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Transforming and managing stands under continuous cover forestry

Silvicultural guidance

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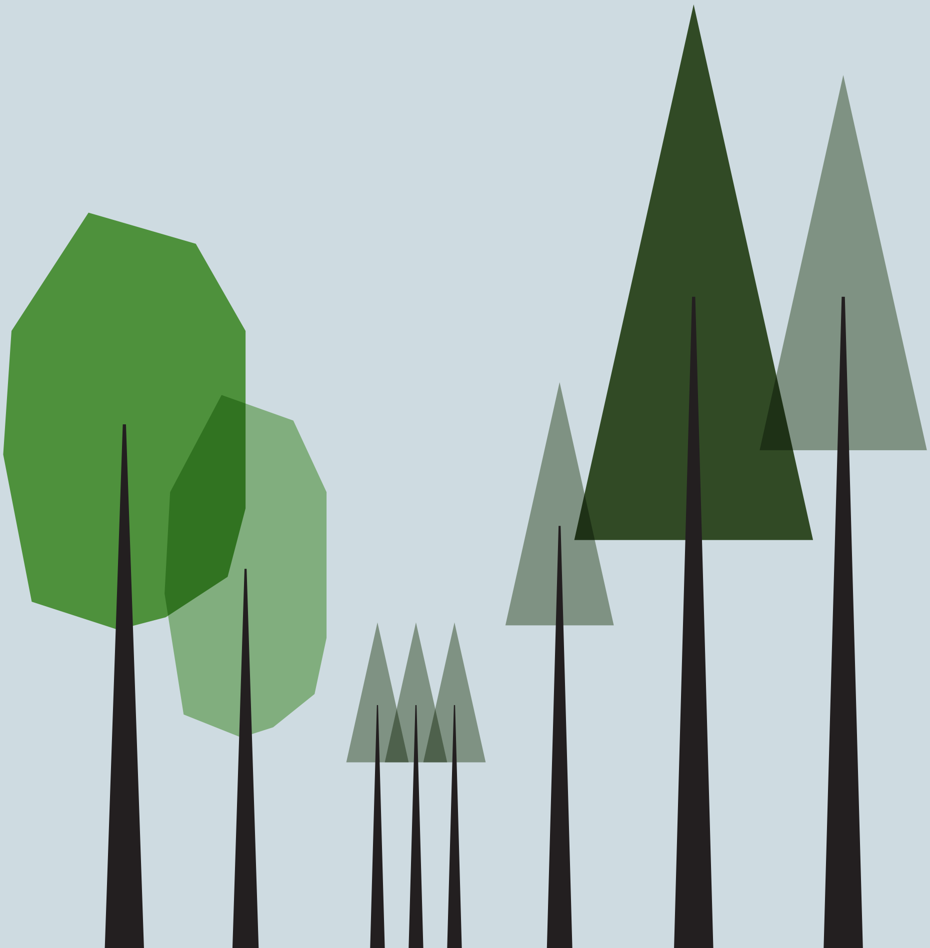


1 Introduction

1.1 Scope of this guidance

The aim of this guide is to provide information to forest managers on both transforming stands to continuous cover forestry (CCF) and on managing stands using CCF approaches. The guide provides you the information to be able to:

- define CCF and decide when it is an appropriate approach to managing a stand
- understand the link between forest stand dynamics and choice of CCF approach deployed
- evaluate the suitability of a stand for transformation to CCF
- plan thinning operations to initiate and maintain stand stability
- create the stand conditions for successful natural regeneration or underplanting
- manage growing stock according to a desired stand structure.

1.2 Background, benefits, and drawbacks of CCF

CCF is an approach to forest management in which a significant proportion of the forest canopy is maintained at one or more levels without clearfelling. Where gaps are created in the canopy, they are less than 0.25 ha so as to maintain a forest microclimate. In most circumstances, CCF has a higher reliance on natural processes, such as natural regeneration, necessitating a deeper understanding of the environmental requirements of the trees and of forest stand dynamics than in clearfell systems. There are many collective names for CCF or allied practices, such as Lower Intensity Management Approaches (LIMA), Low Impact Silvicultural Systems (LISS), and Close or Closer to Nature (C2N) forestry, while CCF is also an element of regenerative forestry (for an explanation of nomenclature, see Additional resources: 1). This handbook takes a broad interpretation of the term 'CCF' since there are a number of methods to achieve it but, compared to clearfell systems, CCF approaches tend to allow a higher degree of management flexibility. Furthermore, the negative impacts of climate change and of exotic pests and diseases may be mitigated by the adoption of stands that: contain a range of species, are structurally complex, comprise a range of age classes, and maintain a forest microclimate. Uncertainties relating to how CCF will be applied and to the ongoing impacts of pests and disease and climate change make a comparison of stand resilience under CCF and clearfell complicated, but Stokes and Kerr (2009) characterise the use of CCF as largely positively impacting many of the important risks facing our forests, including effects from heavy winter rainfall, frosts, and pests and diseases.

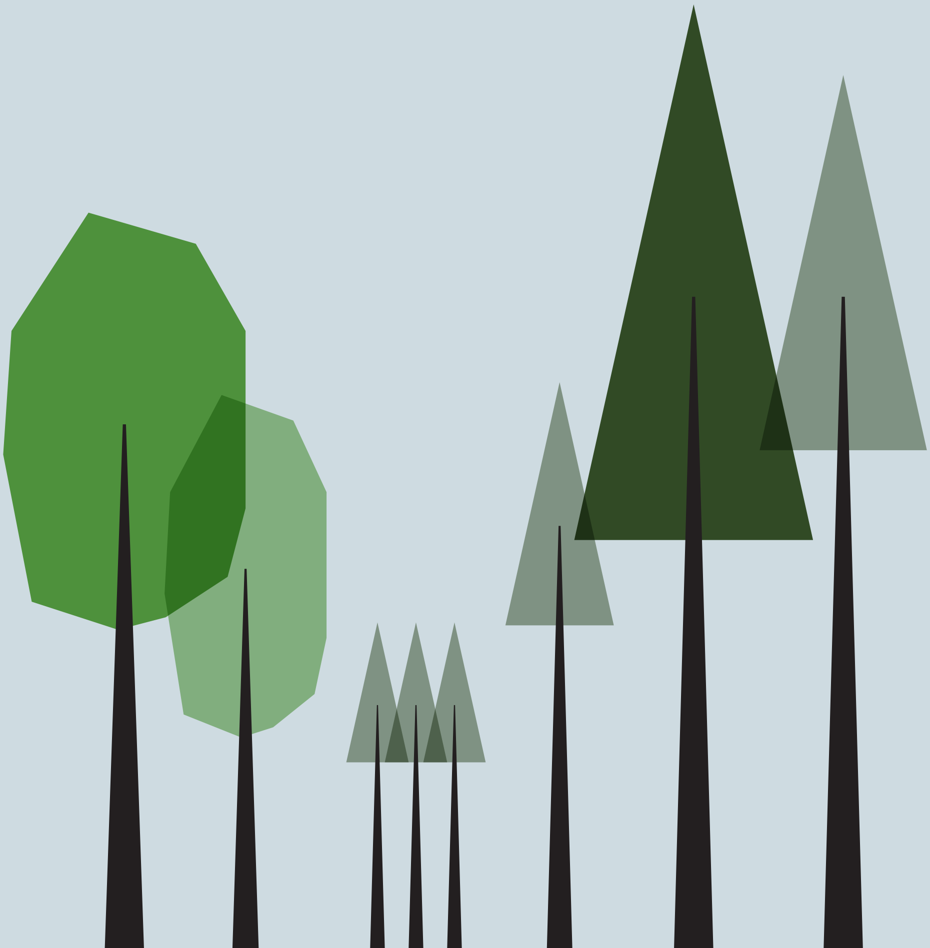
There has been increasing interest in the use of CCF to manage forest stands in continental Europe and the UK, driven by the environmental, economic, and social benefits that can be achieved. Table 1.1 describes how the important stand-related elements of CCF may be beneficial for these types of objectives. However, there are also a number of management challenges that may prevent wider adoption of CCF, reviewed by Mason *et al*. (2022). The review identified several knowledge gaps, including: uncertainty about the resilience of species and complex stand structures to damaging abiotic and biotic agents; how best to incorporate mechanised harvesting methods; a lack of knowledge and training in professional foresters; and uncertainty about yields and the financial returns from CCF. Obstacles to adoption of CCF were also highlighted, which included: limited awareness and experience of CCF stand management and transformation; the impact of high deer numbers on natural regeneration; and grants and markets that favour clearfelling practices. Table 1.1 describes some of these limitations in more detail.

Table 1.1 Elements of CCF and their environmental, economic, and social benefits and limitations

Element of CCF	Forest value	Benefits	Limitations
Increased use of natural regeneration	Environmental	• Trees are often better adapted to their location • Greater horizontal and vertical structural diversity than traditional planting • Natural regeneration is less favoured by browsing deer than planted material	• High deer populations in much of the UK limits application • 'Invasive', unwanted species can predominate • There can be insufficient or excessive regeneration
	Economic	• Can avoid nursery, transport, and planting costs • If densities are high, there may be timber quality benefits • Often more drought resilient than planting stock • Undisturbed rooting and reduced root deformation leads to better establishment and tree stability	• May need to be supplemented by planting, or respaced if dense • Regeneration may not be desirable species or provenances • Use of improved genetic stock is precluded
Continuous canopy	Environmental	• Stable forest conditions can be important for woodland specialists • Less exposure of the soil when harvesting can reduce erosion and carbon loss • Higher interception of rainfall can reduce streamflow and flooding • Stable forest microclimate can mitigate the extremes of climate change	• Can favour shade-bearing and intermediate species of trees • Lack of large, open spaces will be to the detriment of some forest flora and fauna (e.g. nightjars) • Selective harvesting of trees means that a lack of brash can lead to soil damage and rutting
	Economic	• At stand level there can be a continuous supply of forest products	• In clearfell stands, thinnings can also provide intermediate returns
	Social	• Can provide an attractive backdrop and forest environment to areas frequented by the public	• Views may be permanently obscured, but this can be mitigated by careful forest planning
More complex forest structure and composition	Environmental	• The presence of canopy layers provides a wider range of niches, which is important for some taxa (e.g. birds) • Wider range of habitats with shadier and more open areas • Structural complexity through different ages and species of trees may reduce the likelihood of catastrophic damage through wind, fire, and pests and diseases	N/A
	Economic	• Varied canopy layers and complementary species can result in higher biological productivity • Wider range of tree sizes, ages, and species is likely to reduce the risk of catastrophic damage from climate change and pests and diseases	• Forest management tools (e.g. inventory, yield prediction) are focused on stands that are even-aged monocultures • Operations like harvesting are likely to be more complex and may lack economies of scale
	Social	• Can be visually attractive	• Open stands without an understorey increase visibility through the stand
Large trees	Environmental	• Older trees have higher biodiversity value	N/A
	Economic	• Large trees are a bonus if they are of a species that sell at a premium	• Harvesting of large trees may need motor-manual methods • Marketing large trees can currently be a problem if they are oversize for sawmills
	Social	• People find the presence of large trees in a stand attractive	• Older trees can increase health and safety risks to the public

Chapter 2

Basic concepts underpinning CCF



2 Basic concepts underpinning CCF

2.1 Conditions suitable for application of CCF

CCF should only be used in situations where it will be successful and deliver the management objectives. A major consideration in deciding whether to use CCF is windthrow because, as the risk of wind damage increases, the options for using stand management approaches other than clearfelling are reduced.

In general, sheltered sites with good soil drainage and deep soils are likely to be suited to CCF. This is because the ability to thin a stand is a prerequisite for CCF and, in windy sites with shallow or waterlogged soils, the likelihood of windthrow when thinning is increased. The attributes of a stand and its stage of development will also affect the risk of windthrow; for example, species, age of stand, history of thinning, evenness of crown height, and stand stocking density. Another factor to take into account is stand structure. Exposed 'brown' edges (where the edges are recently exposed), small gaps within the canopy, and rough canopies (with trees of varying heights) are particularly vulnerable to windthrow and may make a site less suitable for CCF.

The site and stand appraisal described in this guide focuses on assessing a site and stand in terms of wind-firmness, the potential for natural regeneration, and the suitability of the tree species currently on the site. The site and stand appraisal is divided into two stages: a preliminary stage to sift out clearly unsuitable stands, and a more detailed field-based stage to make the final decision. In general, sheltered sites with soils allowing deep rooting give the most options for stand management, but other factors, such as ease of access and the resilience of soils to frequent machinery movement, should be considered. Further details on stand assessment can be found in Section 5.1.

2.2 Forest stand dynamics

Silviculture applies forest ecology and an understanding of forest dynamics to meet management objectives. Forest dynamics are driven by disturbance and competition. For some forests, these disturbances are small, frequent, and continuous, such as through the toppling of single trees, creating a fine mosaic of gaps in the canopy. These small gaps will favour regeneration of shade-bearing tree species and the creation of irregular stands. In contrast, the disturbances in other forests are less frequent but at a larger scale (e.g. catastrophic windthrow or large forest fires), which creates a coarse mosaic of gaps in the canopy. These large gaps (>0.25 ha) will favour the regeneration of light-demanding tree species and the creation of even-aged stands (Figure 2.1).

However, in many forests, larger and smaller gaps can occur in the same stand. In silviculture, we can adjust thinning interventions based on this knowledge of stand dynamics. For a simple stand structure comprising light-demanding tree species, we can create a large gap infrequently in a stand. If an irregular stand with a complex stand structure is desired, we can create small gaps on a frequent basis within the canopy of the stand.

2.3 Even-aged and irregular approaches to stand management

Nyland (2002) describes three elements to any silvicultural system: regeneration, tending, and harvesting. Examples of these are described in Table 2.1. This guide focuses on high forest and so excludes coppice systems, which can also be managed to provide a continuous canopy.

To a degree, silvicultural systems mimic natural forest dynamics. In systems like the clearfell system, the entire canopy of a stand is removed in one operation, similar to a stand-replacement disturbance such as serious windthrow. In contrast, a single-tree selection system regularly removes individual trees from the stand, mimicking single tree-fall gaps (Figure 2.1). Systems such as these can be divided into two broad categories:

1. Even-aged (or 'simple')
2. Irregular (multi-aged or 'complex').

This division strongly influences the approaches taken when managing a stand. A summary of traditional silvicultural systems and the relationships between them can be found in Table 2.2 and Figure 2.2 respectively or, for more detailed descriptions, Troup (1928) and Matthews (1991).

Table 2.1 Examples of options for regenerating, tending, and harvesting for stand management

Regeneration	Tending/harvesting
• Natural regeneration (seed and suckers) • Direct seeding • Planting (including underplanting) • Coppicing and pollarding	• Whole area harvested at one time • Uniform thinning across the stand • Trees removed in lines, strips, or chevrons • Trees removed in groups • Halo or crown thinning to release specific trees from competition

Figure 2.1 Relationship between type, frequency, and size of natural disturbance events and the forest type and shade tolerance level promoted by them

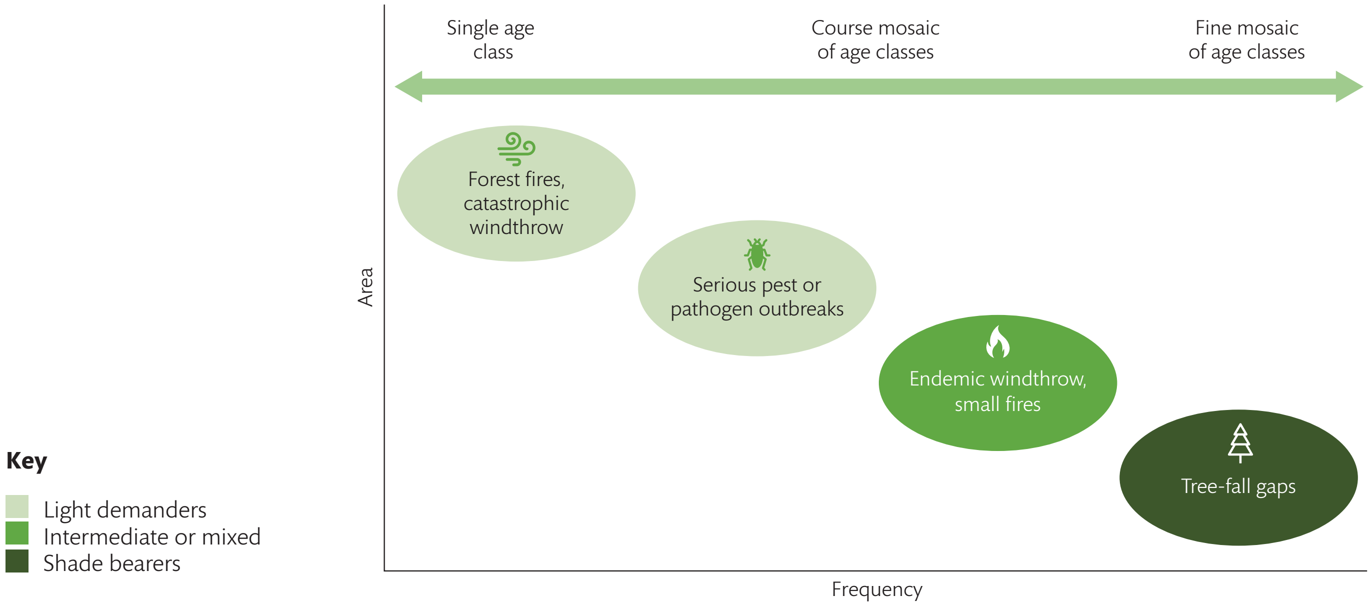


Table 2.2 Summary of traditional silvicultural systems and the thinning and harvesting methods applied to each

Age structure	System	Thinning and harvesting methods
Even-aged	Clearfell	The entire original canopy is removed and the new cohort established, normally by planting.
	Seed tree	A sparse cover of scattered trees is left from the original canopy to provide seed, but not shelter, for natural regeneration. These are removed once successful regeneration is achieved.
	Uniform shelterwood	The original canopy is removed gradually so as to maintain a forest microclimate for the new cohort of trees (naturally regenerated or planted) through a series of uniform thinnings across the stand.
	Group shelterwood	Small groups of trees, not necessarily of the same area, are felled to encourage regeneration in the gaps. Thinning is then undertaken to extend these groups outwards until they meet and the entire original canopy has been removed.
	Strip shelterwood	The original canopy is removed through a series of progressive thinnings confined to strips across the stand. These advance in an opposite direction to the prevailing wind direction. The remaining canopy provides shelter for the developing regeneration in each cut strip.
Irregular	Irregular shelterwood	Patches of advance regeneration are expanded outward, through a series of concentric thinnings, until they meet and the whole canopy has been removed. The stands are more irregular than other shelterwoods.
	Group selection	Groups of trees are felled periodically across size classes to create a coarse mixed-age mosaic.
	Single-tree selection	Single trees are felled periodically across size classes to create a fine mixed-age mosaic.

In even-aged systems, the existing canopy of the entire stand is removed relatively rapidly to encourage the regeneration of an even-aged (trees of the same or very similar age) stand with a single canopy layer. For example, in clearfelling the entire canopy is removed in one operation, which is followed by regeneration (normally through planting). In contrast, irregular systems see continuous regeneration over a longer period, resulting in a stand containing trees of many ages and sizes in multiple canopy layers. In general, irregular stands are considered to be those with three or more distinct cohorts. In many examples of CCF, harvesting, thinning, and regeneration are linked in time and space, which creates opportunities as well as constraints. For example, access within the stand must be planned to allow harvesting of large trees while minimising damage to smaller trees. While even-aged stands are managed on a rotation basis (where there is a defined period between establishment and harvesting), irregular stands are based on tree size and target dimensions.

In general, even-aged stands are more predictable, easier to manage, and supported by straightforward estimation methods for volume, yield, and cost and income. Where wider environmental or social objectives are important, such as habitat and stand structural diversity and prioritising natural processes, irregular stand structures may be better suited. Most applications of CCF in Europe adopt even-aged systems such as the uniform and strip shelterwood methods, with irregular systems being less prevalent.

A comparison of a group shelterwood (simple stand structure) and a group selection system (complex stand structure) is shown in Figure 2.3. The original canopy in the group shelterwood system is removed relatively rapidly to expand groups of natural regeneration. This rapid removal at rotation age results in an even-aged stand. In contrast, the group selection system removes trees from the original canopy more gradually, with the best trees retained until they reach a target diameter (based on the requirements of timber markets). This extended period of removal of the original cohort of trees results in an uneven-aged stand.

Figure 2.2 Classification of high forest continuous cover systems (Pommerening, 2023)

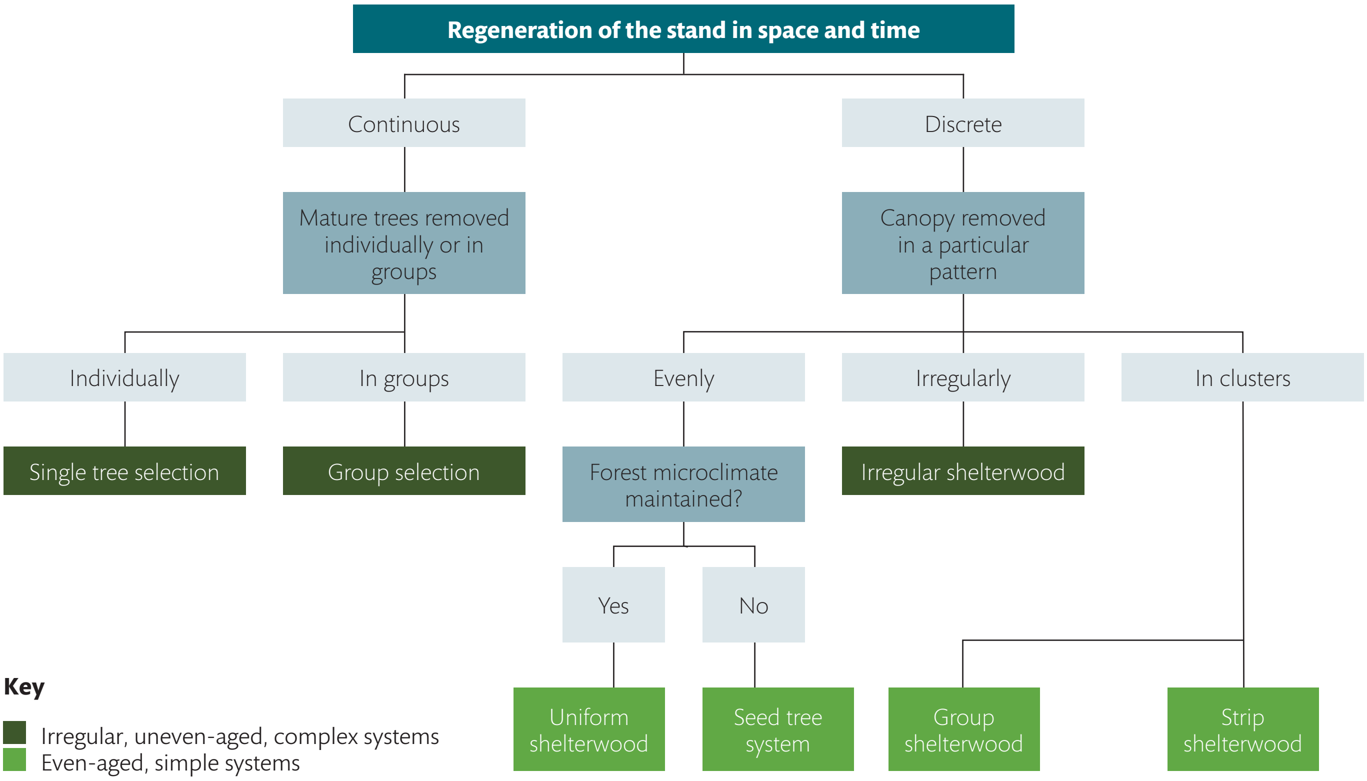
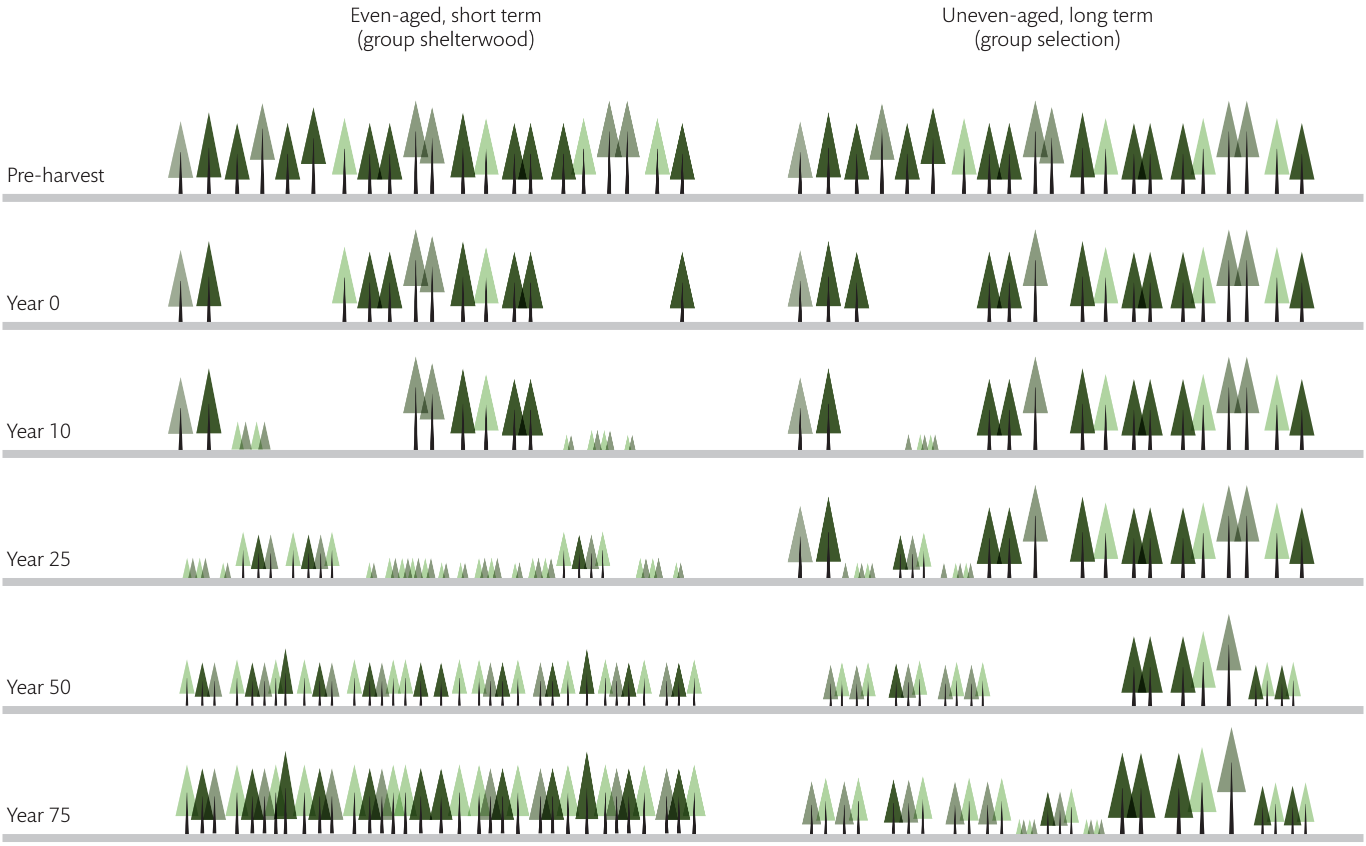


Figure 2.3 Comparison of stands arising from a group shelterwood (even-aged stand) and a group selection system (irregular stand) (based on Government of British Columbia, 2003)



In practice, a stand can have attributes of several systems. For example, there may be uniform thinning applied across the stand in conjunction with releasing pockets of advance regeneration initiated by windthrow. The approach you adopt, whether simple or complex, can have important ecological consequences, as described in Table 2.3.

Table 2.3 Ecological differences between even-aged systems and irregular systems (adapted from Powell, 2018)

Attribute	Even-aged clearfell stand	Even-aged CCF stand	Irregular CCF stand
Canopy	Level, shallow canopy supported by slender stems	Level, shallow canopy supported by slender stems	Deep, irregular canopy supported by sturdy stems
Patchiness	Even light and canopy conditions across the stand	Even light and canopy conditions across the stand (for most of rotation)	Varied light and canopy conditions across the stand, with gaps and dense areas of trees
Stability	Driven by the integrity of the canopy and the mutual support between trees, and is a stand, rather than individual tree, attribute		Depends more on individual tree stability, driven by deep crowns and good rooting which makes each individual tree more stable
Small trees	Small trees supressed and release unlikely to have a positive effect		Small trees released regularly
Species composition	Shade-tolerant and light-demanding species can be successfully established		Generally focused on shade-tolerant, later successional species and intermediate species
Regeneration	Occurs infrequently and over a short period of time		Continuous over time
Site capture	Site can be lost to colonisation by competing vegetation, but control of weeds is easier	Competing vegetation can be controlled by carefully regulating the light under the canopy	Canopy can be manipulated to regulate competing vegetation, but any weed competition can be more difficult to control if it becomes established
Site	Site exposed, without a canopy. Can lead to soil erosion and on wet sites a rise in the water table	Site sheltered by an overhead or adjacent canopy	
Brash	A heavy accumulation at harvesting which increases fire and insect hazard	A continuous, light amount of brash, which reduces fire and insect hazard but can increase risk of compaction during harvesting	

2.4 Stages of stand development

Oliver and Larson (1996) developed a useful four-stage model (Figure 2.4) for even-aged stand development following a major disturbance. You can use these stages as a structure to select approaches to manage stands under CCF (Table 2.4). In conventional clearfelling systems, the trees are normally harvested at the end of the rotation in the late stem exclusion stage, at the age of the financial rotation, or when they are at an optimum size for processing at mills. In CCF systems, some trees are retained for a longer period, with one reason being that they produce copious seeds to enable natural regeneration. Early stand transformation to CCF is practised in the stem exclusion stage (Figure 2.4) and stability is ensured through regular thinning, enabling individual trees to be wind-firm. Late stand transformation is more risky as the trees have already become used to mutual support from others in their cohort and so can only be achieved on certain sites, with certain tree species, and with careful thinning.

When an even-aged stand reaches the stem exclusion stage, competition between the individual trees means that trees occupy different levels in the canopy depending on their rate of growth. These are known as ‘crown classes’, and are important when planning thinning. Table 2.5 describes the four main crown classes: dominant, co-dominant, sub-dominant, and supressed.

Figure 2.4 The four stages of even-aged stand development and the period of early and late stand transformation (adapted from Wilson, 2024)

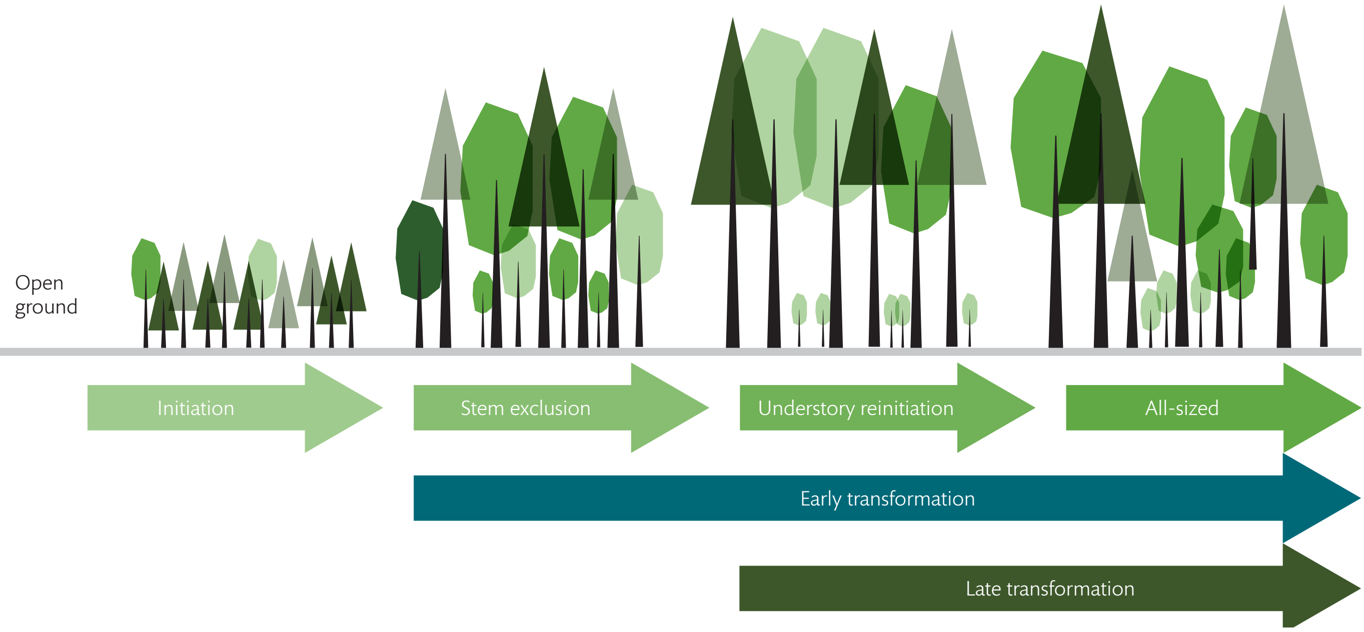


Table 2.4 The four stages of even-aged stand development and their management focuses during transformation to CCF

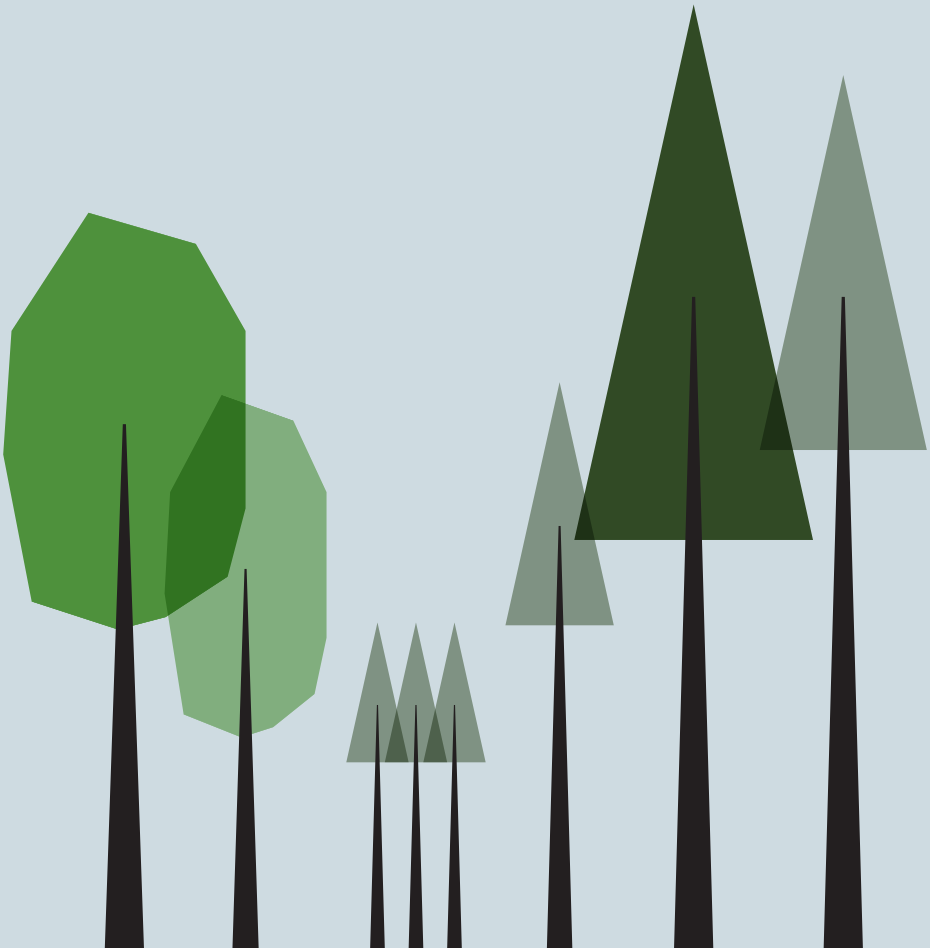
Stage in stand development	**Attribute**	**Management focus for CCF**
Initiation	Trees are growing rapidly, closing canopy and capturing the site to supress competing vegetation. Intense competition between trees has not yet started.	Promote successful natural or artificial regeneration across the stand to establish sufficient seedlings of desirable species.
Stem exclusion	Trees are competing for resources and crown classes have developed.	Thin, often through crown thinning, to maintain individual tree stability but also (if aiming for an irregular structure) to break up the regular spatial distribution of trees in the stand and introduce gaps and groups.
Understorey reinitiation	There is more light in the stand as the canopies are at a greater height and movement in the wind creates gaps between the crowns of neighbouring trees. The trees are also at an age when they produce useful quantities of seed. This increased light and seed supply encourages the development of an understorey through natural regeneration.	As seed is being produced, reduce the canopy and basal area to a level that will encourage germination and growth of natural regeneration (or underplanted seedlings). If a structure with all sizes of trees is required, selectively thin to release trees that are to be retained long-term (frame trees). Remove trees of poor quality.
All-sized	Periodic mortality of large trees has created opportunities for the development of several cohorts of trees, resulting in a multi-canopy forest.	Maintain a structure with all sizes of trees by thinning trees to release those competing with frame trees, and also to ensure the stand conforms to a balanced diameter class distribution. Continue to focus on improving the quality of the stand by selectively harvesting poorer quality stems.

Table 2.5 Crown classes (based on Kerr and Haufe, 2011)

Crown Class	Description
Dominant	The crown extends above the general layer for the stand and intercepts direct sunlight across the top and upper branches. Trees have well-developed and large crowns, which can be crowded along the lower branches. Tree diameter is usually among the largest in the stand.
Co-dominant	The crown is within and helping to form the main canopy for the stand and intercepts direct sunlight mainly across the top and upper side branches. Trees have well-developed crowns but only of medium size that are crowded at the sides. Tree diameter is among the upper range of those present.
Sub-dominant	The crown extends into the lower part of the main canopy and only intercepts direct sunlight to a limited area at the top. The crown is narrow and short. Tree diameter is in the lower range of those present but not necessarily the smallest.
Supressed	The crown is entirely below the main canopy and covered by branches of taller trees with little, if any, direct sunlight reaching it. The crown is small, often lopsided, flat-topped, and sparse. Tree diameter is among the smallest in the stand.

Chapter 3

Operations supporting CCF



3 Operations supporting CCF

The operations used to transform a stand to, or manage a stand under, CCF depend on whether management objectives are best met by an even-aged or irregular stand structure. Another factor that can influence this is the experience and focus of the forest manager; there are many examples of successful management using basic forward planning and limited information on stand structure and composition, many of which are supported by experienced forest managers. There are also successful examples of CCF stand management where a structured, methodical approach based on detailed stand information has been used. Whichever approach is taken, there are four general considerations that should be taken into account in CCF:

- Thin regularly, and start early.
- Keep deer and other damaging mammal numbers low to protect regeneration.
- Focus most attention on releasing and tending quality stems.
- Remember that a level of unforeseen stand disturbance is inevitable.

Additionally, many CCF stands are managed with the aim of diversifying species and thereby broadening future options. For irregular stand structures, there must be a long-term vision for the stand and at least a prescription for the next intervention, although a more extended plan can be useful where continuity of management is likely (for guidance on stand prescriptions, see Additional resources: 1). There are also benefits to managing larger, rather than smaller, blocks of forests under CCF as economies of scale can be realised (see Additional resources: 2).

3.1 Thinning

Thinning is one of the most important forestry management practices: after stand establishment and competition between trees has begun, it is the main intervention that influences tree growth and development. Thinning also has economic benefits, providing regular returns and increasing tree volume and quality from the stand. The approach applied to this productive basis of thinning in clearfell stands is well established (see Additional resources: 3 for guidance). There are, however, many other benefits from thinning, such as maintaining tree vitality and creating conditions suitable for regeneration. While thinning initially increases the likelihood of wind damage, early thinning will develop long-term stability in the remaining trees.

In CCF, thinning is essential as it:

- develops long-term stability in the stand by improving individual tree stability through increasing stem taper and encouraging more extensive rooting
- creates light and other conditions that are conducive to the survival and growth of regeneration
- creates soil disturbance (through harvesting activity), which can encourage natural regeneration
- provides a source of income
- can be used to concentrate increment on the best quality stems.

When thinning, it is important to consider the thinning cycle (the time between thinning operations). This will be influenced by: the site productivity (more productive means a faster recovery to the stand and a shorter cycle); the level of harvest that is profitable; and other resource limitations such as availability of machinery and expert labour. If thinning (particularly early thinning) is delayed, it can be very difficult to attain the desired level of growing stock, since removing high volumes can lead to stand instability and windthrow. Another important factor is wind, with more frequent but lighter thinnings being less likely to result in damage to forest stands in high risk areas than infrequent, heavy thinnings. There are differences in wind resistance between tree species, with broadleaves generally being more wind-firm than conifers, and pines more wind resistant than most spruces and larches (Table 3.1).

Table 3.1 Wind resistance of tree species in Great Britain (Davies, Haufe, and Pommerening, 2008, based on Hart, 1991)

Wind-firm	Moderately wind-firm	Wind susceptible
Alder *(Alnus glutinosa)*	Western red cedar *(Thuja plicata)*	Lawson cypress *(Chamaecyparis lawsoniana)*
Ash *(Fraxinus excelsior)*	Grand fir *(Abies grandis)*	Douglas fir *(Pseudotsuga menziesii)*
Beech *(Fagus sylvatica)*	Western hemlock *(Tsuga heterophylla)*	Norway spruce *(Picea abies)*
Oak *(Quercus robur)*	European larch *(Larix decidua)*	
Sweet chestnut *(Castanea sativa)*	Japanese larch *(Larix kaempferi)*	
Sycamore *(Acer pseudoplatanus)*	Coast redwood *(Sequoia sempervirens)*	
Noble fir *(Abies procera)*	Sitka spruce *(Picea sitchensis)*	
Austrian pine *(Pinus nigra)*		
Corsican pine *(Pinus nigra* ssp. *laricio)*		
Lodgepole pine *(Pinus contorta)*		
Scots pine *(Pinus sylvestris)*		
Omorika spruce *(Picea omorika)*		

3.1.1 Early thinning

Early thinning of stands creates options for the future ways in which they are managed through developing stability in individual trees. Different sites, planting densities, and tree species require their first thinning at different ages, but normally first thinning occurs when the stand reaches a top height of 10–12 m. First thinning of stands is usually systematic (a straightforward, cost-effective way of thinning a low-value crop). For later interventions, crown thinning is the most appropriate way to increase stability while breaking up the uniform canopy. Crown thinning involves felling dominant trees (those that are larger than average) and the gaps created increase the light and warmth reaching the forest floor. Low or intermediate thinnings do not appreciably open up the canopy, while harvesting larger, more valuable trees also provides higher income early in the process of transformation.

3.1.2 Later thinning

Later thinning takes place in the understorey reinitiation stage (Figure 2.4) of stand development. The approaches differ depending on desired stand structure. In a stand destined for an even-aged structure, the overstorey is removed more rapidly and the focus is retaining good quality trees as a source of seed. For an irregular structure, thinning is focused on the longer-term, releasing superior trees from competition while limiting branch formation, maintaining a desired diameter class distribution, and promoting natural regeneration. For both stand structures, felling must be carefully organised in CCF stands to minimise damage to regeneration. Furthermore, thinning also aims to reduce the canopy cover to a level that encourages natural regeneration of desirable species. This is described in more detail in Section 3.2.

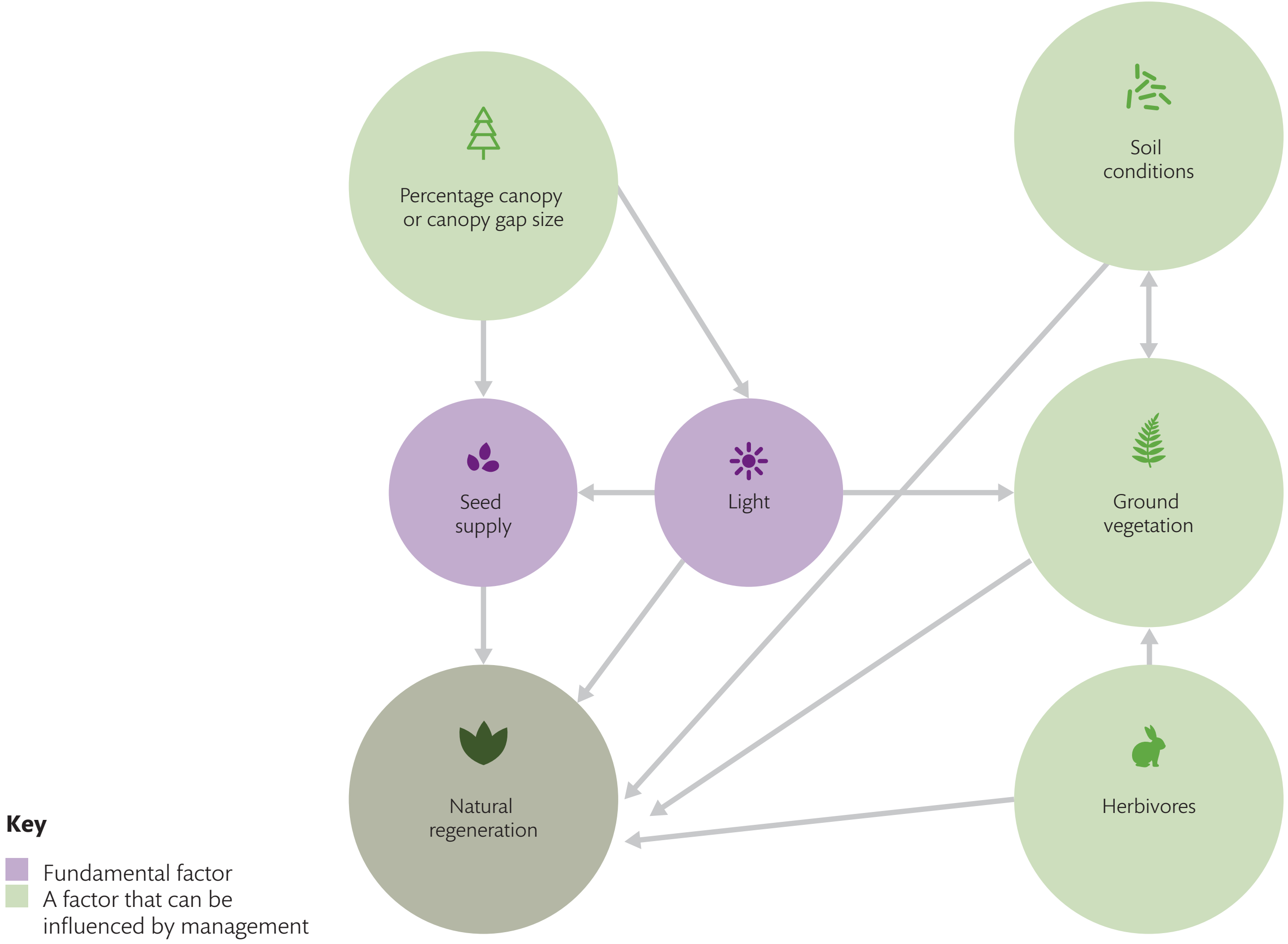
Additionally, if relatively small volumes of dispersed, large trees are being removed, then some planning must be made to reduce compaction, particularly on heavy soils due to the lack of brash to provide a protective layer. Some soil disturbance, however, is beneficial as it scarifies the forest floor, providing a bare seedbed.

3.2 Regeneration

3.2.1 Natural regeneration

Natural regeneration is widely used in CCF, although planting is a more common way of regenerating forests in Great Britain. The main factors influencing the success of natural regeneration are described in Figure 3.1, with poor seed supply and damage by browsing animals particularly common problems.

Figure 3.1 Factors influencing success of natural regeneration (adapted from Helliwell, 1999)



As natural regeneration relies more on natural processes, it is less reliable in stocking a woodland, both in quantity and timescale, than planting. If there is advance regeneration of the desired species already in or on the periphery of the stand or in disturbed areas, then it is likely that natural regeneration will be successful. There are advantages and disadvantages to using natural regeneration to stock a stand, as described in Table 3.2. There are, however, management interventions that can be used to address some of the constraints (summarised in Table 3.3).

Table 3.2 Advantages and disadvantages of using natural regeneration (adapted from Nixon and Worrell, 1999)

Advantages	Disadvantages
Results in a pattern of establishment similar to nature with greater structural and species diversity	Patchy distribution of regeneration over the stand (may need additional planting if too sparse or respacing if too dense)
Potentially less costly than planting	Timing of establishment is less predictable
Conserves important local tree genotypes and parent trees, and resulting progeny are well adapted to the site	Limited scope for change of species or genetic improvement
Less palatable to herbivores than planting stock	
Undisturbed root development in seedlings compared with planted stock	

Table 3.3 Constraints and solutions to obtaining natural regeneration

Constraint	Solution
Most seed is consumed before it germinates.	Ensure there is a good supply of seed by timing opening of the canopy when the trees are old enough to be producing lots of seed and, if possible, when there is a mast year.
Young seedlings are vulnerable to desiccation if their roots do not reach mineral soil.	Consider mechanical or other means of scarification to provide a suitable seedbed with exposed mineral soil.
Seedlings may suffer from competition with weeds.	Create light conditions that favour the seedlings but inhibit weed growth. Focus on sites with nutrient-poor soils where weed growth is less vigorous.
Seedlings may be browsed.	Protect the seedlings and/or reduce populations of browsing mammals.

The closer-to-nature approach of CCF makes using natural regeneration a desirable approach and, in general, this should be the first option. Using natural regeneration does not preclude planting though, which can be used to increase stocking density and diversify the range of species. If using natural regeneration, you will need to accept that it can be a slow process of up to several decades, and the likelihood of success is dependent on managing the combination of factors described in Figure 3.1.

3.2.1.1 Seed supply

A good supply of seed is crucial to successful natural regeneration. Seed production by trees is highly variable from year to year and is affected by the age of trees, the species, the action of seed predators, weather conditions, and the site. Years where there is a high level of seed production by a tree species are known as ‘mast years’: this is a strategy used by the tree both to overcome seed predators and also because seed production is a significant investment of resources, which are then unavailable to the tree for maintenance and growth.

Detailed advice on natural regeneration of conifers can be found in Nixon and Worrell (1999) and of broadleaves in Evans (1988). In general:

- Most forest trees do not start producing large quantities of seed until they are 30–40 years old and the older the tree becomes, the more seed it produces.
- For most British trees, seed dispersal begins during the autumn and extends through to the spring. The exceptions are European larch and pines, which release seed in spring and summer, and cherry which releases seed in summer (Table 3.4).

For conifers, the level of coning can be a good predictor of seed supply: between 50 and 100 cones visible on 25–50% of trees in the stand, not just edge trees, indicates good potential for natural regeneration. The number of cones is best assessed using binoculars at the times shown for coning in Table 3.4. Broadleaves follow a similar pattern to conifers in relation to age and timing of seed production (Table 3.4). The level of seed production for a year can also be assessed through observation using binoculars.

Table 3.4 Age of seed production, intervals between good seed years of conifers and broadleaves, and recommended times to assess flowering, coning, and seed dispersal of conifers

Species	Age at first good seed crop (years)	Age at maximum production (years)	Average interval between good crops (years)	Time of flowering	Time of coning	Time of seed dispersal
Conifers						
Sitka spruce	25–35	40+	3–5	May	Jul–Sep	Nov–Apr
Scots pine	15–20	60+	2–3	Jun–Jul	Aug–Sep	Apr–Jul
Douglas fir	30–35	50+	4–6	May	Jun–Jul	Oct–Apr
European larch*	25–30	40+	3–5	Mar	Apr–May	Feb–May
Japanese larch*	15–20	40+	3–5	Mar	Apr–May	Oct–May
Hybrid larch*	15–20	40+	3–5	Mar	Apr–May	Oct–May
Western hemlock	25–30	40+	2–3	Jun	Jul–Aug	Oct–May
Corsican pine	25–30	60+	3–5	Jun–Jul	Aug–Sep	Mar–Jun
Lodgepole pine	15–20	30+	2–3	Jun–Jul	Aug–Sep	Nov–Apr
Norway spruce**	30–40	50+	**	Jun	Jul–Aug	Nov–Apr
Noble fir	30–40	40+	2–4	Jun	Aug–Sep	Sep–Oct
Grand fir	35–45	40+	3–5	Jun	Aug–Sep	Sep–Oct
Broadleaves						
Ash	20–30	40–60	3–5			Sep–Mar
Beech	50–60	80+	5–15			Sep–Nov
Birch	15	20–30	1–3			Aug–Jan
Pedunculate oak	40–50	80+	3–6			Nov
Sessile oak	40–50	80+	2–5			Nov
Sweet chestnut	30–40	50+	1–4			Oct–Nov
Sycamore	25–30	40–60	1–3			Sep–Oct
Wild cherry	10	30+	1–3			Jul–Aug

* Retains cones for several years ** Rarely seeds heavily

The seed of some tree species maintains its viability over many years and so annual seed production can be augmented by seed in soil seed banks. For example, the seed of ash may remain viable in the soil for up to six years. Other trees, such as beech, may use seedling banks where seedlings persist under the canopy for many years, until released by canopy opening. Conifer seed rarely remains viable for more than a year.

When assessing the potential for natural regeneration, it is also important to consider the dispersal distances of seed from a mother tree. Most seed does not travel very far, although there are differences between species due to seed weight and the effectiveness of their dispersal mechanisms. Most conifers have light seed which is wind dispersed (Table 3.5), and this is also the case for most of our native or naturalised broadleaves. However, for some, such as oak and cherry, mammals and birds are an important agent for longer range dispersal (Table 3.6). In a particular stand there are other factors that influence the distance of seed dispersal, which include tree height, stocking density, exposure, wind speed, and the roughness of the ground vegetation.

Table 3.5 Conifer tree seed weight and potential dispersal distance – estimates of distance from mature trees (20 m in height) within which 80% of seed will fall (Nixon and Worrell, 1999)

Species	Average weight of seed (mg)	Estimated dispersal distance (m)
Western hemlock	1.54	100
European larch	5.88	80
Lodgepole pine	3.33	70
Sitka spruce	2.50	60
Douglas fir	11.36	40
Scots pine	6.06	20

Table 3.6 Broadleaf tree dispersal mode and maximum potential dispersal distance (Harmer, 1999)

Species	Mode	Estimated dispersal distance (m)
Birch	Wind	100
Ash	Wind	50–100
Sycamore	Wind	50–100
Beech	Gravity, mammals	20
Pedunculate oak	Gravity, birds, mammals	20
Sessile oak	Gravity, birds, mammals	20
Sweet chestnut	Gravity, mammals	20
Wild cherry	Gravity, birds, mammals	N/A

3.2.1.2 Providing a favourable seedbed

Bare, mineral soil provides the best conditions for seed germination and early seedling survival. This substrate provides the newly developed roots of the tree access to a reliable source of water and nutrients, while a thick layer of vegetation is likely to hinder natural regeneration. This is particularly the case for tree species with small seeds that have few resources, such as most conifers, where rapid establishment and self-sufficiency is essential. Large seeds, such as beech and oak, have more resources to grow their roots through a vegetation mat to the mineral soil. Indeed, seed of oak and beech germinate better when litter provides some protection from desiccation. A covering of litter and soil also provides some concealment of the seed from potential predators.

There are also differences in type of vegetation cover on the forest floor. Some vegetation, such as mosses and liverworts, can support germination and reliable seedling growth and survival. They are normally associated with wetter areas and present a low level of competition with the seedling (Figure 3.2). However, opening up the canopy will increase the likelihood of this type of vegetation drying out and desiccation of young seedlings. Competitive vegetation like grasses do not provide conducive conditions for natural regeneration (Figure 3.3).

An effective method of improving germination and seedling establishment is to prepare a suitable seedbed, which enables seedlings' roots to reach mineral soil. Mechanical treatments, such as scarification before or after seed fall, can also be effective, as can harvesting in autumn (which will inevitably result in soil disturbance). Both of these methods will expose mineral soil and reduce vegetation cover, allowing seedlings to germinate and establish. In shelterwoods, the initial seeding fellings are intended to open up the canopy and provide disturbance to the forest floor, improving the seedbed. Livestock, such as pigs or cattle, can also provide suitable conditions by breaking up any vegetation and exposing soil, but may damage existing seedlings.

Figure 3.2 Carpet of young Sitka spruce regeneration on a moss forest floor and under a Sitka spruce canopy. This will be vulnerable to desiccation if a dry spell occurs.

Figure 3.3 Lack of natural regeneration in a dense grass sward

3.2.1.3 Providing favourable stand conditions

There is a balance to be struck between providing sufficient light and warmth for seed germination (and then seedling growth) but also providing sufficient shade to supress competition from weeds. Each site will differ, having different microclimates (e.g. aspect) and soils. Each species also has its own light requirements, with pioneer trees being light demanding and later successional trees being more shade tolerant. Additionally, higher light levels are normally needed to maintain seedling growth than to stimulate germination of seed. Some tree species, such as oak and ash, can tolerate greater shade when very young but lose this tolerance within a few years.

There is a strong relationship between basal area, canopy cover, and light levels within a stand. Table 3.7 describes the stand basal areas for different species to obtain germination and subsequent growth of seedlings. These basal areas relate to a stand average and, in reality, there will be variation across the stand due to the uneven distribution of trees and gaps in many systems. In stands located further north in Great Britain, you should consider reducing the basal area as there is generally less ambient light.

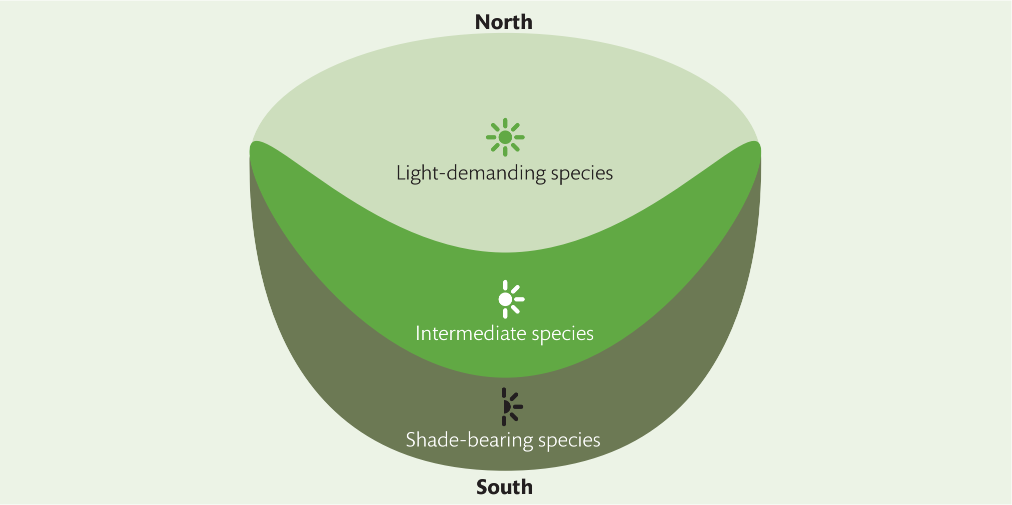
Table 3.7 Light demands of tree species (Mason, Kerr, and Simpson, 1999) and basal area guidance for natural regeneration (Sanchez, 2017 for broadleaves and Kerr, 2008 for conifers)

Species/group	Shade tolerance of seedlings	Basal area (m^2 ha^{-1}) establishment*	Basal area (m^2 ha^{-1}) seedling growth**
European, hybrid, and Japanese larch	Light demanding	20–25***	15–20
Scots and lodgepole pine	Light demanding	25–30***	20–25
Sitka spruce	Intermediate	30–35	25–30
Douglas fir	Intermediate	35–40	30–35
Norway spruce	Shade tolerant	40–45	35–40
Western hemlock	Shade tolerant	40–45	35–40
Ash	Light demanding	14–18	12–16
Sycamore	Shade tolerant	17–21	14–18
Beech	Shade tolerant	17–21	14–18
Pedunculate oak	Light demanding	11–14	9–13
Sessile oak	Light demanding	14–18	12–16
Sweet chestnut	Intermediate	14–18	12–16
Wild cherry	Intermediate	14–18	12–16

*On moderate to fertile sites where vegetation regrowth will be faster and more severe, you may need to increase the basal area for establishment. Examining successful stands nearby will help you determine which basal area ranges are best in your locality.
**Seedlings and saplings are growing well under a canopy when the ratio of the length of the leader to the length of laterals in the upper whorl is ≥1, as shown in Figure 3.5.
***Stands of larch and pine at these basal areas will usually have well-developed vegetation and you will need to consider control or cultivation to start regeneration.

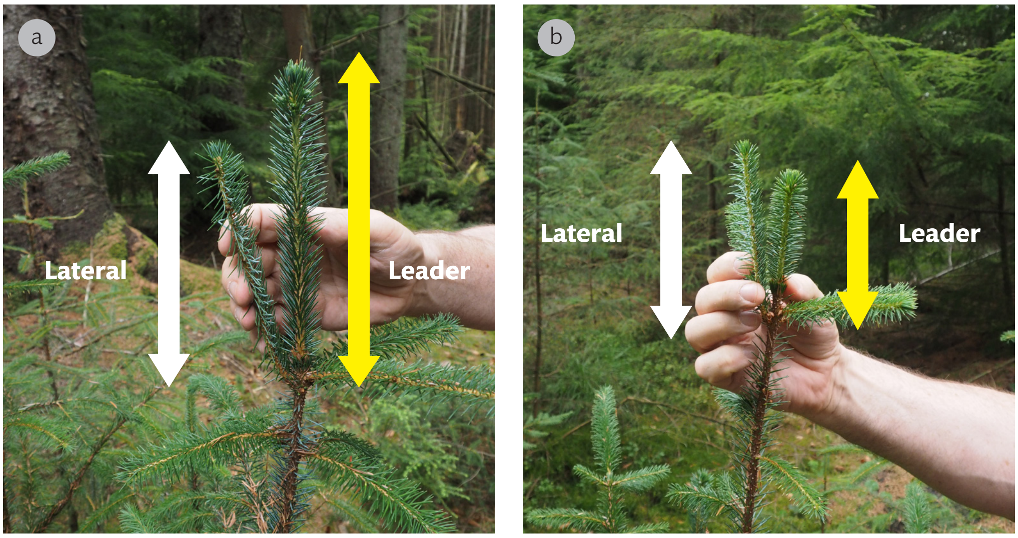
Guidance based on stand basal area is useful for uniform thinning but, if creating gaps within the canopy, consideration must also be given to gap area and orientation. This is because, for example, large gaps introduce more light into the stand than an even thinning to the same basal area reduction. Closure of the canopy also takes longer, so light falls on the forest floor for longer, penetrating the stand from the gap edges. Orientation of gaps is also important: a long, thin gap that is orientated north–south will receive less light than one that is orientated east–west. In most gaps, there will also be a gradient in light across the gap, with certain areas receiving more light than others. An illustration of this is shown in Figure 3.4, which describes zones in a gap most suited to species' light demands. Thus, expanding gaps in certain directions can promote trees with specific light requirements. For example, extending a canopy gap northward will increase the proportion of light-demanding species. However, in reality, the situation is more complex as the higher light levels at the northern side of the gap are likely to encourage colonisation of competitive weeds.

Figure 3.4 Microclimatic zones in a canopy gap and the associated light requirements of trees (Pommerening, 2023)



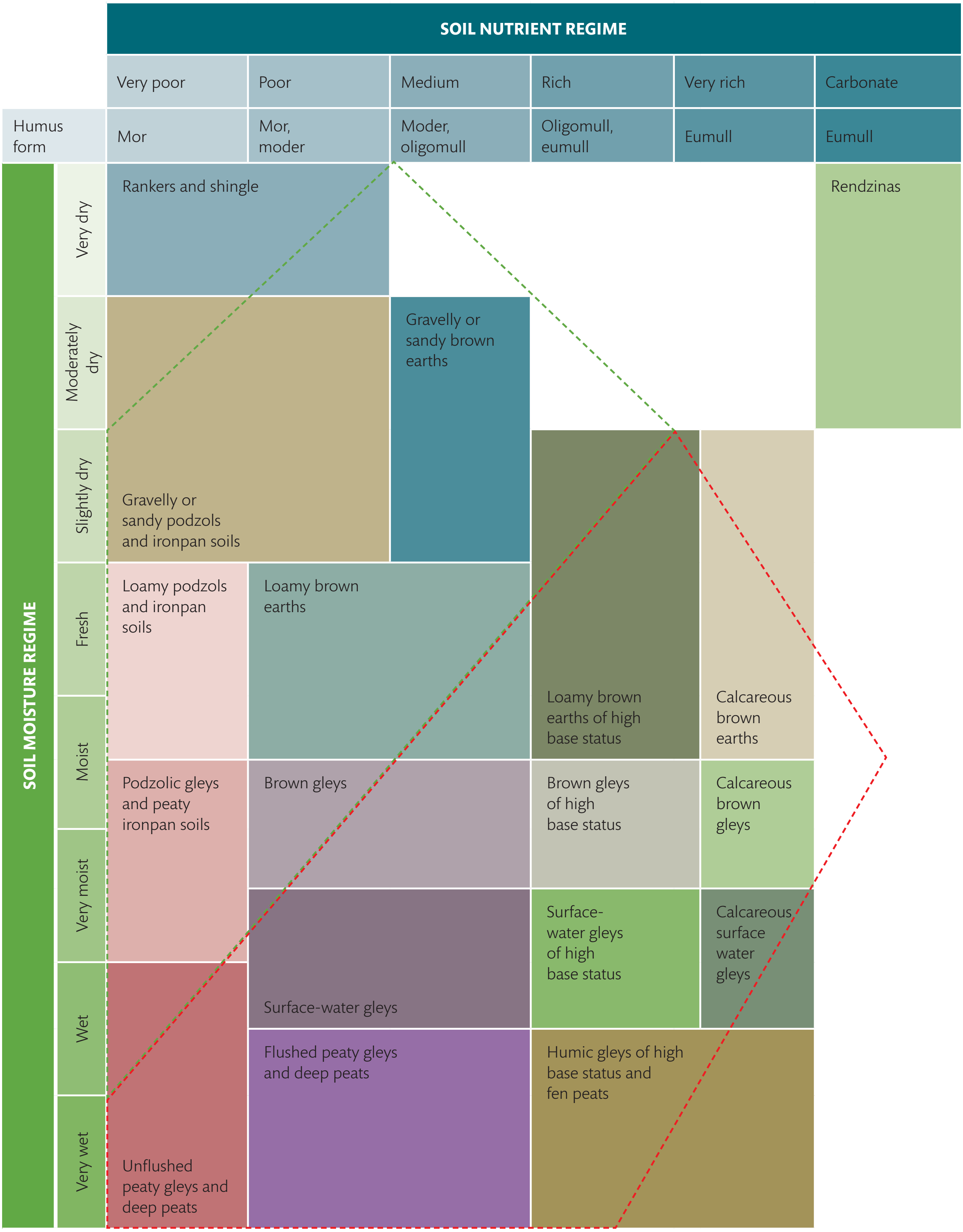
A useful measure of whether there is sufficient light for growth and regeneration of intermediate and shade-bearing conifers (but not silver firs) is the leader:lateral shoot ratio (length of leader divided by length of lateral). Trees allocate resources to counter the most limiting of site resources and so, when a seedling has insufficient light, it allocates more resources to the lateral branches to capture more light, meaning that these grow longer than the leader. In contrast, when the seedling is receiving sufficient light, the leader is the same length or longer than the lateral branches. This means that seedlings that are getting sufficient light have a leader:lateral ratio of >1 and those that are not have a ratio of <1 (Figure 3.5). Broadleaved trees also respond to a lack of light in a similar way, with resources being prioritised to lateral branches.

Figure 3.5 Leader:lateral ratio in conifers. (a) leader:lateral ratio >1 so sufficient light; and (b) leader:lateral ratio <1 so insufficient light. You can use the illustrated method of using your forefinger and thumb to quickly assess this.



While it is possible to obtain natural regeneration of most tree species across a range of soil types, with good silviculture it is usually easier to obtain natural regeneration on poor soils. This is because there is generally less vigorous growth of ground flora to compete with the trees for light, moisture, and nutrients. By creating conditions suitable for natural regeneration, some vigorous, spreading plants (e.g. bramble and bracken) will be able to better exploit these conditions than others. The relative ease with which natural regeneration of conifers can be achieved on different soil types is described in Figure 3.6.

Figure 3.6 Soil quality and the prospects for natural regeneration of conifers (green-bounded soil types are conducive to regeneration, red-bounded soil types are difficult) (modified from Pyatt, Ray, and Fletcher, 2001)



3.2.1.4 Protection from damage

There is a high risk of damage to young trees from mammals and other damaging agents. There are very high populations of deer in Great Britain that damage trees by browsing and bark stripping. Table 3.8 describes the vulnerability of selected broadleaved and conifer trees to this type of damage, although where there are high deer densities all tree species will be damaged (see Additional resources: 4 for more information). Voles, rabbits, and hares can also do considerable damage to young trees, while the grey squirrel is a major source of damage to older trees, particularly broadleaves. Controlling populations of damaging mammals is an important element of protecting regeneration.

Table 3.8 Vulnerability of tree species to deer damage (Armstrong *et al.*, 2003)

Vulnerability	Broadleaf browsing	Conifer browsing	Bark stripping
HIGH	Aspen	Silver fir	Willow
	Willow	Douglas fir	Ash
	Oak	Larch	Rowan
	Rowan	Norway spruce	Aspen
	Norway maple	Scots pine	Lodgepole pine
	Sycamore	Sitka spruce	Norway spruce
	Beech	Lodgepole pine	Scots pine
	Lime	Corsican pine	Larch
	Hornbeam		Douglas fir
	Birch		Sitka spruce
	Alder		Silver fir
			Oak
			Alder
LOW			Birch

The approaches for tree protection take two basic forms: individual tree protection and protection of trees within a defined area. Conventional physical protection of individual trees involves using tree shelters or guards (for more guidance, see Additional resources: 5), while small exclosures may be used to protect a number of trees from damaging animals. The positive effect of these exclosures on obtaining natural regeneration can be considerable (Figure 3.7) and they can also be used to protect planted trees (for more guidance, see Additional resources: 6). Additionally, due to the exclosures' small size, they only need to be stock fenced, rather than deer fenced, as deer avoid being confined within a small area. Black protective netting attached to overstorey trees has also proved effective in protecting a group of trees. The fencing material can be moved to other areas once the regeneration is successfully established. If underplanting, establishing groups of seedlings at high density is effective and means that browsing and other damage is generally confined to the outer edges of the group. For further information, including appropriate group size and gap size for light-demanding, intermediate, and shade-tolerant species, see Additional resources: 6.

Figure 3.7 Use of exclosures to protect natural regeneration from browsing

3.2.1.5 Predicting success with natural regeneration

There have been a number of attempts to develop models that predict the likelihood and amount of natural regeneration of common conifers from site and stand variables. These have incorporated important attributes such as advance regeneration of seedlings and saplings, area of bare ground or moss, amount of cone production, deer impact index, and number of years since last thinning. So far none of them reliably predict potential for natural regeneration. As such, a general recommendation is that the presence of advance regeneration where there is disturbance within or adjacent to a stand should be used as an indicator of regeneration potential.

3.2.1.6 Respacing

While in some instances it will prove difficult to obtain regeneration, in others there can be an overabundance of seedlings. Where there is an excess of regeneration, respacing must be undertaken, which can be very expensive. Leaving dense natural regeneration by delaying respacing results in smaller, less stable young trees, which negatively affects the future wind-firmness and value of the stand (see Additional resources: 7 for further guidance). When trees are around 1.5–2.0 m in height, respacing can be undertaken at a target density of about 2000–2500 stems per hectare on wind-firm sites. On sites where wind stability is limiting, a single operation leaving a target density of 1750–2000 stems per hectare should improve growing space without compromising timber quality.

For broadleaves, particularly those like oak, a higher stocking density than that adopted for conifers is likely to produce straighter stems and less branching. Leaving respacing until trees are slightly larger, about 2 m tall, will enable selection of better-quality stems for retention. Without respacing, vigorous trees (and not necessarily those with good form) will dominate. If there is very dense regeneration, it is recommended that the first respacing reduces stocking densities to about 10 000 stems per hectare, with a further intervention two to three years later to reduce stocking density to 2500–3000 stems per hectare. However, this has a significant cost; an alternative is Garfitt's spaced cleaning method, which involves releasing a pair of trees more than 2 m apart from one another by clearing competing trees within 1.2 m of them. These pairs of trees should be dispersed with about 7–8 m spacing between them. The remaining matrix is left unthinned (see Additional resources: 8 for further guidance).

Techniques commonly used in continental Europe include snapping leaders and ring barking a proportion of stems. These methods prevent overtopping of the remaining stems, but retain side shade, which improves timber quality by encouraging straight, upward stem growth while reducing growth of branches. Additionally, if these treated stems create a ring around the stems to be retained, they will provide some protection from browsing. This approach can also be used to moderate the competition from less desirable species, such as western hemlock, in mixed natural regeneration.

3.2.2 Planting

Planting is the most widely used method to regenerate forests in Great Britain. Planting in the open is the most common type of this method, but a technique that is particularly relevant to CCF is underplanting, where trees are planted under an existing canopy. For this technique to be successful, the light conditions below the canopy or in the canopy gap must be sufficient to allow survival and growth of the desired species (see Additional resources: 6 and Table 3.7 for guidance on the canopy cover ranges needed). Group planting within the middle of gaps created in the canopy is another potential approach.

Underplanting provides opportunities to: change or diversify species (such as introducing shade-bearing trees) and provenances; establish a new cohort where desired species will not regenerate; create a mixed stand; or fill in areas of poor natural regeneration. For example, Douglas fir has been planted in parts of the Lake District on north-facing slopes that are too cold and damp to support seed germination for natural regeneration. The main benefits of underplanting compared with planting in the open are summarised in Table 3.9. For a particular site and species combination, the benefits to survival and growth of underplanting must outweigh the impacts of lower levels of light, which is often slower growth.

Table 3.9 Comparison of the advantages (green) and disadvantages (purple) of underplanting and planting in the open (modified from Stokes, 2024)

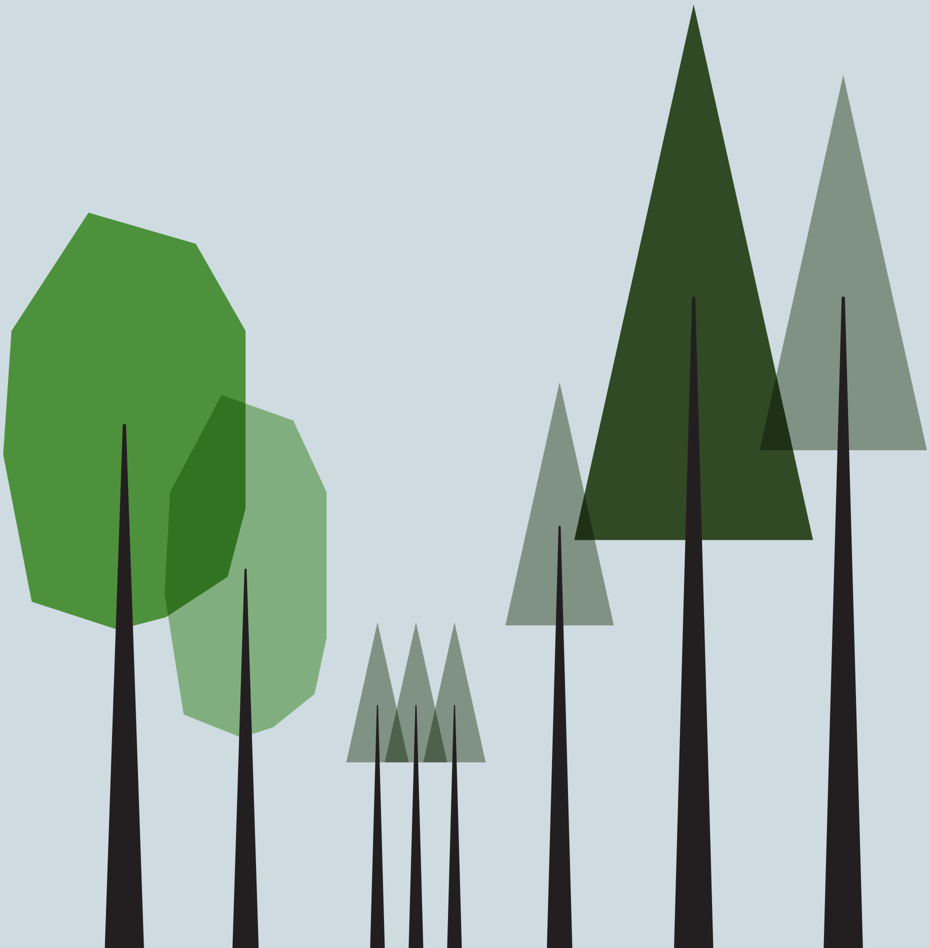
Underplanting	Planting in the open
🟩 Lower windspeeds	🟩 Higher light levels
🟩 Milder temperatures and less frost in winter	🟪 Colder temperatures and more frost in winter
🟩 Cooler and higher humidity in summer	🟪 Hotter and drier in summer
🟩 Less exposure to extreme rainfall events	🟪 More exposure to extreme rainfall events
🟪 Lower light levels	🟪 Higher windspeeds
🟪 Risk of damage by ongoing thinning operations	🟪 Pressure of time to restock post harvesting
🟪 Management of browsing can be challenging	🟪 Greater risk from insect (weevil) damage due to higher levels of brash
🟪 Difficulties recording extent and location in mapping systems	🟪 Shade-tolerant species can struggle as not their preferred environment

Group planting takes advantage of the gaps created in the canopy by most CCF systems and involves planting trees in a cluster (or group) within those gaps. Different zones across each gap will be suited to different tree species, depending on the gap's area, shape, and orientation, as well as the light demands of the desirable tree species (Figure 3.4). For both underplanting and group planting, establishing trees in tight clusters has a number of advantages, particularly protection from browsing of the inner trees by the outer trees (see Additional resources: 6 and 9 for more information). Examples of underplanting and group planting are shown in Figure 3.8.

Figure 3.8 Examples of underplanting and group planting. (a) Planting of broadleaves in tree shelters under larch at Coombs Wood, Cumbria; and (b) group planting of Douglas fir under Douglas fir at Peil Wyke Forest in Cumbria. Other shade-tolerant conifer species have been planted under the Douglas fir to diversify the forest.

Chapter 4

Planting a new CCF stand



4 Planting a new CCF stand

There are very few examples of new stands that have been established specifically for management under CCF; most examples of stands managed under CCF are those originally planted under a clearfell system and then transformed into CCF. However, many recently planted broadleaved stands are unlikely to be managed as clearfells. To create an irregular stand on a new planting site, staggered planting is used in some parts of continental Europe, but this delays site capture and is likely to lead to weed problems, particularly on richer sites.

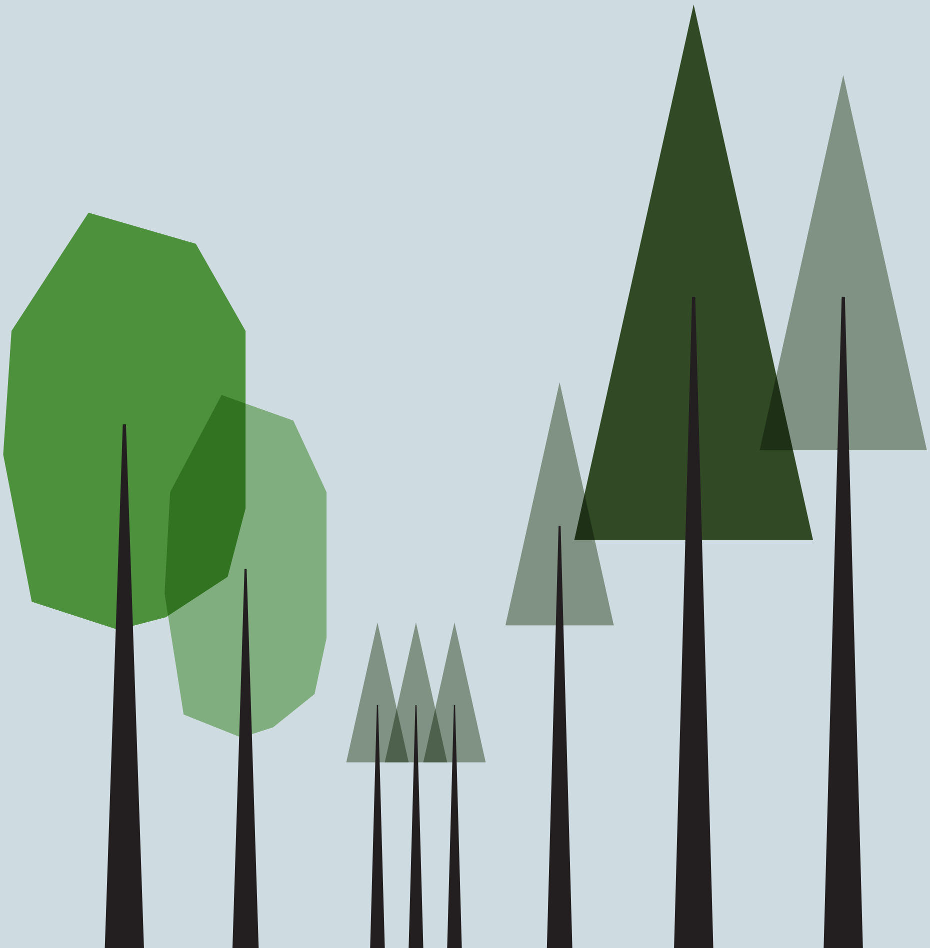
With early and appropriate thinning, most stands can be developed as CCF. An advantage of doing this is that many new CCF stands are likely to be composed of several species, and evidence suggests that certain mixtures may be more wind resistant than single-species stands (Cameron, 2020). To create robust mixtures, it is important to consider the growth rate and shade tolerance of the desired species, as these factors influence the compatibility of the species and the planting pattern chosen. A mixed stand decision support spreadsheet has been developed to support decision-making for mixed stands of two species (see Additional resources: 10). To create a robust, multi-species and structurally varied stand, Rodwell and Paterson (1994) recommend planting discrete groups of a single species, with variable spacing between groups. An example of a similar approach is provided by ProSilva Ireland (Appendix 1), which illustrates the transition from a mixed regular planting to an irregular stand within 74 years.

A new CCF stand may also be planted on a restock site. If the individual trees in the previous stand are wind-firm, it may be useful to retain individual live and dead trees, small groups of trees, and understorey vegetation. This approach is favoured in British Columbia, Canada as a means of increasing structural and habitat diversity and creating, at planting, a stand with two distinct cohorts. At Faskally Forest, Perthshire, some of the original trees dating to the early 20th century were retained. Any natural regeneration that has occurred can also be retained on a restock site to increase the species and structural diversity when planting. UKWAS (2024) recommends long-term retention of existing forest structures, focusing on trees or stand elements that have particular value for biodiversity.

Where wind is not a constraint on a restock site, the seed tree system can be applied. This involves retaining widely spaced, individual trees distributed evenly across the stand at 25–50 trees per hectare. These trees are retained not to create a forest microclimate but to act as a seed source, and will be removed following successful natural regeneration. The spacing between the retained trees needs to be close enough to ensure good coverage of seed across the site (Tables 3.5 and 3.6). Direct seeding can also be used to establish CCF stands and removes the unreliability of seed supply associated with natural regeneration (see Additional resources: 11 for guidance).

Chapter 5

Transforming an existing stand

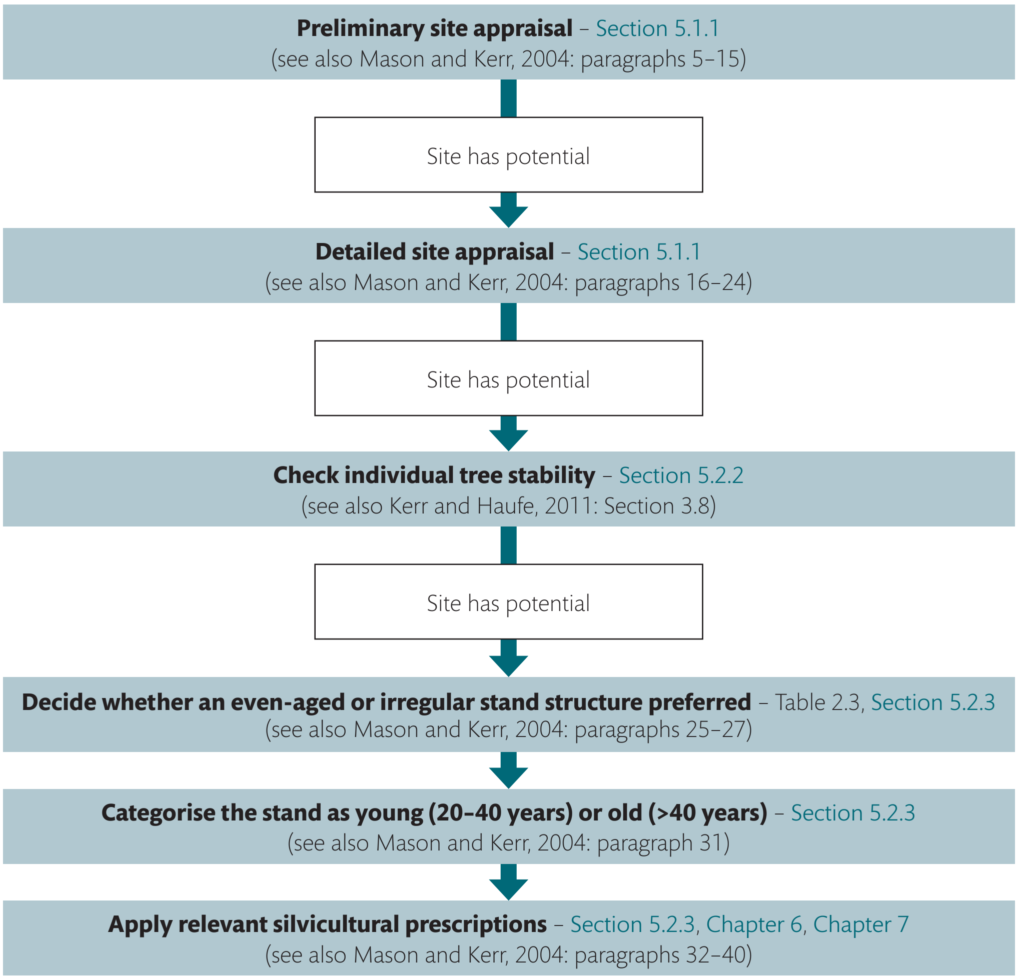


5 Transforming an existing stand

Where CCF best meets management objectives, transformation should only be applied on sites and in stands where the probability of success is high. Some CCF approaches, such as strip shelterwoods, are more appropriate for exposed sites. If the site is not appropriate for CCF, you should adopt a different silvicultural option, such as clearfelling. However, when the stand is not suitable for transformation to CCF, for example due to a lack of wind-firmness, it may be possible to move to CCF in the next rotation.

A method has been developed to determine site and stand suitability for transformation. This method has two stages: the first (a quick, preliminary assessment) enables sites to be included or excluded as potential candidates for CCF through a simple scoring system; the second stage (a detailed assessment) includes assessment of stand structure, advance regeneration, ground flora, litter layer, damaging mammals, and access. Sections 5.1.1 and 5.1.2 provide a summary of this process, but for a more detailed description please see Additional resources: 12. Figure 5.1 describes the stages involved in transformation of a stand and relevant Forestry Commission guidance.

Figure 5.1 Steps in transformation of a stand to CCF



5.1 Site and stand appraisal

5.1.1 The preliminary assessment

A crucial aspect used to assess a site's suitability for transformation to CCF is information about the depth and nutritional status of the soil, which is often not available at a sufficient resolution. If the soil type is not recorded, a survey of the soil at the site is recommended (see Additional resources: 13 for more details on how to conduct a soil survey). Information about the soil type can then be inputted into Forest Research's Ecological Site Classification (ESC) online tool, which is designed to aid in selecting suitable tree species for a given site. ESC is used in two of the four steps in the preliminary assessment for CCF.

Step 1: evaluate the wind-firmness of the stand.

Wind-firmness is evaluated in two different ways depending on the age of the stand. For a young stand (20–40 years old) it is recommended that the decision support tool ForestGALES be used to assess the stability (see Additional resources: 14). For older stands (40+ years old) the method is more complicated and combines information on stand basal area and its relation to the thinning threshold basal area, its thinning history, and soil type in terms of rooting depth (see Additional resources: 3 for further guidance). Regularly thinned stands, below the threshold basal area and on soils that allow deep rooting are most likely to be wind-firm.

Step 2: assess the site's soil fertility.

The potential for natural regeneration is strongly influenced by weed competition, which in turn is influenced by soil fertility. If information about the site's soil type and nutritional status is not already available, a soil survey will enable you to identify the soil type and ESC parameters to characterise the nutritional and moisture status of the soil. You can also use indicator plants when present to categorise the soil fertility and soil moisture status (see Additional resources: 15 for more information). The soil type (combining nutrition and moisture status) is used to score the likelihood of success of natural regeneration (Figure 3.6).

Step 3: select tree species that are suitable for the site and management objectives.

The tree species present on the site should meet management objectives and be suited to the site both now and in the future under climate change. Based on the climate and soils of the site, ESC will categorise the climatic suitability of the tree species present on the site now and under different emissions scenarios. This assessment from ESC should be augmented where possible with local knowledge of performance of tree species. These categories are used to determine a score for species suitability.

Step 4: calculate the overall site suitability score.

The scores for wind-firmness, natural regeneration, and tree species suitability are combined to provide an overall site suitability score. Sites where the risk of wind damage is low, the probability of natural regeneration is high, and where desirable species are well suited to present and future climates are the best candidates for transformation.

5.1.2 Detailed assessment

If the preliminary site evaluation shows that the site and stand have good or moderate potential for transformation to CCF, then a more detailed assessment is justified. This involves a simple assessment ('Yes' or 'No') in the forest of the following criteria:

- Past thinning has produced trees with well-developed crowns as potential seed bearers.
- Stems are of good quality, with little damage or risk of timber degrade.
- There is either no evidence to suggest that tree stability is at risk (such as large areas of recent windthrow, small crowns, limited buttressing of stems) and little evidence of thinning (Figure 5.2), or strong evidence of individual tree stability (Figure 5.3).
- There is strong evidence that natural regeneration of the desired species can be obtained, such as advance regeneration present in the stand.
- Competitive ground vegetation is not present and unlikely to form when the stand is thinned – if it is difficult to judge how vegetation will develop, look at canopy gaps or similar open areas nearby.
- The litter layer is not deep (<5 cm depth).
- Local populations of mammals (deer, hares, rabbits) are under control and will not impact heavily on regeneration.
- Suitable harvesting machinery is available or could be secured to work the site and the site is already racked or racks could be established.

A further consideration, though not part of the detailed assessment, is whether there is good access to the site to facilitate harvesting. For a more detailed description of this process, see Additional resources: 12. This additional information can be used to adjust the suitability of the site, as determined by the preliminary assessment. The sites most suited to transformation will have potential for natural regeneration (presence of advance regeneration, little browsing, suitable soil, and ground flora conditions for regeneration) and an appropriate stand structure and quality (regularly thinned, good quality and healthy stems, no large areas of windthrow). Some 'No' observations can be moved to a 'Yes' or 'not applicable' as some of these attributes can be altered through remedial management interventions. For example, a lack of natural regeneration of a desirable species can be compensated for by underplanting.

Figure 5.2 Strong evidence of stand instability: windthrow and spindly, thin trees due to a lack of thinning

Figure 5.3 Heavy buttressing, a radial root system, and lots of seed indicate a wind-stable tree, and the large number of cones and lack of vegetation on the forest floor indicate potential for natural regeneration

5.2 Transforming the stand

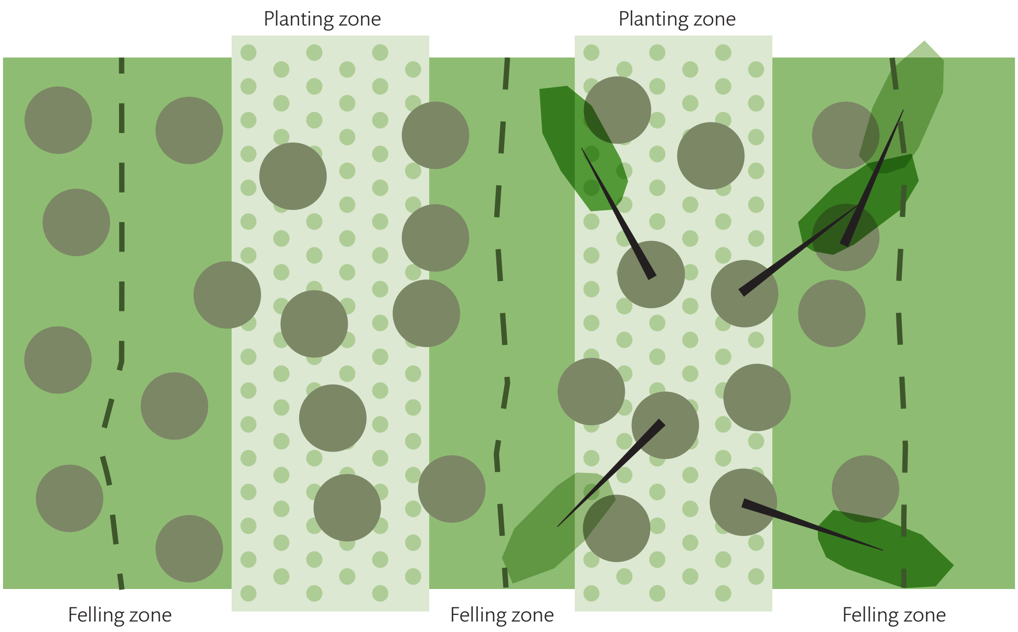
The following guidance complements that presented in Mason and Kerr (2004), which describes how to transform an existing stand. The approach used for transformation depends on whether it is applied to younger or older stands, as well as whether an even-aged (simple) or irregular (complex) structure is desired. The earlier that transformation is applied, the greater the likelihood of success in developing a stable stand; for some older stands it will not be possible to transform them to a CCF system, and this will need to be left for the next rotation. Most of the productive forest stands in the UK are even-aged monocultures in the stand initiation or stem exclusion phases of their development.

5.2.1 General operational considerations

An important consideration, whatever approach is chosen, is the provision of access within the stand for harvesting and extraction. The number of extraction racks should be kept to a minimum, while allowing good access to maximise the potential area for regeneration. It is recommended that racks initially be established every 20 m and about 4–5 m wide to allow harvesters to access trees across the stand. These do not appreciably reduce the productivity of the stand as the canopy and roots will grow across them. If extraction is undertaken with forwarders, brash protection of the soil in racks needs consideration, particularly in older stands. Two approaches are recommended: (1) using more winching on slopes; and (2) alternate rack harvesting. Normally the harvester and forwarder will travel on all racks, but in the alternate rack system the harvester travels along all racks, while the forwarder only travels along alternate racks. The harvester operator fells the trees so that they can be processed from every alternate rack, which results in a good covering of brash in these racks (see Additional resources: 16 for more information about this method).

When harvesting trees in stands with natural regeneration, or where underplanting or group planting has taken place, careful planning and directional felling is required to reduce damage to the young trees (Figure 5.4). Harvesting may involve mechanised, manual, or a combination of both methods depending on tree size, stand conditions, and other factors such as steepness of the site.

Figure 5.4 The importance of directional felling and establishing planting zones and racks 20 m apart to reduce damage from harvesting (Kerr and Haufe, 2016)



5.2.2 Early and late transformation

For conifer stands, early transformation largely relates to stands in the stand initiation and stem exclusion phase, which is normally up to 40 years old. Late transformation focuses on older stands that are producing reasonable quantities of seed and will be in the understorey reinitiation stages of stand development (Figure 2.4). For broadleaved trees with slower growth and older age to reach significant quantities of seed, the early stage is likely to be longer.

The earlier a stand is transformed to CCF, the greater the number of options available to the forest manager. Early CCF transformation involves a lot of thinning to promote stability of the stand. Initial thinning will likely be systematic, such as lines, although some advocate crown thinning at this stage (see Additional resources: 17 for more information). Later thinnings should, however, be crown thinnings to make substantial openings in the canopy and develop wind-firmness in the remaining trees.

Starting transformation early also enables a network of permanent extraction routes to be developed. These ensure that any compaction of the soil is confined to these areas. In general, harvesting should not be carried out on heavy soils when wet, to reduce the risk of compaction. The distance between the racks is dictated by the reach of the harvester boom, which currently has a maximum of 10 m, allowing a distance of 20 m between racks. Thinning, particularly line thinning, is used to create a network of racks within stands to allow access for harvesting. In early thinnings there is usually sufficient brash to prevent damage to the soil along racks.

Once a stand has reached an age suitable for first thinning, which is normally when the stand reaches a top height of 10–12 m, it should be thinned regularly, with the thinning cycle being determined by growth rate but also by practical operational considerations (such as the thinning programme for adjacent sub-compartments). For slow-growing stands of conifers and for broadleaves there is more flexibility in the timing of thinning, but for fast-growing stands thinning must be frequent (every three to five years) to maintain stand stability. In general, no more than 20% of basal area should be removed in any thinning so as not to compromise stand stability.

For successful later transformation, it is crucial that the trees in the stand are individually wind-firm. This depends on factors such as when and how often it has been thinned, intensity of thinning, and also site characteristics such as exposure, soil depth, soil water conditions, and whether cultivation and drainage has been practised. There are thought to be differences in wind-firmness between tree species, but there is little experimental evidence to support this. It is likely, however, that in winter evergreen conifers are more susceptible to wind damage than deciduous broadleaves, although broadleaves are generally grown on more sheltered sites anyway. If there are concerns about wind stability, then the volume thinned should be reduced to below 20% and the thinning cycle shortened.

For conifers, two ratios can be used to determine stand stability. The first ratio (the height:diameter ratio) relates to the stem taper, as trees with more tapered stems have greater stability. This ratio is calculated by *h/dbh* (where *h*=height and *dbh*=diameter at breast height, both expressed in metres). The second ratio (relative crown length) relates crown depth to total height, as trees with a well-developed crown will have grown in more open stands, with less competition, and will have developed greater individual tree stability. This second ratio is calculated by *cl/h* (where *cl*=crown length and *h*=height, both expressed in metres).

For relative crown length, a tree with a ratio of >0.5 is stable, between 0.3 and 0.5 is marginally stable, and <0.3 is very unstable. Table 5.1 describes the influence of the ratio of tree height to dbh on stability, tree shape, and management.

Table 5.1 Stability index, the degree of stability in the stand, and recommendations for harvesting and other aspects of management, based on experience in north-west England (Browning, 2025)

Height: dbh ratio	Degree of stability	Tree attributes	Harvesting options	Other management advice
<45	Individually stable trees	Open-grown tree, very stable, high degree of stem taper, deep crown, heavy branching	No restrictions	Can remove up to 30% of basal area to encourage regeneration
45–80	Stand has good social stand stability	Stable, very tapered stems to moderately tapered stems	No restrictions	Can remove up to 30% of basal area to encourage regeneration on sheltered freely draining soils
80–100	Stand is becoming less stable	Stems very slender, risk of stem snap	Consider reducing thinning intensity on exposed sites; do not exceed 20% removal of dominants and co-dominants	Initiate crown thinning as soon as possible to encourage more stable trees to develop
100–110	Stand is unstable		Reduce thinning intensity; line thinning only; no intermediate thinning	May not be suitable for CCF transformation but may improve. Plan for two low intensity line thinnings then reassess
110+	Stand is very unstable		Line thin only and only on sheltered freely draining soils. Reduce thinning intensity to max 12% (i.e. one line in eight removed)	May not be suitable for CCF transformation but may improve. Plan for two low intensity line thinnings then reassess

5.2.3 Transformation for different stand structures

Stand structures have been divided into two broad categories: even-aged (simple) stands and irregular (complex) stands. Even-aged stand structures are created using a rotational forestry approach. This involves retaining the stand for a defined period (the rotation) between regeneration and removal of the original canopy, which creates an even-aged stand. This includes the clearfell system and, under CCF management, most shelterwoods. In the clearfell system, the canopy is completely felled and then the stand is restocked, normally through planting. However, in shelterwoods the regeneration takes place before the canopy is completely removed. In this transition period a shelterwood has two canopy layers and cohorts but, for most of its life, the stand has a single canopy layer and cohort of trees. In contrast, complex systems have no set period between regeneration and removal of trees in the canopy and the stand that is created is multi-aged. Some of the management implications of even-aged and irregular stands are described in Table 2.3. The methods used for transformation to CCF depend on the desired stand structure as well as the age of the existing stand; the guidance that follows separates out younger and older stands and whether the desired stand structure is even-aged or irregular.

5.2.3.1 Younger stands and an even-aged stand structure

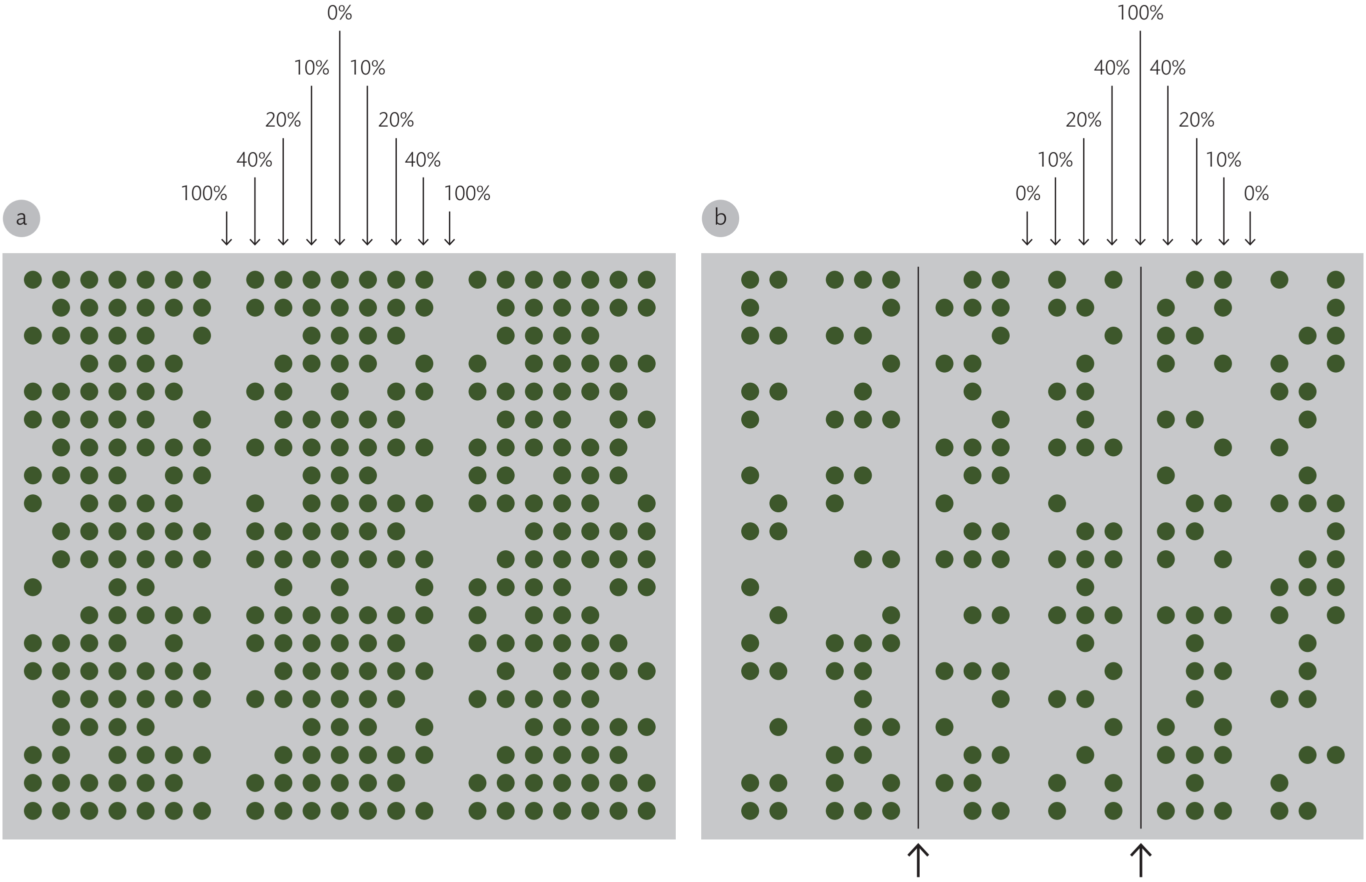
To transform a younger stand (20–40 years old) to an even-aged stand structure under CCF, the aim is to create a shelterwood or seed tree system (Table 2.2). Thinning will be heavier (+10–20%) than marginal thinning intensity, as recommended in a conventional thinning (see Additional resources: 3), and the aim is to develop individual tree stability.

A later consideration is the basal area required to trigger germination (seeding fellings) and then allow the regeneration to grow (regeneration fellings); suitable basal areas are described in Section 3.2.1.3 and Table 3.7 and differ between light-demanding and shade-bearing species. For many tree species, production of adequate quantities of seed starts at around 40 years (Table 3.4) and so for species like spruce you may need to consider extending the rotation a further 10–20 years past the financial rotation. The arrangement of the retained trees depends on the chosen shelterwood system and whether you will be creating gaps or strips, or uniformly thinning the stand (Table 2.2). The system applied is likely to be determined at least in part by the pattern of any advance regeneration, whether it is relatively even across the stand (uniform shelterwood) or in distinct groups (group shelterwood). Whatever approach is adopted, it is recommended that crown thinning is used to make significant openings in the canopy.

5.2.3.2 Younger stands and an irregular stand structure

Transforming a stand to an irregular structure is more involved than for an even-aged structure. As early as possible, but not before the stand has reached a top height of 10–12 m, racks should be cut to enable access. Following this, crown thinning should be applied to open up the canopy and create variation in gaps and clumps of trees across the stand. An alternative and more complex approach to crown thinning, that has been applied in limited situations in upland spruce stands in Wales and Ireland, is graduated density thinning. In the first thinning, the initial operation removes every eighth line of trees for access. Then the percentage of stems in each of the remaining seven rows differs (Figure 5.5) varying from no thinning to 40% of the trees in two of the lines. In the second thinning, the pattern shifts, with the unthinned row from the first thinning now being the row in which the trees are completely removed (Figure 5.5). Subsequent thinnings are crown thinnings (Wilson *et al*., 2018). This is a more complicated pattern of thinning than crown thinning and is likely to be more difficult for harvester operators to apply in the forest.

Figure 5.5 Graduated density thinning indicating proportion of trees removed per row (Vitková and Dhubháin, 2013): (a) first thinning intervention; (b) second thinning intervention



When some patchiness in canopy has been established across the stand, the aim is then to create a stand with vertical layers and where the diameter class distribution is balanced (lots of small trees, a moderate number of medium sized trees, and few large trees conforming to negative exponential tree number–diameter distribution; see Section 7.2.3). To provide a foundation for the transformation, frame trees (those that are retained until they meet a target diameter) should be identified and marked. When the wind stability has been confirmed using the height:diameter and relative crown length ratios, frame trees are selected based on their quality for timber; for an irregular stand structure they should not necessarily be evenly distributed across the stand. Tree quality is based on stem straightness and a lack of coarse branching. The generally coarser branching and deeper crowns of dominant trees may encourage selection of co-dominant trees.

An important aim of developing an irregular stand is to improve timber quality. This is achieved through selection and promotion of the best quality trees by thinning and involves identification and retention of frame trees and management of trees in their vicinity. Superior trees are those with considerable potential to produce high quality timber (see Additional resources: 18 for further guidance on assessing attributes like stem straightness). The aim of this is to concentrate growth on the very best quality trees through releasing them from competition, which also encourages further development of individual tree stability.

When thinning, trees other than those of the best quality should be removed, starting with the poorest stems first. In addition to a focus on stability and quality, there are other practical considerations for selection of frame trees (see Table 5.2). These include otherwise suitable trees whose root development may be limited by waterlogging (close to a drain or water course) or that are damaged by compaction of soil by machinery (close to extraction racks and timber stacking areas). Furthermore, some frame trees are likely to be retained for objectives other than timber production, such as for habitat.

Table 5.2 Other considerations for selection of frame trees (Browning, 2019)

Attributes favouring selection	Attributes excluding selection
Best depth of crown out of the trees available in the immediate area	On the edge of an extraction rack, drain, or watercourse
Signs that it has put out anchorage roots (usually this can be seen as the development of thick buttressed roots visible above the ground)	Suppressed by larger trees
Free from damage or disease	Adjacent to previous timber stacking areas
One of the largest trees and in the upper canopy	Damaged
Matches the preferred species identified for the site	

While thinning needs to focus on removing the poorest stems, it must also create an environment that promotes and encourages development of the best quality stems and stable frame trees. Trees neighbouring frame trees can be classified into three categories: competitors, protectors, and educators, and each category has a different role in stand improvement (Table 5.3). Figures 5.6 and 5.7 highlight the differences between frame tree thinning and conventional thinning.

Table 5.3 Three categories of trees in irregular stands and their relationship to frame trees and management (Sanchez, 2017)

Category	Role	Management
Competitors	Trees that are of the same dbh as the adjacent frame tree or larger, where the crowns are in competition with superior timber trees	Should generally be removed when thinning
Protectors	Ensure the quality of superior timber trees by minimising branching, development of epicormics, sun damage to bark, and wind damage	Retained for a long time
Educators	Enhance the overall quality of the stand by improving the general form of trees and limiting growth of ground vegetation	Retained for a long time

Figure 5.6 A conventional approach is to remove supressed trees of small size and those that are damaged or of poor quality (red crosses). The most rapid growing trees of good quality are retained. This creates a more uniform stand, but early thinning in particular provides a poorer financial return since small trees are removed (Davies, Haufe, and Pommerening, 2008).

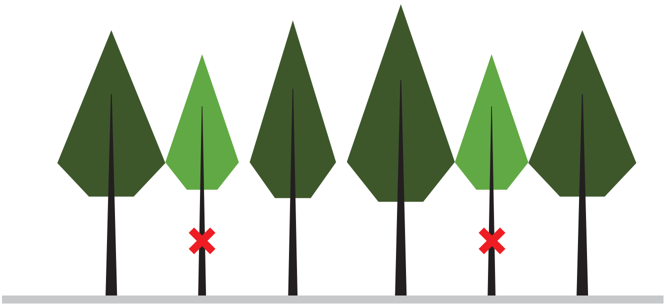
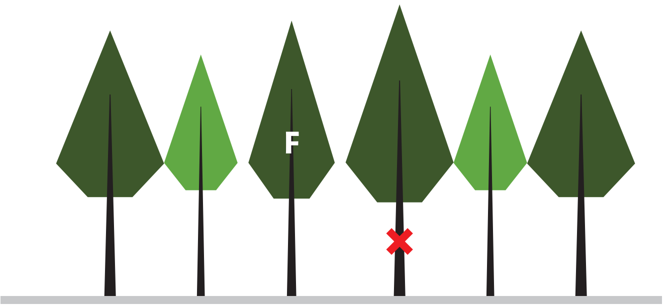


Figure 5.7 Superior and stable individuals are selected as frame trees (F) and they are released by thinning dominant competitors (red cross). This creates a less uniform stand structure and improves financial returns since larger trees are harvested (Davies, Haufe, and Pommerening, 2008).



Gaps are created by removing groups of trees, which are selected to release large, high quality individual frame trees from competition under a group selection system. This increases the irregularity of the stand and provides areas with higher levels of light where seedlings can develop.

The number of frame trees required varies depending on the light demands of desired species, the target diameter, and how far thinning has progressed within the stand. Guidance on an appropriate number of frame trees varies, but Kerr (2008) recommends less than 50 trees per hectare and Browning (2025) advises retaining between 30 and 50 frame trees per hectare, which would require them to be roughly spaced 18 m to 14 m respectively if distributed evenly (although the distance between trees will not be regular as variation in canopy cover across the stand is an aim). The number of frame trees is likely to decrease during transformation; Wilson (2025) suggests starting with a higher number of 120–160 frame trees per hectare and Sanchez (2017) 100–140 trees so as to allow for later refinement of the selection and loss due to damaging agents, with a final number of less than 50 trees per hectare. The number of frame trees selected depends on the light demands of desirable species and the desired structure of the stand (see Section 7.2).

5.2.3.3 Older stands and even-aged stand structure

There is less opportunity to develop individual tree stability within an older stand (>40 years old) than in developing an even-aged CCF structure in a younger stand. As such, the stability of the existing trees is crucial to success. It is likely that thinning will need to be lighter, and for the removal of the original canopy to be undertaken over an extended period. This is also likely to increase the period required to obtain sufficient regeneration. A particularly appropriate shelterwood for late transformation is the strip shelterwood, where the original canopy is removed in successive strips in the opposite direction to the prevailing wind. This ensures that for much of the transformation period a large proportion of the stand is sheltered by a wind-firm portion. If regeneration is not forthcoming, then underplanting can be used or the stand can be clearfelled and replanted.

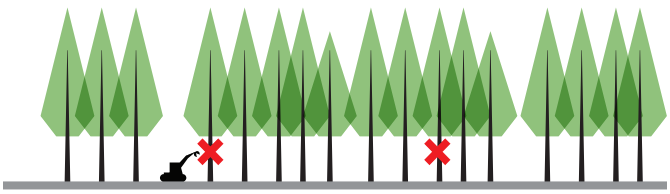
5.2.3.4 Older stands and irregular stand structure

This is the most difficult option to achieve as it involves creating gaps in a canopy when wind-firmness has not been developed in individual trees. This is particularly problematic when thinning has been delayed in the past. As such, the site and stand appraisal described in Section 5.1 and the associated stability indexes are important in deciding whether to go ahead with transformation. If the decision is to transform a stand on a wind-firm site, then less than 20% of basal area should be removed in any thinning. However, this can conflict with opening up the canopy sufficiently to provide conditions suited to natural regeneration of desired tree species. Additionally, the lack of a developed vertical structure, as well as the single cohort of trees, means that transformation is likely to require extending the life of the stand beyond the age at which target diameter is reached.

An example of transformation of older spruce stands in Belgium is shown in Figure 5.8, which provides a visual representation of late transformation. For inventory and volume estimation, see Additional resources: 19.

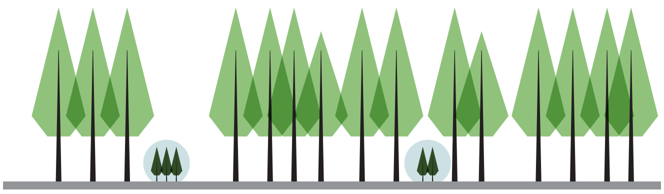
Figure 5.8 Thinning in a mature spruce stand (>60 years old) for transformation to a complex stand structure (Sanchez, 2017)

Year 0

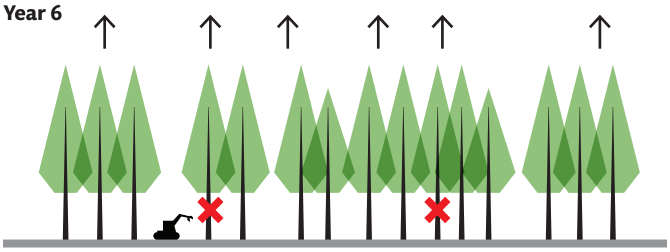


Harvesting: between 4 and 7 m²/ha, preferentially large trees

Year 5

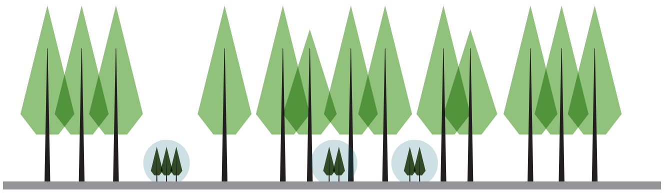


Year 6

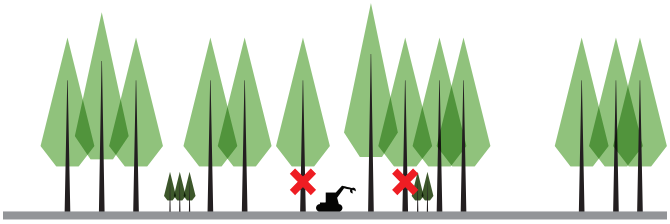


Harvesting: between 4 and 7 m²/ha, preferentially large trees

Year 11

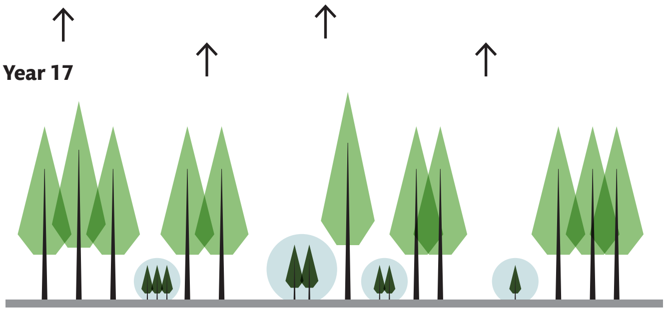


Year 12

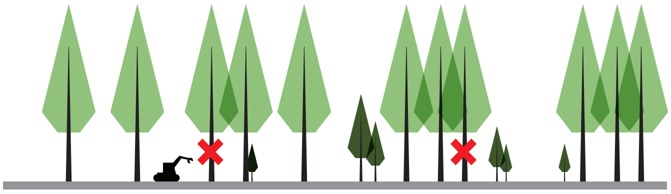


Harvesting: between 4 and 7 m²/ha, preferentially large trees

Year 17

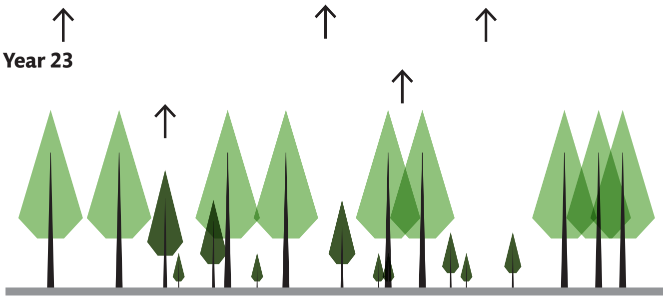


Year 18

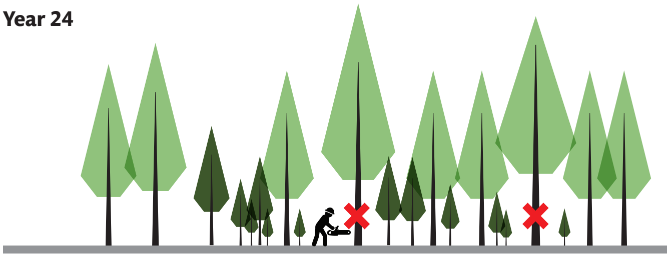


Harvesting: between 4 and 7 m²/ha, preferentially large trees

Year 23

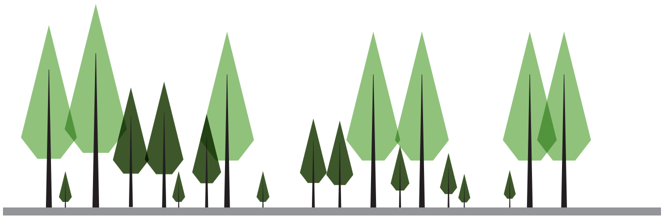


Year 24



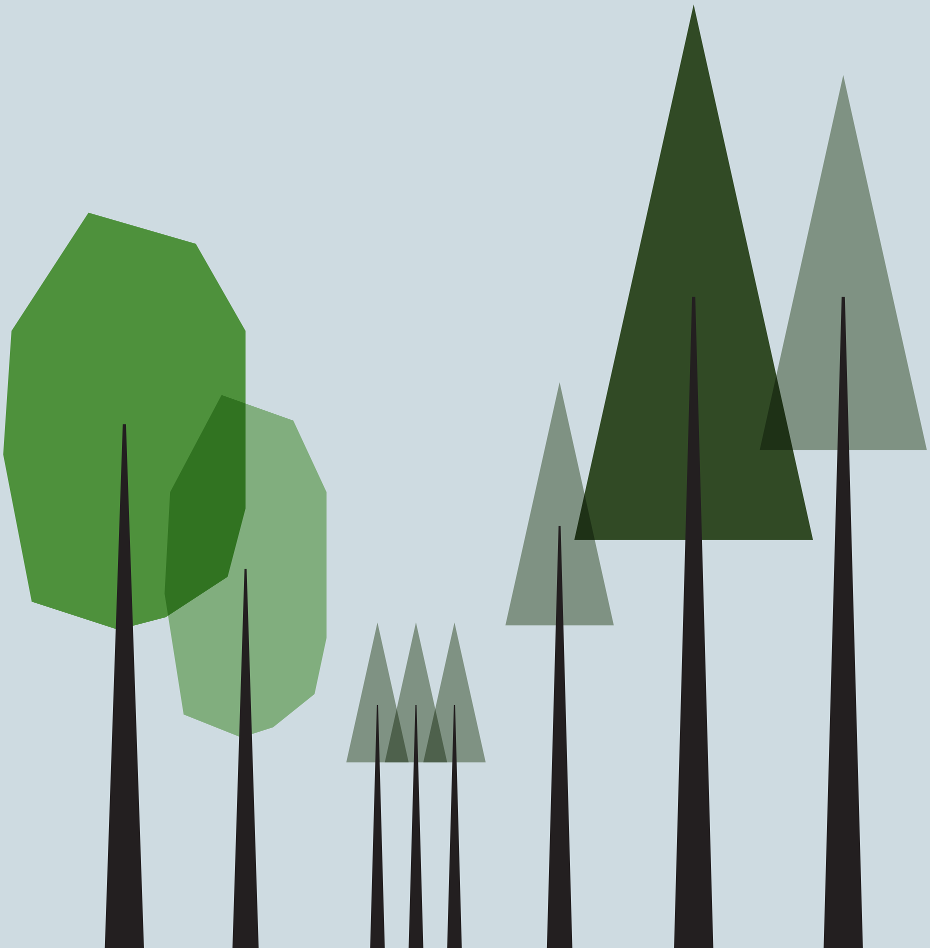
Harvesting: between 4 and 7 m²/ha, preferentially large trees

Year 29



Chapter 6

Management of even-aged stands



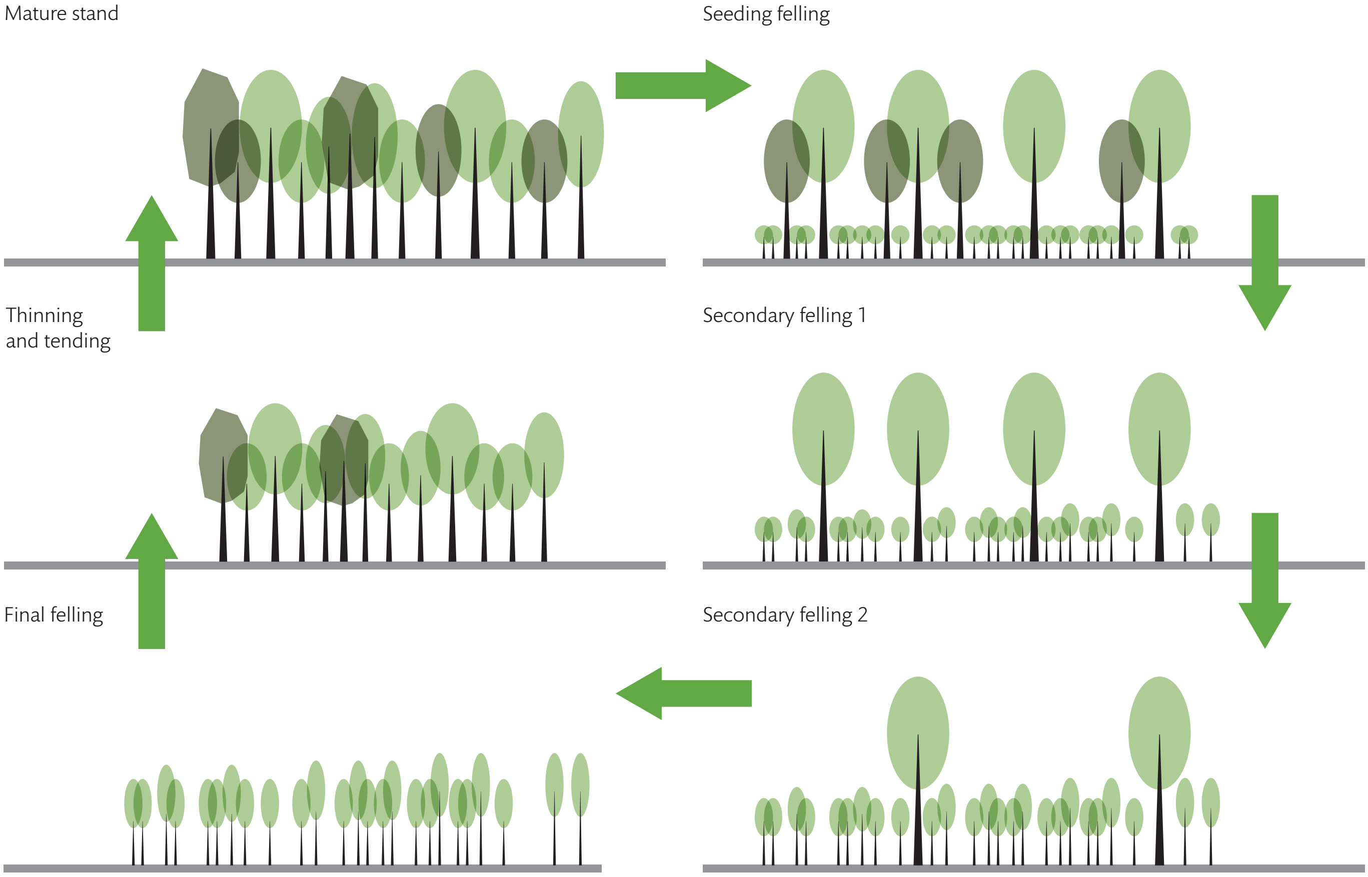
6 Management of even-aged stands

The aim of management is to encourage regeneration (natural or through underplanting) within a relatively short time (<20% of the rotation), thereby creating a simple structure, even-aged stand. The original canopy is progressively removed to facilitate germination and then to release regeneration. These are known as shelterwood systems and there are many variations. The management of all shelterwood systems is the same, until the regeneration stage is reached and then different approaches are adopted to opening the canopy.

6.1 A framework for managing even-aged stand structures

For all even-aged CCF stands (managed as shelterwoods) there is the same sequence of operations. The way these operations are applied spatially within the stand determines the type of shelterwood. First, the trees in the stand should be stable, with well-developed crowns to support copious seed production if natural regeneration is to be used. Then, when the stand is old enough to produce a good supply of seed, it is managed through a series of regeneration fellings (Figure 6.1) which progressively remove the original canopy. Transformation of young and older stands to an even-aged (simple) structure has been described also in Sections 5.2.3.1 and 5.2.3.3.

Figure 6.1 The general framework for operations in a shelterwood



6.1.1 The seeding felling

The seeding felling, which is the first to promote regeneration, is directed at opening up the canopy sufficiently to create light, warm conditions on the forest floor to stimulate seed germination and to allow survival of the resulting seedlings for two to three years. As regeneration must be achieved over a shorter time period than in an irregular stand, thinning may need to coincide with mast years and, where the seedbed conditions are not ideal, remediation by scarification may be necessary. Basal area of the canopy must be appropriate to the light requirements of the desirable tree species (Table 3.7) and care must be taken not to promote growth of competing vegetation.

6.1.2 Secondary fellings

Once initiation of natural regeneration or underplanting has been successful, the canopy must be further reduced to provide sufficient light for seedling growth. This is achieved through a series of secondary fellings, which further reduce the cover of the original canopy. The cycle and intensity of these fellings will depend on the light requirements of the desired tree species. For light-demanding species, like Scots pine, the canopy should be heavily thinned and might be removed in one or two thinnings (wind stability permitting). In contrast, shade-bearing species like beech will require lighter thinnings over a longer period of 20–30 years (Matthews, 1991). If mixed-species stands are desired, it can be difficult to apply thinning that produces regeneration in the desired balance of species and so underplanting can be a useful way of modifying the composition.

There are two broad patterns of removing the original overstorey: uniform thinning of the canopy and by creating gaps in the canopy (the gaps can be roughly circular, strips, wedges, or other shapes). Three contrasting systems are described briefly in the following sections: the uniform system, the group system, and the strip system (more detailed accounts can be found in Matthews, 1991).

6.1.3 The uniform system

The uniform system involves successively and evenly thinning the canopy across a whole sub-compartment (Figures 6.2 and 6.3). Early interventions involve removing particularly poor quality young trees and those of unwanted species. Keeping the stand dense improves the overall quality of the trees and, once the trees reach a top height of >10 m, thinning begins. When the stand reaches a top height of 15–18 m, the seed trees (those of good quality and stability, that will remain in the canopy for longest) can be selected and their crowns released to encourage seed production. When the seeding and regeneration fellings begin, the stand should be composed of tall, straight trees with well-developed crowns that form a complete canopy. This is reduced through the seeding and regeneration fellings to a target density of between 100 and 200 trees per hectare (see Additional resources: 20 for further guidance).

Figure 6.2 Uniform system showing the stages of (a) original stand structure; (b) seeding felling; (c) regeneration felling; (d) final removal of the canopy; and (e) the newly regenerated even-aged stand (Troup, 1928)

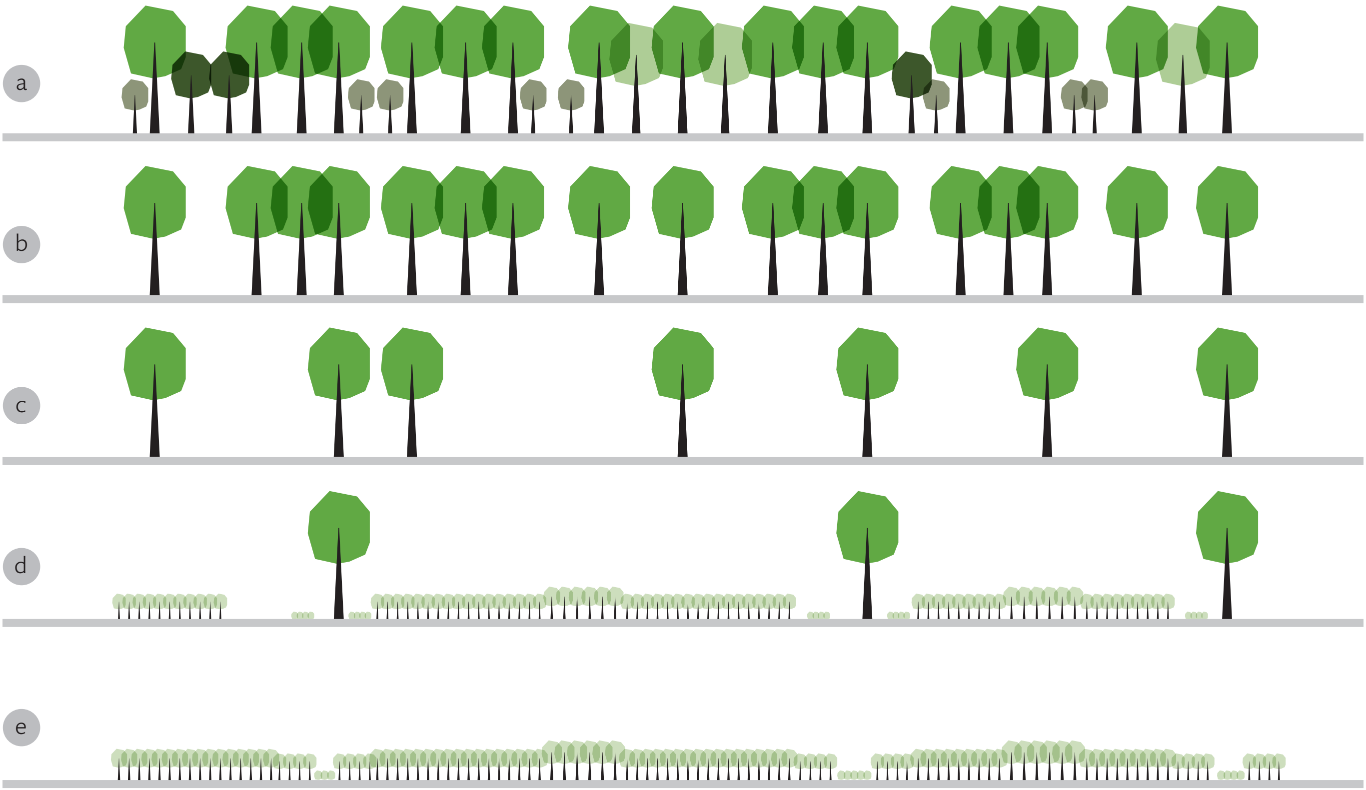
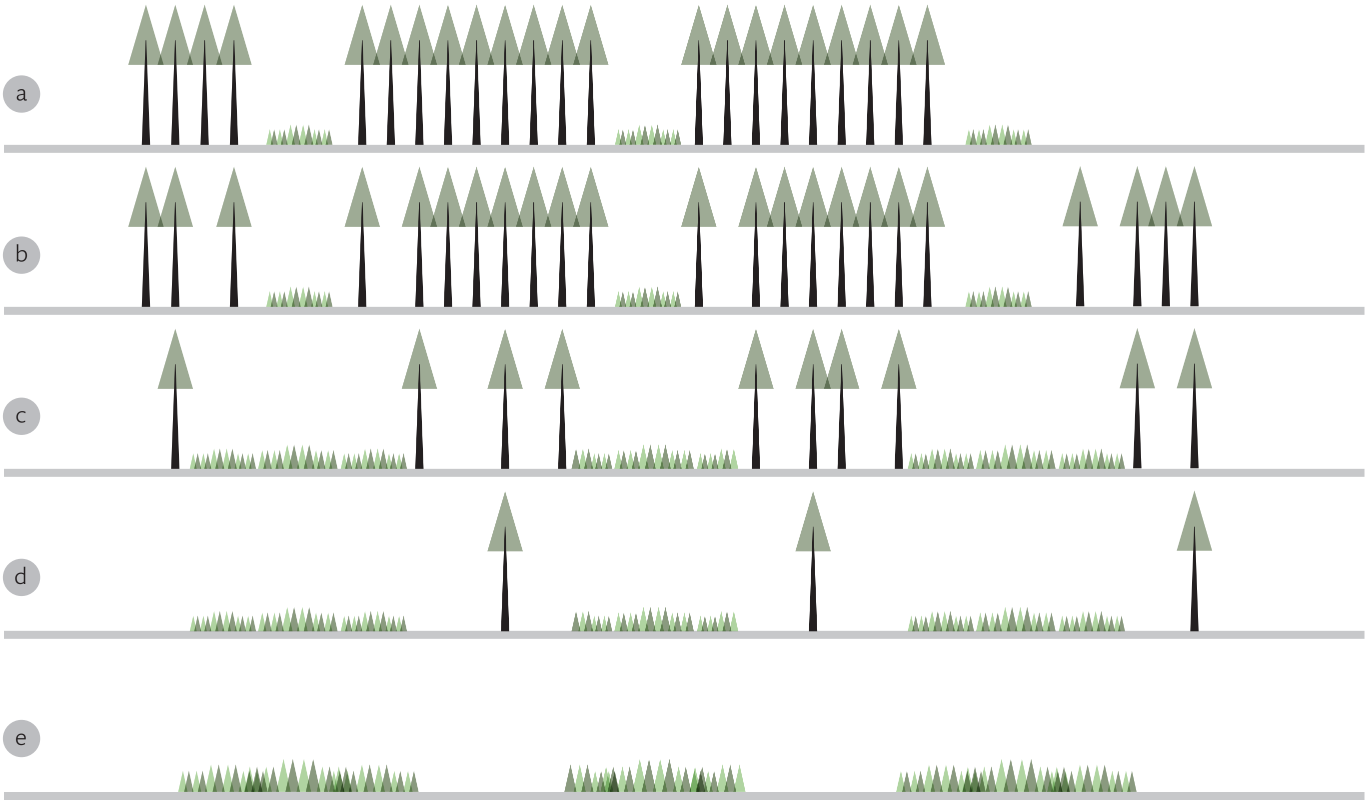


Figure 6.3 A uniform shelterwood of Scots pine in Strathspey, Highlands, Scotland. Photo: Edward Wilson

6.1.4 The group system

This system focuses on extending groups of advance regeneration through concentric series of seeding and regeneration fellings that extend outwards from the edges of original groups. If there are insufficient natural gaps and groups of advance regeneration across the stand, more are created. Eventually, the increasingly large groups join and the original overstory has been removed (Figure 6.4). The width of the fellings and the period between them can be used to influence the species composition of the natural regeneration. Wide fellings in rapid cycles favour light-demanding species while narrow fellings in long cycles promote more shade-bearing species. Although group shelterwoods result in a two-storied, even-aged structure, there is some variation in the newly regenerated stand and they can be used as a stepping stone towards achieving a more irregular future structure.

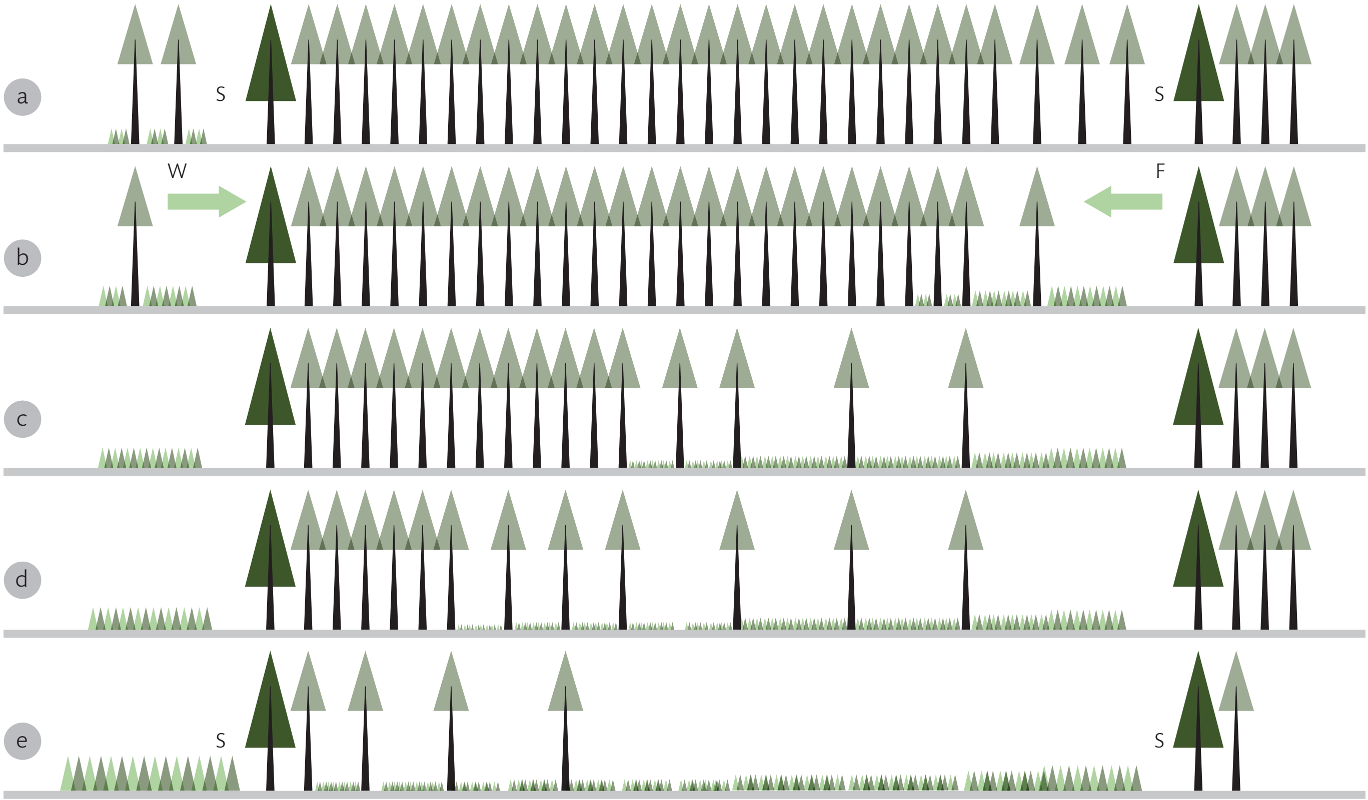
Figure 6.4 Group shelterwood system showing the stages of seeding felling to increase the groups of advance regeneration: (a) stand with small patches of advance regeneration; (b and c) regeneration fellings; (d) final removal of the canopy; and (e) the newly regenerated even-aged stand (Troup, 1928)



6.1.5 The strip system

The strip system involves seeding and regeneration fellings organised as narrow strip fellings within the canopy. In the Black Forest, Germany, these are about 20–30 m for the seeding felling and about 75 m for the seeding felling to final felling (Matthews, 1991). On sites where wind is a constraint, these strips progress in an opposite direction to the prevailing wind direction, leaving a wind-firm edge until the final part of the canopy is removed (Figure 6.5). Regeneration is often more rapid in the strip system than the uniform system due to the side light from the adjacent strip and large amounts of seed from the neighbouring area of intact canopy.

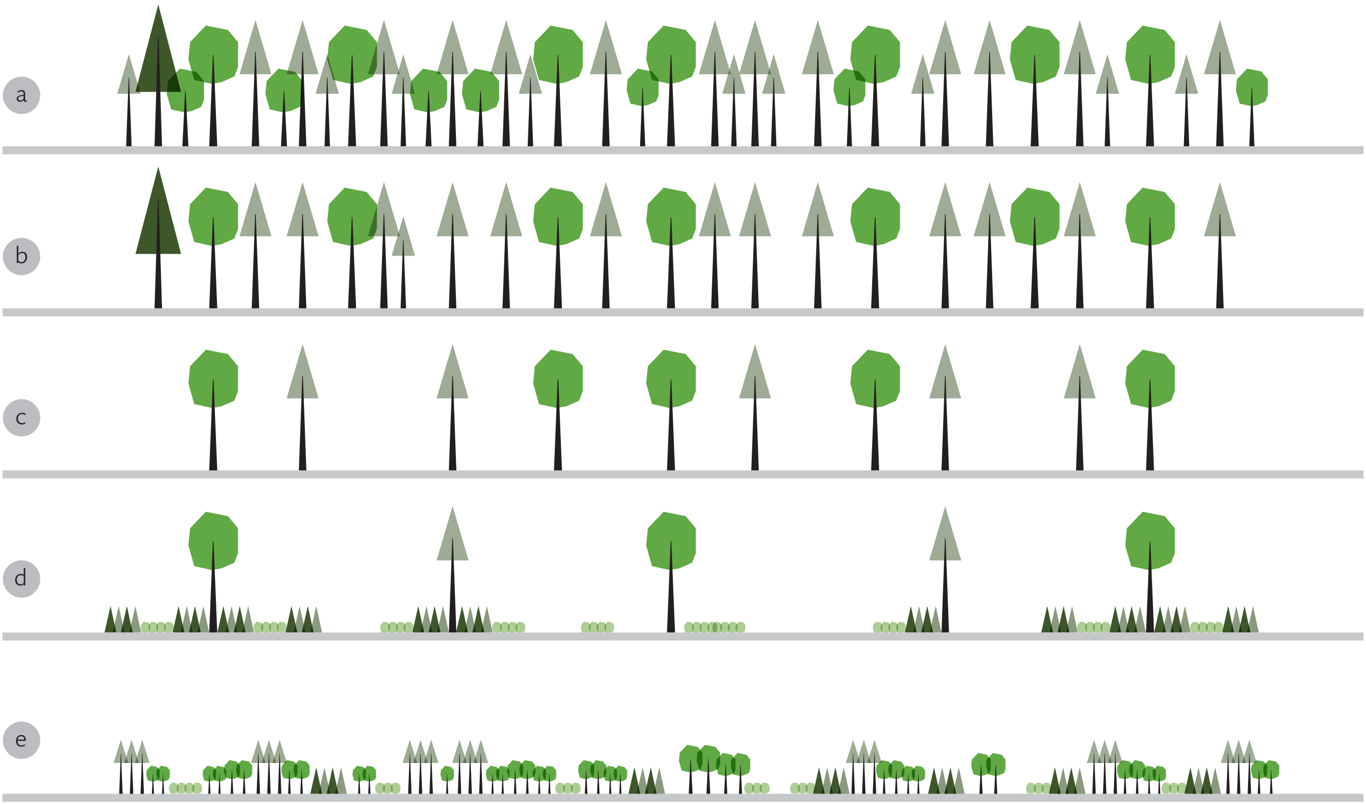
Figure 6.5 Strip system showing the stages of (a) seeding felling; (b–d) regeneration fellings; and (e) final removal of part of the canopy, with fellings (F) advancing in the opposite direction to the prevailing wind (W) towards a wind-firm edge of the strip (S) (Troup, 1928)



6.1.6 The irregular shelterwood

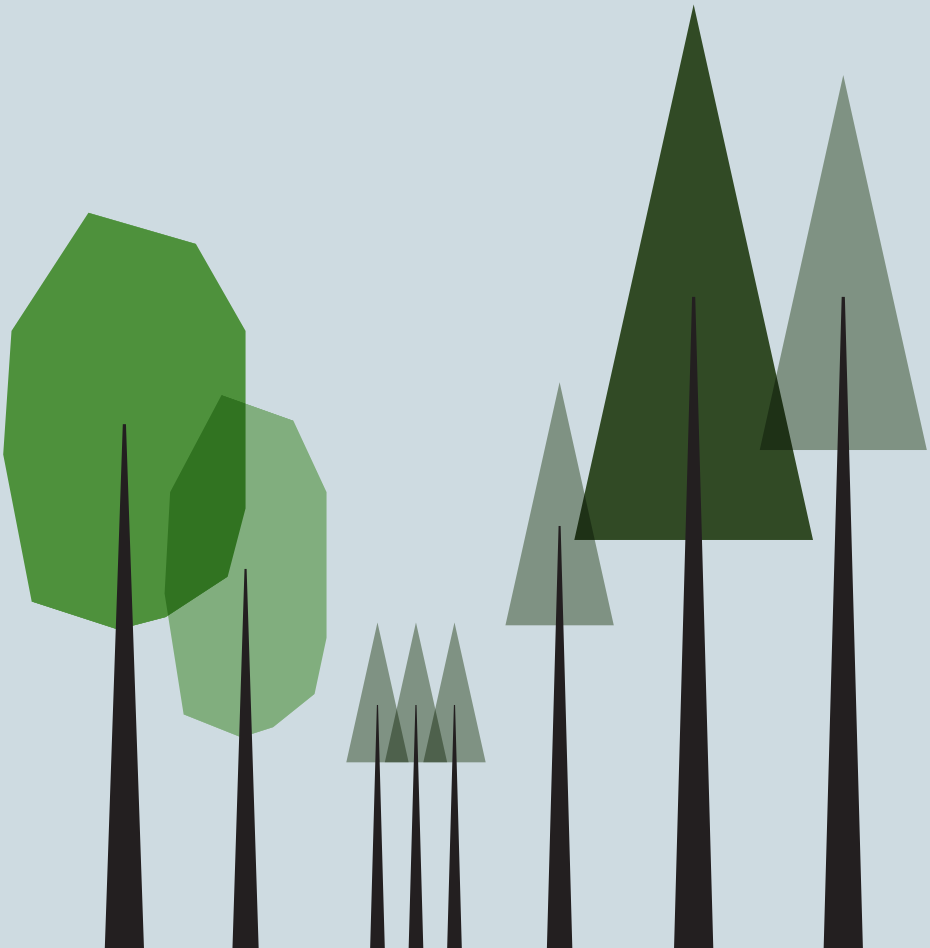
The irregular shelterwood is an approach that extends from a somewhat even-aged stand structure to an irregular structure. It has many variants; Raymond *et al.* (2009) describes three types commonly adopted in the USA. The approaches include those where the original canopy is entirely removed (as with other shelterwoods) but also variants where elements of the original canopy are retained past the rotation. A characteristic of all types is the extended period of >20% of rotation length, allowing the development of stands with a degree of irregularity. This long period of opening up the canopy favours the development of shade-bearing tree species. Troup (1928) notes that in the Black Forest, Germany, this system has been used to convert mixed-species stands to those of silver fir. An example, describing the Swiss Femelschlag system, is shown in Figure 6.6. In this variation of the irregular shelterwood the original canopy is completely removed and a somewhat even-aged canopy is developed. This flexible system can also be used to develop fully irregular stands.

Figure 6.6 Swiss Femelschlag system in a spruce, silver fir, and beech forest: (a) mixed-species stand of 40–60 years old, ready for regeneration to start; (b) seeding felling followed by; (c and d) successive regeneration fellings to create; (e) a young, somewhat irregular stand of up to 50 years old (Troup, 1928)



Chapter 7

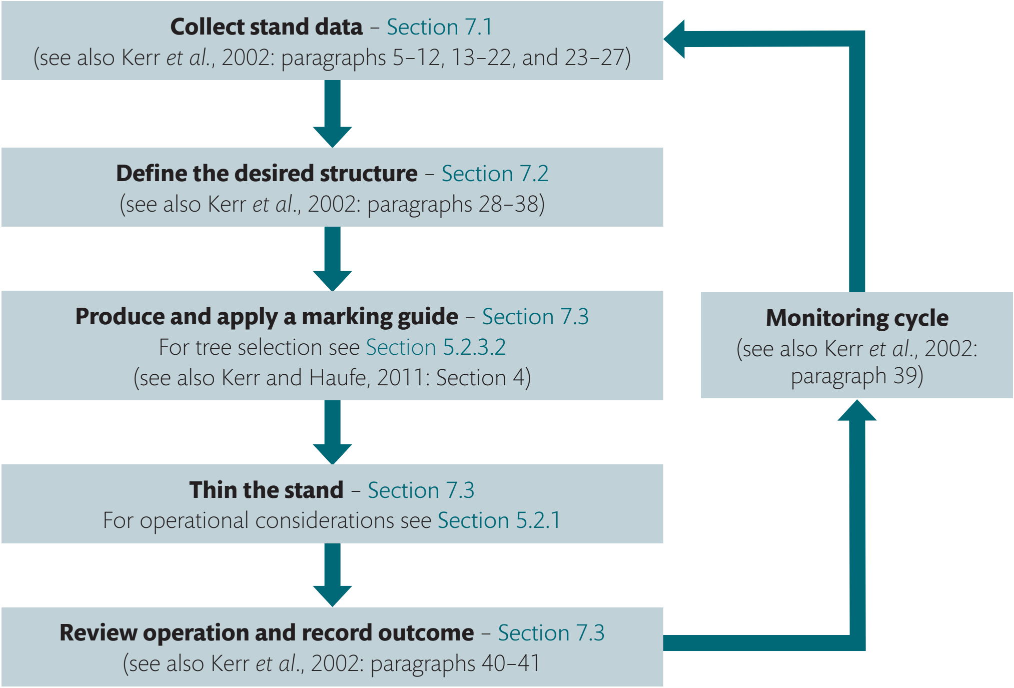
Management of irregular stands



7 Management of irregular stands

There are several stages in managing irregular (or complex) stands, as described in Figure 7.1. These stages provide a rational structure for operations. The information in this section complements that presented in Kerr *et al*. (2002) and Kerr and Haufe (2011) (see Additional resources: 21 and 17 respectively).

Figure 7.1 Stages in management of complex stands



7.1 Collect stand data

7.1.1 Stand inventory

Management of an irregular CCF stand involves regular thinning of trees across a range of diameter classes to:

- maintain a balanced diameter class distribution (negative exponential tree number–diameter distribution)
- regulate competition
- provide opportunities for regeneration
- harvest frame trees that have reached their target diameter.

A spreadsheet has been developed as a tool to compare the actual stand diameter distribution with an ideal distribution based on the BDq approach, where basal area, target diameter, and the q factor are entered. It also provides information needed for marking the trees for thinning (see Additional resources: 22).

7.1.1.1 Measuring stand characteristics

For even-aged stands (e.g. those managed under clearfell and shelterwoods), there are established methods for estimating basal area, volume, and productivity (Yield Class) (Matthews and Mackie, 2006). For irregular stands, there are two main aims of undertaking an inventory:

1. to assess the structure and composition of the stand to inform interventions
2. to estimate the basal area, volume, and quality of the trees in the stand.

The variation in tree size, species, and stocking density makes obtaining a precise assessment of characteristics of the stand more difficult than in even-aged stands. Sampling is more intensive; it can be achieved through random or systematic sampling and by using permanent fixed plots, temporary plots, and plotless (relascope) sampling (or a combination of these methods). Management of irregular stands during the early years needs no more information than for simple stands, but as an irregular stand develops, an increasing range of information is required, as shown in Table 7.1.

For late transformation, or to manage stands that already have an irregular structure, two main approaches to stand inventory are currently used in Great Britain. These are a method based on Forestry Commission Information Note 45 (Kerr *et al*., 2002) and an abbreviated form of a European method used by SelectFor and developed by the Irregular Silviculture Network in Europe. A further method that has been tested in Ireland is a 'VISUAL' assessment developed in France (Lejeune and Rondeaux, 2002), which relies on a degree of expertise in the assessor to assign trees visually (without dbh measurement) to different dbh classes, but which has the advantage of rapid assessment. A comparison of inventory methods used in Great Britain (excludes the VISUAL method) is presented in Table 7.2.

We recommend using the approach detailed in Forestry Commission Information Note 45 initially to provide useful baseline data for stand transformation and management. Another option is the SelectFor method, which has been tested across several European countries. Adopting their methods allows you to compare your stand information with many others in the Irregular Silviculture Network.

Table 7.1 Inventory data requirements and stage of stand development

Stand data collected	Stage of stand development		
	Initiation	Stem exclusion	Understorey reinitiation/all-sized
Number of trees	✓	✓	✓
Proportion of species	✓	✓	✓
Stand basal area		✓	✓
Stand volume		✓	✓
Height:diameter ratio		✓	✓
Relative crown ratio		✓	✓
Tree quality		✓	✓
Diameter class distribution			✓
Natural regeneration			✓
Method of inventory	Stocking density assessment – increased intensity (to account for greater variation in distribution across the stand)	Even-aged stand inventory (e.g. B6 plot method; Matthews and Mackie, 2006) and individual tree quality assessment when selectively thinning	More complex approaches to provide data on BDq and on quality of trees in the stand. Consider Forestry Commission Information Note 45 or the SelectFor method as potential approaches

Table 7.2 Comparison of two CCF inventory methods

Element of survey method	**Survey method**	
	Forestry Commission Information Note 45	**SelectFor**
Lifespan of plots	Permanent and/or temporary	Permanent
Number of plots	For areas of up to 5 ha, sample >60 trees using 25 plots. For areas above 5 ha, sample >75 trees using between 25 and 35 plots depending on area, using one extra plot for each additional 2 ha above 5 ha	Normally about 10 plots
Sampling method	Systematic	Systematic
Size of tree plots	Trees are stems >7 cm dbh. A circular plot of 0.01–0.05 ha depending on stand stocking density is used.	Normally about 15 trees (≥17.5 cm dbh) per plot. Trees included based on dbh and distance from plot centre.
Tree location within plots	Not recorded	Bearing and distance from the plot centre
Measurements for trees	Species, dbh (no assessment of stem quality)	Species, dbh, total height, height of mid-crown on stem, crown radii, quality class
Size of pole or sapling plots	Stems >1.3 m tall and <7 cm dbh. Where sapling or regeneration densities are high or low the plot area can be varied, but the same plot centre should be used as for the tree plot.	Circular plot of 10 m radius from plot centre. Stems between 7.5 cm and 17.5 cm dbh.
Measurements for poles or saplings	Species and whether small or large (small: <3 cm dbh; large: ≥3 cm and <7 cm dbh).	Species, dbh, total height, quality. Quality tree locations also recorded
Size, number, and location of regeneration plots	Uses sapling plot area.	Three circular plots located 10 m from plot centre at 0, 120, and 240 degrees north with 1.5 m radius.
Measurements for natural regeneration	Estimate of the number in the plot and also the number that have been browsed by deer.	• If regeneration <0.5 cm height, record percentage ground cover • Class 1 (between 0.5 m and 1.5 m height): species and height recorded • Class 2 (>1.5 m height, <2.5 cm dbh): species, height, and dbh recorded • Class 3 (>1.5 m height, ≥2.5 cm dbh): species, height, and dbh recorded
Other	Estimate of percentage cover of competitive vegetation within plot.	

7.2 Define the desired structure

To create an irregular stand that produces a consistent, sustained yield of timber, certain conditions should be met:

- The canopy must be opened up to enable growth and natural regeneration. This can be regulated by using stand basal area.
- An upper dbh limit is useful for each species. This ensures that the harvested trees are merchantable.
- A size class distribution that has many small trees leading to few large trees is needed to provide a 'production line' of timber. This is because mortality is much higher in small trees than larger trees.

The approach we suggest to managing irregular stands follows the BDq system. This requires defining three stand variables: the stand basal area (B), the target diameter (D), and the quotient of diminution (q). These are described in the following sections.

7.2.1 Setting a stand basal area

Basal area (B) is probably the most important stand variable to measure as it impacts regeneration, individual tree growth, and site occupancy. The appropriate stand basal area will vary by site productivity and the tree species that are being promoted. Richer sites provide more resources and so can support a higher level of biomass and hence a larger basal area. The light requirement of desirable species is also an important consideration, with natural regeneration of light-demanding species necessitating a more open canopy and lower basal area than shade-bearing species. Indicative basal areas are provided for a range of species in Table 3.7. While the overall basal area is a guide, in systems where gaps are made in the canopy, the area and orientation of the gaps are also important (Section 3.2.1.3 and Figure 3.6). If establishing and maintaining a mixed-species stand is the aim of management, the basal area should vary across the stand to provide light and other conditions suited to the varying light demands of different tree species.

7.2.2 Defining a target diameter

Frame trees provide the basic structure for an irregular stand but will need to be removed at some point to provide growing space for the development of younger cohorts of trees. A target diameter (D) is often used to define the time at which individual frame trees are harvested. This is dictated by the log size where the price per cubic metre has peaked, and differs by species. For example, large Douglas fir has high value niche markets, but most softwoods (including spruce) do not, with the price dropping in Great Britain for logs over 1 m^3 in volume or around 65 cm dbh (Forest Research, 2025).

For most broadleaves, the price paid per cubic metre normally increases with log volume up to about 3 m^3 when increases begin to level off (Forest Research and Grown in Britain, 2024). In northern Germany, broadleaves are generally felled when their dbh reaches between 60 cm and 80 cm (Pommerening, 2023), while for high quality stems a similar range of target diameter is applied to forests in France (Susse *et al*., 2011). For some species there may be other considerations that influence target diameter; for example, large cherry trees (>60 years old) tend to develop heart rot and so should be harvested before this age (Savill, 2019). However, in general, the poorer the quality of the tree, the earlier it should be removed. Additionally, some trees larger than the target diameter may be retained for non-timber benefits.

The larger the chosen target diameter, the smaller the maximum number of frame trees that can be accommodated. This number is also influenced by the light requirements of different tree species, but 50 trees per hectare should be a maximum for final frame trees (Kerr, 2008), with more selected if they are to be thinned in later interventions for stand transformation (see Section 5.2.3.2).

7.2.3 Defining the shape of the diameter class distribution

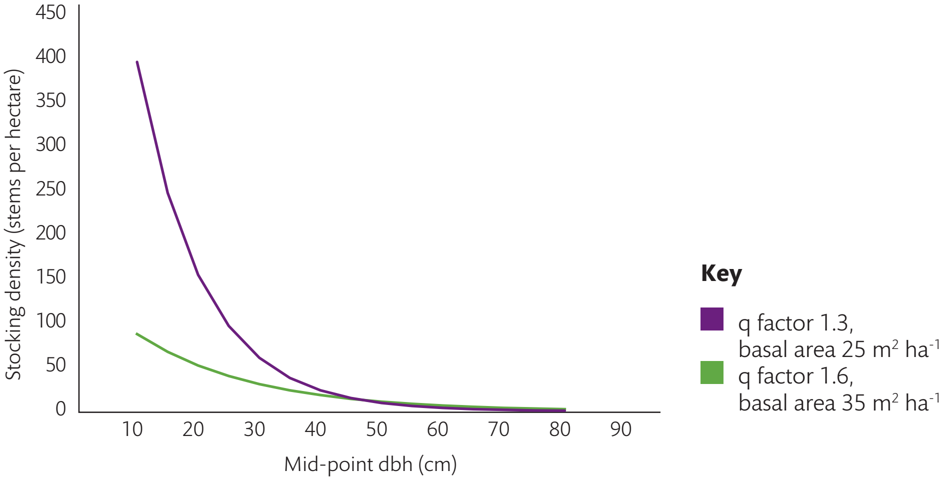
For a balanced, normal stand, the q factor (or quotient of diminution) describes the slope of the diameter class distribution, which is a negative exponential tree number–diameter distribution. The q factor is the ratio of the number of trees in a diameter class compared with the number in the next smallest diameter class. Table 7.3 illustrates the effect of q on the number of stems per hectare to support one tree in the 77–81.9 cm diameter class.

Table 7.3 Examples of tree stocking densities (stems per hectare) by diameter classes for three diameter distributions with a target diameter of 77–81.9 cm

Dbh (cm)	q=2	q=1.5	q=1.2
77–81.9	1.0	1.0	1.0
72–76.9	2.0	1.5	1.2
67–71.9	4.0	2.3	1.4
62–66.9	8.0	3.4	1.7
57–61.9	16.0	5.1	2.1
52–56.9	32.0	7.6	2.5
47–51.9	64.0	11.4	3.0
42–46.9	128.0	17.1	3.6
37–41.9	256.0	25.6	4.3
32–36.9	512.0	38.4	5.2
27–31.9	1024.0	57.7	6.2
22–26.9	2048.0	86.5	7.4
17–21.9	4096.0	129.7	8.9
12–16.9	8192.0	194.6	10.7
7–11.9	16 384.0	292.0	13.0

The larger the q factor, the steeper the slope of the curve and the greater number of small trees that are required to produce a specific number of large trees. This will reflect a species' ecology, while the position of the curve on the y-axis varies depending on stand basal area. The shape of the curve (or q factor) can be chosen to provide a desirable stand structure: a small q factor favours large diameter trees, and a larger q factor favours small diameter trees (Figure 7.2). These decisions can reflect local markets; for example, strong demand for small roundwood such as firewood would favour a low q factor, with more intensive thinning of smaller size classes.

Figure 7.2 Comparison of stand diameter class distributions with the same target diameter but different basal areas and q factors. Both stands have a target diameter of 80 cm.



In continental Europe, a minimum dbh of 8 cm is generally adopted as this means that the central dbh for each size class is a round number (e.g. for 8–12 cm dbh the central point in the range is 10 cm, for 13–17 cm it is 15 cm). A way of simplifying inventory is to use broader dbh classes. These need not be uniform and can be based on diameter thresholds for different markets. Broader size classes can also facilitate marking of trees for thinning.

7.3 Marking and thinning the stand

7.3.1 Creating a marking guide

To maintain the desired stand structure, trees across the range of sizes must be felled during thinning. The desired stand structure should be considered a guide, as there may be practical and other reasons for tree selection. For example, there may be a desire to promote one tree species to the detriment of another; there may be economic reasons for harvesting a smaller number of small trees; or leaving a greater proportion of large trees may be beneficial to seed supply and natural regeneration. Harvesting should not remove more than 20% of basal area on a wind-firm stand in any operation and should not go below the lower limit of the basal area for the desired species (Table 3.7). As described in Section 5.2.3.2, the focus of marking trees for removal should be on selecting and releasing frame trees and maintaining an underlayer in the canopy to improve form and supress branching while reducing the overall canopy density sufficiently to stimulate natural regeneration or maintain growth of underplanted trees.

The following guidance is based on that from Kerr and Haufe (2011). Figure 7.3 shows the stand dbh distribution from an inventory superimposed on the desired diameter class distribution. There is an excess of small and large trees in this example. Table 7.4 illustrates how a simple marking guide can be developed for a stand of 25 m^2 ha^{-1} basal area, a q factor of 1.2, and a target diameter of 75 cm.

Figure 7.3 The desired and actual dbh class distribution in a stand with target basal area of 25 m^2 ha^{-1}, a q factor of 1.2, and a target diameter of 75 cm

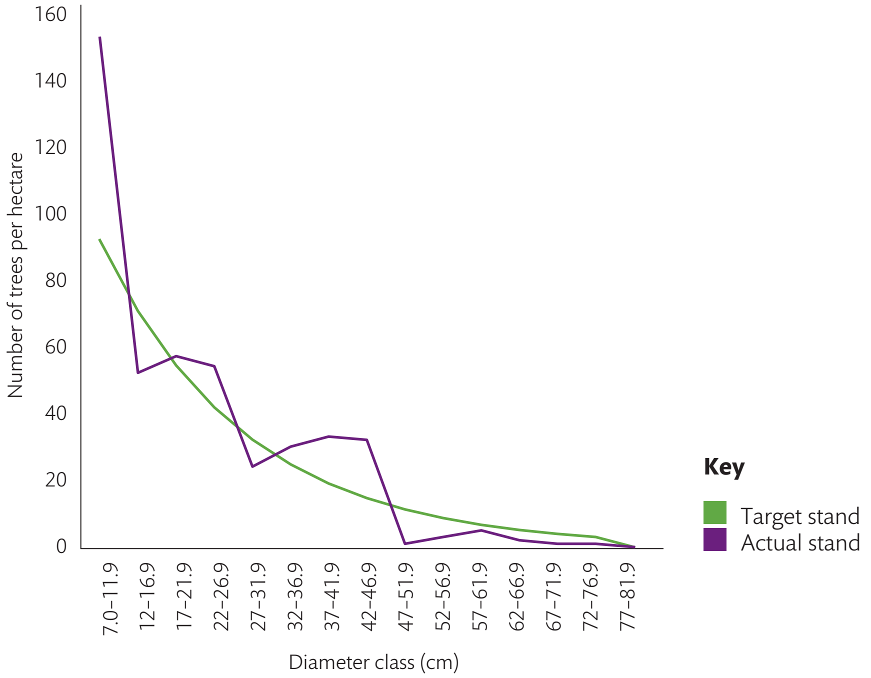


Table 7.4 Marking guide for the stand in Figure 7.3

Tree size	dbh class (cm)	Actual number of trees/ha	Target number of trees/ha	Difference	Marking guide	
Small	7–26.9	315	258	57	1 tree in	6
Medium	27–41.9	87	76	11	1 tree in	8
Large	42–56.9	36	34	2	1 tree in	24
Very large	>57	9	19	-10	1 tree in	N/A
		447	**387**	**60**		

The diameter class distribution and associated marking guide can be generated from the data collected in your inventory using a spreadsheet developed by Forest Research (see Additional resources: 22).

7.3.2 Monitoring cycle and data storage

Collection of stand data should be conducted before thinning and on a cycle of between five and ten years, depending on species and site productivity. There may, however, be good reasons for more frequent assessment of elements of the stand structure. Additionally, some stand elements may need more frequent monitoring than others. For example, where natural regeneration has proved difficult, a stocking density assessment of natural regeneration may be required to inform a decision as to whether to underplant.

Access to historic data is crucial to understanding the development of complex stands, and so developing a robust means of storing past monitoring data is crucial. The target structure (basal area, target diameter, and q factor) should be recorded with a rationale for choosing that structure. Photo-monitoring (taking photos across time from the same location) can augment the quantitative data obtained through stand inventory.

7.3.3 Predicting volume growth

Predicting volume growth in multi-species, uneven-aged stands is much more complicated and intensive than in even-aged monocultures. This is because stands of even-aged monocultures are much more uniform and so reliable estimates of volume can be obtained through relatively low intensity sampling. In Great Britain, there are currently yield models for a limited range of species and silvicultural treatments developed for production forecasting of even-aged monocultures. Even these can underestimate or overestimate volume by 20%, and so should be used at a forest, rather than stand level for production forecasting.

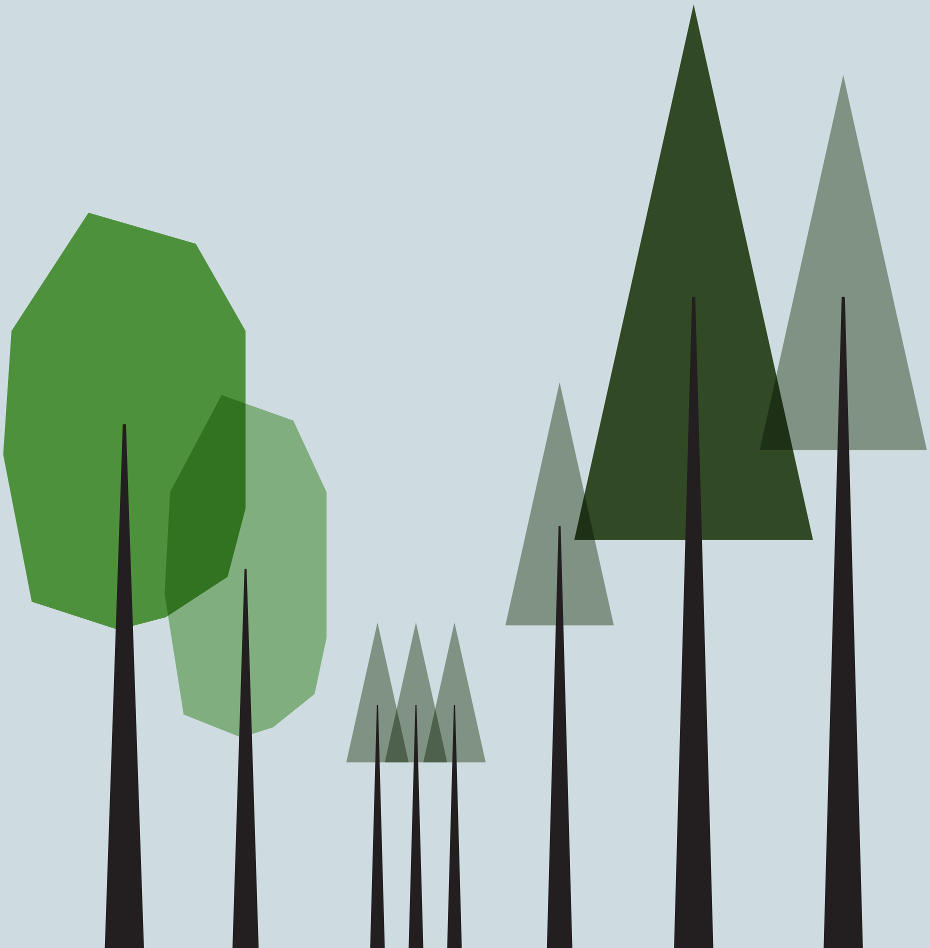
To obtain predictions of yield at a stand level in complex stands, a traditional approach is to use periodic enumeration of permanent plots of all merchantable trees in each dbh class. A stand table projection method can then be used to estimate volume yield. This has four elements:

1. Estimating diameter growth by species and diameter class
2. Predicting survival rates by species
3. Estimating ingrowth
4. Creating a local single-entry volume table (one that relates tree diameter to tree volume).

Publicly available, structured guidance on this approach is not yet available in Great Britain, but Deffee (2014) provides a worked example using the Association Futaie Irrégulière (AFI) abbreviated method of inventory and volume estimation.

Chapter 8

Conclusion



8 Conclusion

CCF offers an important approach to diversifying forest structure and species at a stand, forest, and landscape level and has potential to increase the contribution our forests make to producing quality timber, supporting biodiversity, and increasing carbon sequestration. There are a range of options within CCF, with systems that create both even-aged and irregular stands. Whichever approach is adopted, there are some basic considerations when managing stands under CCF:

1. Thin regularly, and start early.
2. Keep deer and other damaging mammal numbers low to protect regeneration.
3. Focus most attention on releasing and tending quality stems.
4. Remember that a level of unforeseen stand disturbance is inevitable.

There is a growing body of knowledge and experience of CCF in Great Britain, and there is much experience that we can draw upon from continental Europe. Ultimately, the success of CCF rests upon careful site and stand selection, an understanding of the ecology of the desirable tree species, selecting an approach that meets management objectives, and developing an appropriate monitoring and management framework.

9 Additional resources

1. Haufe *et al*. (2024) Forest Development Types: diversification of existing forests
2. Continuous Cover Forestry Group (2022) 30 years of applying CCF in Perthshire [video]
3. Forestry Commission (2015) Thinning control
4. Armstrong *et al*. (2003) Protecting trees from deer: an overview of current knowledge and future work
5. Potter (1991) Treeshelters
6. Kerr and Haufe (2016) Successful underplanting
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10. Kerr *et al*. (2020) Establishing robust species mixtures [spreadsheet]
11. Willoughby *et al*. (2004) Creating new broadleaved woodland by direct seeding
12. Mason and Kerr (2004) Transforming even-aged conifer stands to continuous cover management
13. Kennedy (2023) The identification of soils for forest management
14. Forest Research ForestGALES: webpage and user manual
15. Pyatt, Ray, and Fletcher (2001) An ecological site classification for forestry in Great Britain (see p. 26 for more information on using indicator plants to categorise the soil fertility and moisture status)
16. Continuous Cover Forestry Group (2021) Applying CCF on steep ground and with big trees [video]
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18. Price *et al*. (2017) Assessing the stem straightness of trees
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20. Ireland (2009) CCF operational best practice: final overstorey removal in uniform shelterwood
21. Kerr *et al*. (2002) Monitoring the transformation of even-aged stands to continuous cover management
22. Kerr (2022) A spreadsheet for calculating a target diameter distribution to guide management of uneven-aged stands

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Appendix 1: Planting a CCF stand – Pro Silva Ireland

Figures A2.1 to A2.4 illustrate the recommended approach to establishing CCF stands adopted by Pro Silva Ireland (2024).

Figure A2.1 Planting pattern of a mixed stand for CCF at age 4 years (Pro Silva Ireland, 2024).

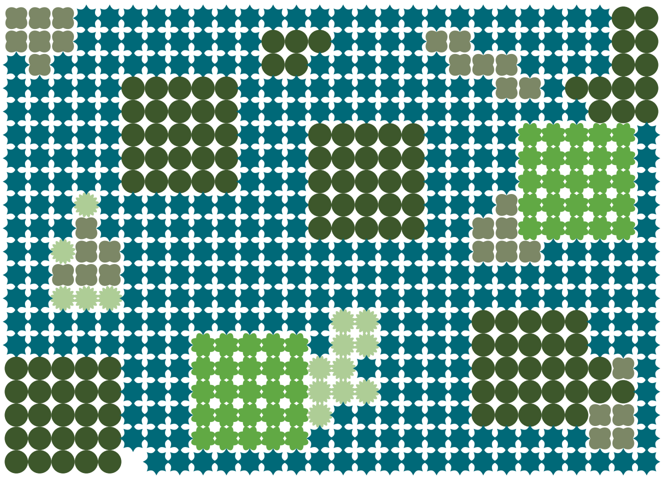


Figure A2.3 Layout of a mixed stand for CCF at age 45 years. Sitka spruce sawlogs have been harvested, with some retained for seed source and habitat value. Increasing irregularity in growing space and growth rate has been achieved. Pockets of regeneration have appeared. (Pro Silva Ireland, 2024)

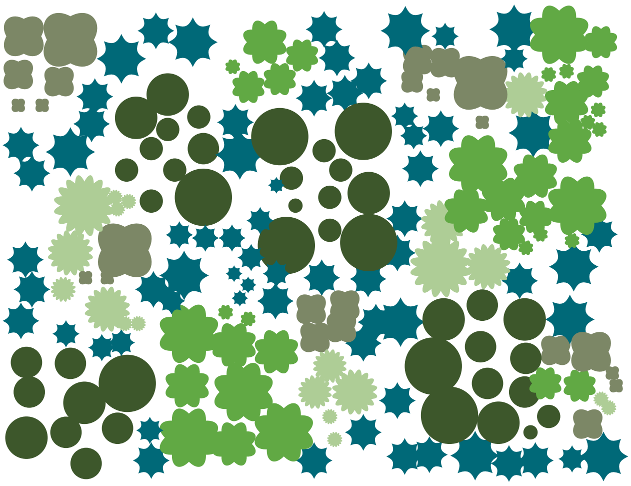


Figure A2.2 Layout of a mixed stand for CCF at age 20 years. The first thinning has been completed with removal of wolf trees when stand stability allows and one or two competitors to quality trees. Some irregularity in growing space and growth rate has been achieved (Pro Silva Ireland, 2024).

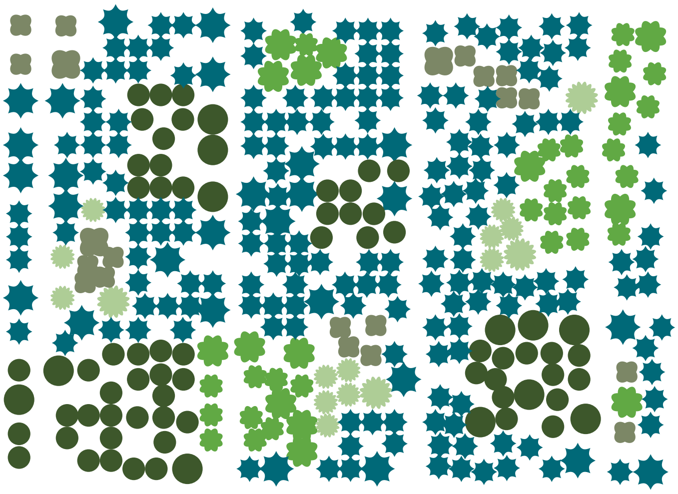
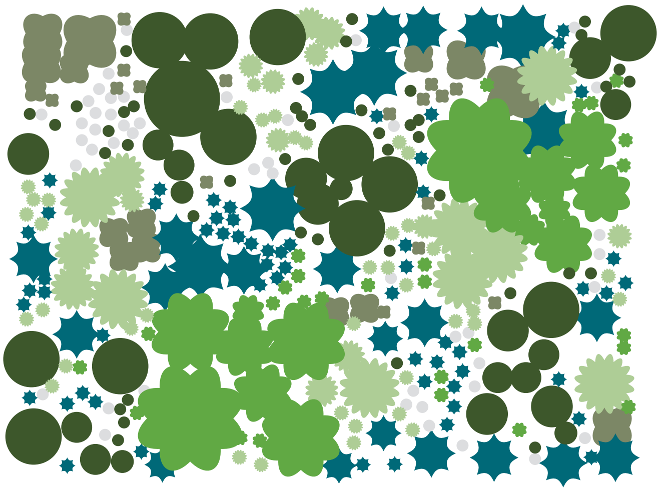


Figure A2.4 Layout of a mixed stand for CCF at age 75 years. Douglas fir sawlogs have been harvested, ongoing harvesting of trees of other species Sitka spruce and birch dominate the regeneration but other species also represented. Dense regeneration may require respacing (Pro Silva Ireland, 2024).



Key

✷ Sitka spruce
● Douglas fir
✿ Pedunculate oak
✺ Birch
✤ Additional broadleaves

Glossary

Basal area	Usually expressed in square metres per hectare (m^2 ha^{-1}), it is the sum of the cross-sectional areas of the stems of a stand measured at 1.3 m above the ground (known as breast height)
Continuous cover forestry (CCF)	An approach to forest management in which a significant proportion of the forest canopy is maintained at one or more levels without clearfelling
Irregular (or complex) CCF structure	A forest in which there are three or more canopy layers
Cohort	A group of trees of the same or similar age
Diameter at breast height (dbh)	The diameter of the stem of a tree measured at 1.3 m above ground level (see Matthews and Mackie, 2006 for conventions)
Final Crop tree	A tree selected to grow to final harvest which is selected for vigour, species, size, timber potential, or conservation value
Frame tree	A final crop tree in a complex CCF structure
Intermediate species	A species that can regenerate under a light canopy or in very small gaps (0.05 ha) and requires the canopy to be opened up relatively rapidly to ensure good seedling growth
Light-demanding species	A species that produces seedlings that can only survive and grow in the open or under a very sparse canopy or in large gaps (>0.25 ha). Also referred to as shade intolerant
Seed tree	A final crop tree in a simple CCF structure
Even-aged (or simple) CCF structure	A forest in which there are one or two canopy layers
Shade-tolerant species	A species that produces seedlings that can survive and grow under a dense canopy of a mature stand or in very small gaps (0.05 ha)
Target diameter	A desired maximum diameter for timber trees in a complex CCF structure, determined by market demand
Threshold basal area	In CCF, threshold basal area is used to determine if the stand canopy is sufficiently open to allow germination and then survival and growth of natural regeneration of desired species
Transformation	The process of increasing within-stand structural diversity in even-aged forests

This guidance aims to support the transformation and management of stands under continuous cover forestry (CCF). There are many challenges to adopting a CCF approach and it is essential that you encourage stand stability through thinning, keep deer populations low to encourage regeneration, focus on promoting quality trees, and accept there will be some unforeseen disturbance. It is important before managing a stand under CCF to assess its suitability.

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