest management in the State of Baden-Württemberg Federal Republic of Germany. Report to the Winston Churchill Memorial Trust.

Pommerening, A., and Murphy, S.T., 2004. A review of the history, definitions and methods of continuous cover forestry with special attention to afforestation and restocking. (U.K.) Forestry **77**(1): 27-44.

Schütz, J-P., 2002. Uneven-aged silviculture: tradition and practices. (U.K.) Forestry **75**(4): 327-337.

Seidel, K.W., 1983. Regeneration in mixed conifer and Douglas-fir shelterwood cuttings in the Cascades Range of Washington. USDA Forest Service, Research Paper PNW-RP-314.

Tesch, S.D., and Korpela, E.J., 1993. Douglas-fir and white fir advance regeneration for renewal of mixed-conifer forests. Can. J. For. Res. **23**: 1427-1437.

Wampler, M., 1993. Growth of Douglas-fir under partial overstorey retention. Masters thesis, University of Washington, Seattle.

Williams, H.; Messier, C. and D.Kneeshaw, 1999. Effects of light availability and sapling size on the growth and crown morphology of understory Douglas-fir and lodgepole pine. Can. J. For. Res. **29**: 222-231.

Wilson, E.G., 1979. Thinning as an orderly discipline: a graphic spacing schedule for red pine. J.For. **77**: 483-486.

Woodall, C.W.; Perry, C.H.; Miles, P.D., 2006. The relative density of forests in the United States. Forest Ecol. and Man. **226**: 368-372.

York, R.A.; Battles, J.J.; Heald, R.C., 2002. Edge effects in mixed conifer group selection openings: tree height response to resource gradients. Abstract 27 in 2001 Blodgett Forest Research Symposium. University of California, Center for Forestry.

York, R.A.; Heald, R.C; Battles, J.J.; York, J.D., 2004. Group selection management in conifer forests: relationships between opening size and tree growth. Can.J.For. Res. **34**: 630-641.