Transformation to continuous cover forestry: a review

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Abstract

Continuous cover forestry (CCF) is an approach to forest management that is gaining increasing attention. Although not a new concept, a number of developments have prompted a renewed consideration of this approach. These have centred on societal concerns about the negative impacts of clearfelling as well as broader societal expectations of multi-purpose management of forests. With renewed interest in CCF, the process of transforming even-aged stands that are currently managed under the clear-cut system to CCF has begun in a number of countries.

The objective of this paper is to present a review of the scientific literature on transformation to CCF. The review is organised according to a series of questions that address the issue of transformation; i.e. where and when is it appropriate to consider transformation; how long does the transformation process take; and what are the drivers to transformation. The review concludes with a brief overview of existing long-term transformation trials in the UK.

The review of the literature identified that there was a limited number of papers on the topic of transformation and most of these emanated from the UK and Central Europe. For this reason the review was expanded to include literature on the starting point and end result of transformation which is typically (although not exclusively) an even-aged (regular) structure and an uneven-aged (irregular) structure respectively. The most common themes in the transformation literature concerned the structure of stands being transformed and the initial stages of the transformation process.

Keywords: *Silvicultural systems, stand structure, economics, stability, biodiversity, climate change.*

Introduction

Continuous cover forestry (CCF) is not a silvicultural system in itself (Yorke 1998). Instead it involves the use of silvicultural systems whereby the forest canopy is maintained at one or more levels without clearfelling (Forestry Commission 1998). More restrictive definitions of CCF are often used. Von Gadow (2001, p. 2) for example indicates that CCF is "the use of systems that are characterized by selective harvesting; the stand age is undefined and forest development does not follow a cyclic harvest-and-regeneration pattern".

The current consideration of CCF continues the debate which emerged at the end of the 19th century in Central Europe about the relative merits of regular and irregular silviculture (Mason et al. 1999). At that time Europe had just gone through a period of industrialisation and population growth. Demand for timber increased

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and unregulated selection fellings led to the overuse and uncontrolled exploitation of forests (Pommerening and Murphy 2004, Schütz et al. 2012). In response, a very rigid approach to silviculture and management evolved (Matthews 1989). Even-aged plantations, often of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.), were established and managed under the clear-cut system throughout Europe with the aim of quickly restoring forest cover (Hanewinkel 2009) and ensuring that large quantities of wood were produced (Schütz et al. 2012). However, it was not long before these plantation forests began to suffer wind damage (Hanewinkel 2009) prompting some European foresters to move towards "more flexible methods of silviculture and management" and towards more irregular forms of forest stands (Matthews 1989, p. 11). The term "continuous forest" (*Dauerwald*) was introduced by a German forester, Möller, at the beginning of the 20th century (Möller 1922) with the principles of avoiding clearfelling to maintain forest conditions and of abandoning the concepts of age-class and rotation (Helliwell 1997). For the first half of the 20th century Swiss foresters attempted to implement the selection system in almost all forests (Schütz 1999). However, the clear-cut system continued to be widely used throughout Germany and France as forest authorities resisted the use of the selection system fearing it would lead to uncontrolled exploitation similar to that witnessed previously (O'Hara et al. 2007).

The use of the clear-cut system was widespread in Europe throughout much of the 20th century, with an associated decline in interest in CCF (Pommerening and Murphy 2004). However, in the 1980s and 1990s alternative silvicultural systems to clearfell attracted renewed consideration. There were a number of drivers that emerged concurrently at international level to stimulate this interest. First, there were societal concerns about clearfelling which focussed on the negative visual impacts (Mason 2007). There was increasing acceptance of the multi-functional forest paradigm and a belief that alternative approaches to clearfell would be better able to deliver on this forestry model (Mason et al. 1999). Following the UNCED Summit in Rio in 1992, one of the aims of forest policies worldwide was to increase the structural and species diversity of forests and CCF was considered a means of achieving greater diversity (Mason 2007). The societal concerns about clearfelling and the changing expectations of the functions of forests coincided with a decline in the health of second and third generation Norway spruce stands in Central Europe (Hasenauer 2004). The continued instability of these stands was highlighted when they suffered extensive wind damage during a number of catastrophic wind storms (Kenk and Guehne 2001). A strategy was adopted to convert these pure conifer plantations to mixed stands. This process also involved a change in the stand structure from regular, even-aged to more irregular, uneven-aged (aka "transformation") (Hanewinkel 2001) with a "heavy emphasis on continuous high forest cover and rich structural diversity" (von Lüpke et al. 2004, p.123). Thus, within Europe CCF began to be considered as a suitable approach to forest management. In Ireland, interest in CCF has also developed and the reasons for this and an overview of the current situation regarding the practice of CCF in Ireland are outlined in detail in Vítková et al. (2013; this issue).

Silvicultural systems that deliver CCF

There are a number of high forest silvicultural systems that can be used to implement CCF including the shelterwood systems (uniform, group, strip and irregular), and the selection systems (group and single-tree) (Figure 1). These systems generally rely on natural regeneration, although planting is used where a different provenance or species is required.

The key difference between all the aforementioned systems and the clear-cutting system is that in the latter, entire coupes are felled and usually regenerated artificially, while some element of canopy cover is retained in the other systems. In shelterwood systems the old stand is removed in a series of regeneration fellings, while in selection systems single trees (or small groups) are removed throughout the forest (Smith et al. 1997). Forests managed under the selection system are often referred to as *Plenterwald* forests.

Categorising high forest silvicultural systems as shelterwood and selection systems as outlined above is quite common. However, another approach relates to the resultant forest structure, i.e. even-aged silvicultural systems versus uneven-aged systems. Often CCF is associated with uneven-aged silviculture; however, the more inclusive definition of CCF used by the Forestry Commission in Great Britain means that even-aged stands that are produced using the uniform shelterwood system, for example, would also be considered CCF. The term irregular silviculture/silvicultural system is also used as a synonym for uneven-aged silviculture, with Helliwell and Wilson (2012) describing both as leading to forests

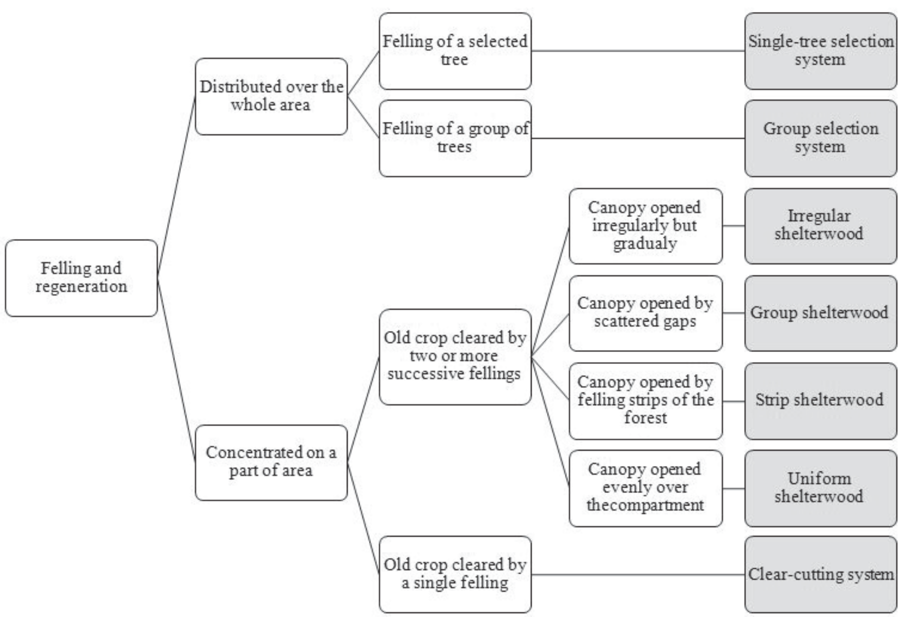

Figure 1: *A classification of high forest silvicultural systems adapted from Matthews (1989).*

with at least three size classes intimately mixed. The systems also vary according to the degree of canopy influence with the clear-cutting system having the least, the shelterwood systems providing canopy protection during establishment and early growth of seedlings, while the selection systems are characterised by the dominance of canopy influence throughout the life of the stand (Coates and Burton 1997). Coates and Burton (1997) further suggest that silvicultural systems can be classified into two groups based on the distribution of canopy trees after harvest; the first group includes systems where canopy trees are evenly distributed after harvest (i.e. uniform shelterwood, single-tree selection); the second group create gaps in the tree canopy (i.e. group, irregular and strip shelterwood and group selection). They argue that the measurements of gap size and gap dispersion are means of describing any silvicultural system along a continuum. O'Hara et al. (1994) further support the view that silvicultural systems can be viewed as structural gradients from clear-cut to single tree selection system.

In the context of the renewed interest in CCF and in transforming even-aged stands, it is timely to examine the research that has been conducted on the topic of transformation. Hence the objective of this paper is to present a review of the scientific literature on transformation to CCF. The literature review is organised into sub-sections addressing some key questions relating to transformation, i.e. where and when it is appropriate to consider transformation; how long the transformation process may take; and the reasons as to why forest owners opt to transform their stands. A review of some existing long-term transformation trials is also presented. The approach used to gather information for the review is also described.

Methods

To identify relevant papers for this review, Google Scholar, Scopus and EBSCO Host Premier Search were used to search for original studies in peer-reviewed journals. Books, newsletters, research reports and research information notes relevant to the topic were also included in the review. The search was conducted using primary keywords (Table 1) and their combinations. In addition, the combinations of individual primary keywords and individual secondary keywords (Table 1) were used.

Transformation to continuous cover forestry

What is transformation?

Transformation describes the process of changing an even-aged stand, typically managed under the clear-cut system to CCF management. It involves the gradual change of forest structure (Pommerening 2006), typically from one that is very simple and homogenous to one that is highly variable and with many complex interactions (O'Hara 2001). Mason and Kerr (2004) allow for the possibility that the outcome of transformation may be a simple structure with only one or two canopy layers. Occasionally the term conversion is used interchangeably with transformation (e.g. Hale et al. 2004); however, conversion can involve a rapid

Table 1: *A list of primary and secondary keywords used when searching for papers for the current literature review.*

Primary keywords	Secondary keywords
Continuous cover forestry	History
Transformation	Wind
Uneven-aged silviculture/forests/structure	Stability
Irregular silviculture/forests/structure	Biodiversity
Alternatives to clearfell/clear-cutting/clear-cut	Recreation
Near-nature forestry	Economics
Close-to-nature forestry	Climate change
Selection system	
Group selection system	
Group shelterwood	
Uniform shelterwood	
Irregular shelterwood	
Strip shelterwood	
Plenterwald	
Clearfelling	
Silvicultural systems	

change in forest structure (von Lüpke et al. 2004); hence transformation is considered a special form of conversion (Hasenauer 2004).

Oliver and Larson (1996) defined stages of stand development that are often used as a model of how a "natural even-aged" stand might naturally transform (O'Hara 2001) to a more irregular (multi-cohort) structure over time:

- Stand initiation – after a disturbance, new individuals of a species continue to appear for several years.
- Stem exclusion – after several years, new individuals do not appear and some of the existing ones die. The surviving ones grow larger and differ in height and diameter; first one species and then another may appear to dominate the stand.
- Understory re-initiation – later, forest floor herbs and shrubs and advanced regeneration again appear and survive in the understory, although they grow very little.
- Old growth stage – much later, overstory trees die in an irregular fashion, and some of the understory trees begin growing into the overstory.

In natural even-aged stands, the understory re-initiation phase may emerge as tree mortality in the overstory provides the growing space for a new cohort to develop through natural regeneration (O'Hara 2001). Transformation can therefore be described as an acceleration of natural development (such as that outlined above) to achieve the desired forest structure (Malcolm et al. 2001).

Where is transformation appropriate?

In outlining where transformation is appropriate it is important to take into account location as well as site factors. Yorke (1998) identified locations where CCF (and hence transformation) is desirable as those:

- with high landscape value;
- used for recreation purposes;
- in close proximity to towns;
- with environmental protection designations;
- where restocking after clearfell would prove uneconomic.

The size of the stand should not be a limiting factor as studies in Europe have shown that transformation can be applied on a large scale as well as on properties only a few hectares in size (Schütz 2001). Nevertheless, it is generally agreed that applying transformation is only possible in areas with suitable conditions for the desired management including:

- an overstory of the desired species and genetic quality (Mason and Kerr 2004);
- the presence of natural regeneration of a desired species (Yorke 1998, Malcolm et al. 2001, Mason and Kerr 2004);
- suitable light conditions at ground level (Malcolm et al. 2001);
- absence of competing vegetation to the natural regeneration (Yorke 1998, Mason and Kerr 2004);
- absence of browsing of advance regeneration and of seeds and cones (Mason and Kerr 2004);
- low to moderate windthrow hazard (Yorke 1998, Mason and Kerr 2004).

When is it appropriate to transform?

Transformation that is initiated early is most likely to be successful since tree stability declines as an even-aged stand develops at a high density (Cremer et al. 1982). Stability is a key issue as the transformation process will inevitably open up the stand and release individual stems, thereby increasing the risk of windthrow. For this reason Hale et al. (2004) recommend that transformation be initiated at pole stage. Starting transformation in older stands depends on the features of the given stand, i.e. thinning history, soil type and the rooting depth (Mason and Kerr 2004); however, on exposed sites the risk of windthrow may be so great in these stands that it may not be practical to transform them (Hale et al. 2004).

Adequate natural regeneration is the main requirement to ensure successful transformation once stand stability has been achieved (Schütz 2001). The age when the stand begins to produce good quantities of seed is therefore of great relevance to the process (Malcolm et al. 2001). Although some tree species such as Scots pine, lodgepole pine (*Pinus contorta* Doug.) and European larch (*Larix decidua* Mill.) start bearing seeds early, the best seed crops are unlikely to be produced until about 10–20 years later (Savill 2013) (Table 2). However, enrichment planting may be used if the stand is too young or a different species is desired (Matthews 1989).

Suitable light levels are required for successful natural regeneration and for the successful progress of transformation. Hale (2004) identified the understory light

Table 2: *Earliest and best age for seed bearing for major commercial species, adapted from Savill (2013).*

Species	**Earliest age for seed bearing (years)**	**Best age for seed bearing (years)**
Scots pine	10–20	>60
Lodgepole pine	10–20	30–40
Norway spruce	30–35	50–60
Sitka spruce (*Picea sitchensis* (Bong.) Carr.)	30–40	>50
European silver fir (*Abies alba* Mill.)	25–30	40–60
Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)	30–35	50–60
Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)	20–30	40–60
European larch	20–30	40–60
Oak (*Quercus* spp.)	40–50	>80
Sycamore (*Acer pseudoplatanus* L.)	25–30	40–60
European beech (*Fagus sylvatica* L.)	50–60	>80
Ash (*Fraxinus excelsior* L.)	25–30	40–60

and associated stand basal area values required for successful seedling regeneration and growth of some commercial conifer species:

- light demanding: larch (>40% light[1], ~20 $m^2\ ha^{-1}$) and Scots pine (35% light, ~25 $m^2\ ha^{-1}$);
- intermediate: Sitka spruce (20% light, ~30 $m^2\ ha^{-1}$) Douglas-fir (15% light, ~35 $m^2\ ha^{-1}$);
- shade tolerant: western hemlock (10% light, ~40 $m^2\ ha^{-1}$).

The importance of thinning in the transformation process

O'Hara (2001) proposed that the first step in the transformation process should mimic the understory re-initiation phase of Oliver and Larson's (1996) model of stand development, shown earlier, by promoting a new cohort of trees. However, in windy climates, transformation will have to start earlier with the aim of promoting stability in the stand. Thinning regimes are therefore key elements in the transformation process (Schütz 1997; cited in Mason 2002) and in stands being transformed thinnings should start earlier and be heavier than normal (Mason and Kerr 2004). This will promote crown (essential for future seed production) and root development along with greater diameter increment, the combination of which should increase stability. Heavier thinning will also be required to ensure that the critical values of stand basal area necessary for successful regeneration to occur.

Low thinning (thinning from below) is commonly used in coniferous plantations and it involves the removal of most of the subdominant and suppressed trees. However, it is expected that there will be an increased use of crown thinning

[1] Percentage of incident light transmitted through the canopy.

(thinning from above) in stands being transformed to and/or managed under CCF (Mason and Kerr 2004). Crown thinning favours the early selection of better quality trees, i.e. frame trees (sometimes referred to as final crop trees, target trees, Z-trees, future trees or elite trees), by removing competing stems thereby encouraging growth of the selected trees (Cameron 2002). Frame trees are selected on the basis of the following desirable properties: straight stem, light branching, good vigour, no visible damage or defects and healthy foliage. During the thinning operation, one to three of their competitors are removed. The number of frame trees per hectare is determined by the final size of the trees. Davies et al. (2008) provide a guide to the number of frame trees according to species and the target diameter. They indicate that for a target diameter of 60 cm, the number of frame trees varies from 68 for ash to 247 for western red cedar (*Thuja plicata* Don ex D.Don). In general, it is recommended that frame trees are pruned to increase their quality and secure better financial return. The remaining trees in the forest (non-frame trees) are sometimes referred to as "matrix trees" that are meant to support the frame trees.

Graduated density thinning (GDT) is a thinning pattern currently being used in the process of transforming young stands to CCF management in a number of private forests in Wales and Ireland. It was developed by a Latvian-born forester, Tallis Kalnars, and applied by him in a number of woodland estates in Wales that were undergoing a transformation process in the 1980s. During the first thinning, the racks are cut in every eighth row and 40% of trees from the row immediately adjacent to the rack are removed. In the second row from the rack, 20% of the trees are removed and 10% of the trees are removed from the third row (Figure 2a). The fourth row, which is situated half way between the racks, remains intact (Davies 2009). This unthinned centre row is considered to be a stabiliser row acting as a risk management tool mitigating the risk of windblow (Morgan pers comm). Selection of

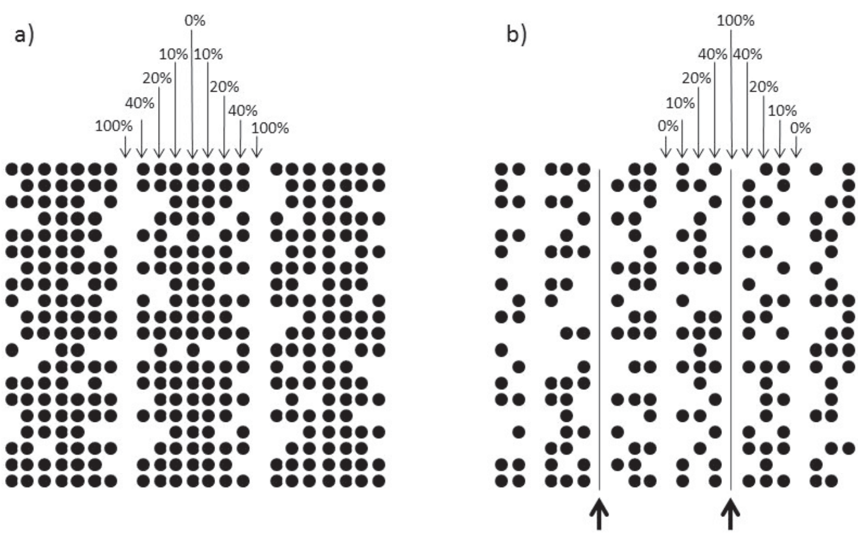

Figure 2: a) *a pattern of graduated density thinning during the first intervention; b) a pattern of graduated density thinning during the second intervention.*

the trees to be removed is based on quality. In the next thinning, the intact rows are removed to make new racks, the previous racks abandoned, with further selective thinning taking place on either side of the new rack according to the given intensity (Figure 2b). The permanent racks are chosen during the third thinning intervention. The number of interventions that follow the pattern outlined varies according to the site and stand. Typically crown thinning or target diameter thinning follows. The proponents of the system claim that it leads to a more stable stand and one that is structurally diverse. As it also involves a systematic removal in both the first and second thinning it is considered to provide higher early thinning returns than conventional thinning (Morgan pers. comm.). The validity of these claims is currently being tested in a thinning experiment set up in 2010 in two Sitka spruce stands in Ireland, which is expected to provide meaningful results in the near future.

Graduated density thinning should not be confused with variable density thinning (VDT), another thinning pattern that has a tradition of use in uneven-aged forests in Central Europe (e.g. Schütz 2001; cited in Pukkala et al. 2011). It involves thinning a forest at different intensities in patches of approximately 0.1 to 0.5 ha (Ibid.). This leads to greater structural heterogeneity in the forests (Aukema and Carey 2008).

An important silvicultural tool that is frequently used during the process of transformation to CCF is target diameter harvesting. This may follow a number of thinning interventions. It involves the removal of stems that have reached a certain minimum (target) diameter (Tarp et al. 2005). By removing these larger trees, the smaller trees are released from competition and are given more growing space. Sterba and Zingg (2001) used target diameter harvesting in the conversion of a Norway spruce stand in Austria and found that the smaller trees reacted well to the crown release and made efficient use of the stand area gained. This practice diversifies the tree sizes throughout the forest stands and improves stability, which are important aspects when CCF management is applied.

When is transformation complete?

The transformation process is relatively new, particularly in the UK and Ireland. Forest managers in these countries will therefore need guidance as to how to identify when transformation is complete and how to manage the transformed stand in the long term. The desired output of many (although not all) transformation processes is an irregular stand structure. Cameron and Hands (2010) outline four basic characteristics describing the 'balanced state' of an irregular stand:

- the shape of the diameter distribution should follow an approximate negative exponential relationship (reverse-J curve) (see Figure 3);
- the stand increment should remain more or less the same from one harvesting intervention to the next (Meyer 1952);
- the relative consistency of stocking density and basal area between harvesting interventions;
- the requirement for sufficient natural regeneration of the appropriate species (Sterba 2004) and for adequate recruitment of saplings into the smallest measurable diameter classes to maintain the diameter distribution (Meyer 1952).

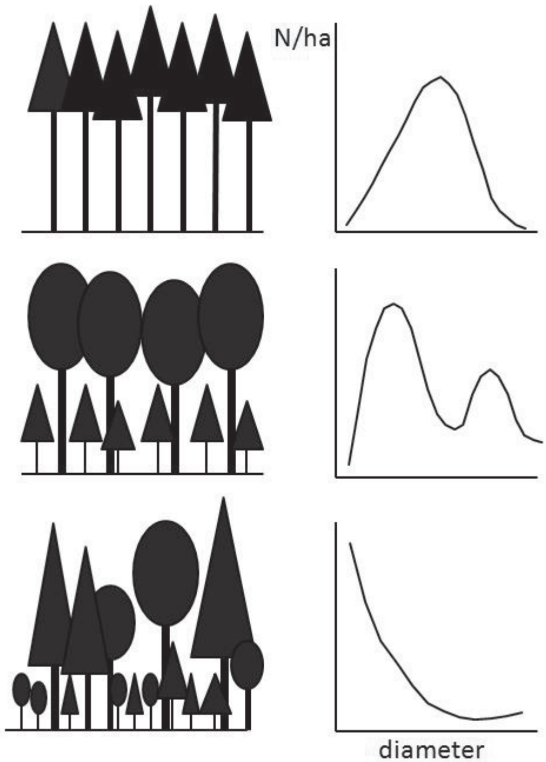

Figure 3: *Forest stand structure with appropriate diameter distribution showing an even-aged structure on the top (uni-modal diameter distribution, e.g. even-aged plantation), uneven-aged with two ages in the middle (bi-modal diameter distribution of two-storied forest, e.g. uniform shelterwood) and uneven-aged with numerous ages on the bottom ('reversed-J curve' diameter distribution, e.g. group selection system).*

The diameter distribution in a stand that exhibits a negative exponential shape is one where "each diameter class has fewer stems than the adjoining smaller diameter class" (Matthews 1989, p. 167) with the ratio between the number of trees in one diameter class to the number in the next larger class being a constant, referred to as the q factor (Kerr 2001). Such a distribution is often referred to as a reverse-J diameter distribution (Figure 3). This feature can be used by forest managers to guide felling during the transformation process and is commonly used to guide management in uneven-aged stands. The actual structure of the stand is compared to an idealised reverse-J curve and the difference between the two is used to decide the number and size of trees to be removed (Ibid). In North America, the q factor was adopted as the primary method of stocking regulation in uneven-aged stands (O'Hara 1998). Yet O'Hara (2001, p. 84) cautioned that uneven-aged stands need not always follow the perfect reverse-J-diameter distribution to gain diverse structure and that the "notion of balanced uneven-aged stands appears to be little more than an attempt to inflict arbitrary human values to ecological systems". Kerr

(2001) also acknowledges that it is not the only way to manage uneven-aged stands but nevertheless he has used it to assess progress in a long-term transformation trial (Kerr et al. 2010) arguing that it is relatively easy to understand and implement (Kerr 2001).

In balanced stands, stand increment should remain more or less the same from one harvesting intervention to the next (Meyer 1952). This equilibrium stand increment, more commonly referred to as equilibrium growing stock, is represented in terms of the volume (m^3 ha^{-1}) across broad DBH categories (Ibid). This feature can be used by forest managers to assess the progress of transformation (Poore 2007) and to guide the long-term management of the transformed stands. For example, in the lowland European silver fir, Norway spruce and European beech selection forests in Switzerland, the equilibrium growing stock is described as 20% volume in the 16–32 cm diameter class; 30% in the 33–52 cm diameter class and 50% in the >52 cm diameter class (Poore 2007). These values act as targets for management in these stands and harvesting is guided by them. The equilibrium growing stock will vary according to the species composition and site with more fertile and sheltered sites having a higher proportion of large trees (Ibid.). Consequently the target percentage per diameter class can vary from 21/22/57 to 21/37/42 for various sites in the Swiss Juras (Schütz 1989). To date there is no information on the equilibrium growing stock for any of the commercial tree species in Ireland and UK, hence further work would be needed if such an approach were to be used to guide management in transformed stands in these countries (Kerr 2001).

Transformation from a regular to a fully irregular structure can take more than 100 years (Schütz 2001). Transformation in the Glentress trial (see below) was originally expected to take 60 years; this has now been revised to 90 years (Wilson 2013). Kenk and Guehne (2001) indicate that the period involved in transformation can range from 20–60 years. Ultimately the time required to achieve successful transformation varies according to the desired structure with transformation to a two-story stand likely to take a much shorter period than to a fully irregular stand. Wilson (2013) noted that much work in transforming stands is adaptive without a clearly defined end point.

Why transform?

In a previous section, the locations and sites which would be suited to transformation have been outlined. Ultimately the decision to transform a stand will be determined by the objectives of the forest owner. Throughout Europe forest authorities are choosing to transform stands in the belief that CCF will lead to greater stability. There is also an assumption that greater biodiversity and amenity will be associated with CCF. Other forest owners are opting to transform stands for economic reasons. It has also been suggested that stands managed under CCF will be more resilient to the effects of climate change. In this section these issues will be explored. As research on the transformation process per se is quite limited, this section will include comparisons between the starting point and end result of transformation which are assumed to be an even-aged (regular) structure and an uneven-aged (irregular) structure, respectively. It is acknowledged that in reality both the start and end points of transformation may lie somewhere in between these extremes.

Stability in CCF stands

A key driver to the move from even-aged stands to uneven-aged stands in Central Europe was the high levels of windthrow experienced in the former. Lanier (1994), for example, found that the windblown volume in regular stands amounted to 150% of the annual cut compared to 15% in selection forests following a storm in 1967 in Switzerland. More recently Dvorak et al. (2001) found significantly lower wind damage levels in irregular stands compared to regular stands after the storm Lothar in Switzerland in 1999. von Lüpke and Spellman (1999) claimed that diversification of species within a stand lowers its susceptibility to various natural hazards, including wind, since individual tree species respond differently to hazards due to their varying morphology. Furthermore diversity in size is also important with Otto (2000) noting that although extensive damage to both regular and irregular stands occurred in 1972 in lower Saxony, the understory of the irregular stands remained largely undisturbed. Yorke (1998) similarly noted that storm damage in uneven-aged forests tends to occur on the tallest trees with the remaining size classes staying intact. In reviewing studies on the relative stability of irregular stands, Mason (2002 p. 348) explained that many comparisons are confounded by the effects of site which led him to conclude that "it is still unclear whether irregular stands will be less, similarly, or more vulnerable to wind" in the UK. Nevertheless, studies conducted in wind tunnels have confirmed that the presence of smaller sub-canopy trees reduces the loading on the main canopy trees by providing support and absorption of energy from the canopy-penetrating gusts (Gardiner et al. 2005).

While the end result of the process of transformation may be a more windfirm stand, the process of transformation in itself may create an unstable stand. Such concerns led Yorke (1998) and Mason and Kerr (2004) to recommend that transformation should only be considered in windfirm sites as inevitably older, taller trees will be exposed during the transformation process. However, the timing and approach used to the initial thinning during transformation, i.e. earlier and heavier, should promote stability.

Biodiversity and recreation

Since a drive toward increased biodiversity partly explains the increased interest in CCF it is important to consider whether there are data to support this assertion. Stokes and Kerr (2009) note that the use of CCF will lead to:

- extended rotation lengths and older trees;
- greater diversity of vertical structure;
- a greater mix of species;
- increased spatial heterogeneity at the landscape level if harvesting occurs at a range of scales.

Older stands have greater structural diversity (Peterken et al. 1992) which is shown to be associated with greater biodiversity (Aukema and Carey 2008). Similarly greater spatial heterogeneity is associated with higher biodiversity levels

(Churchill et al. 2013). Hence Stokes and Kerr (2009) conclude that there is evidence that the factors associated with CCF will help maintain and enhance biodiversity. However, they caution that the benefits will depend on the nature of the woodland and its position in the landscape.

Biodiversity levels in different silvicultural systems were compared in a number of studies. For example, Légaré et al. (2011) compared beetle biodiversity in Canadian forests where selection cutting, irregular shelterwood and clear-cut (using protection of advanced regeneration and soil) had been applied. An old-growth irregular stand was used as the control. Beetle communities were highest and similar in the selective cutting treatment and the control, a finding attributed to the higher volume of deadwood in these treatments.

A comparison of the impact of clear-cutting and shelterwood cutting on flora in Norway spruce forests found that the latter was less destructive to the forest flora than the clear-cut system (Hannerz and Hånell 1997). The positive effects were most pronounced in vascular plants and bryophytes. That study was carried out in stands managed under the uniform shelterwood system; the authors indicated that using other shelterwoods (e.g. irregular shelterwood) may further reduce the impact of harvesting on the ground flora due to the retention of individual trees for longer periods of time.

Overall, O'Hara (2001) emphasises that the structure of individual stands is less important than the distribution of stands within a landscape from a biodiversity viewpoint. Biodiversity is likely to be maximised by landscapes that include both even-aged and uneven-aged stands (Kerr 1999).

It is generally assumed that uneven-aged management offers a more "scenic" alternative than even-aged management (Hoffman and Palmer 1996). There is some evidence to support this assumption. Ribe (1992), for example, explored the public perception of the scenic beauty of shelterwood and clear-cuts. He found that the clear-cut system was considered to have less scenic beauty than the shelterwood. Nielsen et al. (2007) and Meyerhoff et al. (2009) found that the public prefer more diverse stand structures and less intensive harvesting to single storey forests and clearfelling. More recently, a study investigating preferences for different forest types in terms of recreation revealed that the public in four regions of Europe, i.e. Great Britain, the Nordic Region, Central Europe and Iberia, preferred "close-to-nature" forestry over intensive even-aged forests and woody biomass production (Edwards et al. 2012). Forests that are older (50+ years) were preferred over any other phases of development, i.e. medium, young, and establishment. These results indicate that forests managed under CCF are likely to be preferred by the public for recreation as under these systems trees are retained longer until older and the forest structure is closer-to-nature.

<u>Economics of CCF management and the transformation to CCF</u>

A limited number of studies have addressed the financial implications of the transformation process. Davies and Kerr (2011) produced an economic analysis of the clearfell/replant system and the following three transformation scenarios for Sitka spruce in the UK (beginning at a stand age of 25 years):

1. transformation to a simple structure using natural regeneration (Scenario 1);
2. transformation to a simple structure using underplanting after the failure of natural regeneration (Scenario 2);
3. transformation to a complex structure (Scenario 3).

They compared the net present values (NPV) for each of the following CCF rotation scenarios, i.e. 20 years, 100 years and in perpetuity. Higher overhead costs of management were assigned to the transformation scenarios: 150% to the first two and 200% to the latter to reflect the lack of experience among UK forest managers in using these management approaches. The three transformation processes were found to be less costly than the clearfell and replant scenario over a 20-year period, a finding that was attributed to the high initial thinning returns during transformation (Davies and Kerr 2011). Over the 100 year period, the clearfell and replant produced the highest NPV, although the NPV for Scenario 1 was similar. Finally, the highest NPV value in perpetuity was recorded for Scenario 1 because natural regeneration is cheaper than artificial regeneration (even accounting for re-spacing costs). Davies and Kerr (2011) emphasise the importance of successfully achieving natural regeneration as the NPV of Scenario 2 which includes a requirement for underplanting was low for all options.

Knoke and Plusczyk (2001) also compared a transformation scenario with a clearfell system in Norway spruce in Germany. They found that the transformation strategy yielded lower levels of timber and income overall. However they noted that as the income from transformation occurred earlier and was more uniformly distributed over time, the NPV of transformation was greater than for the clearfell system.

A case study from Oregon, USA compared the short-term financial returns from different management options including a no-thin, thin for even-age, clearfell and a "partial cut for uneven-aged"; the latter was considered to mimic the early stages of a transformation process (Emmingham et al. 2002). The authors took a short-term view (10 years) as they considered this would be the time horizon over which most private forest owners in the US would make comparisons. The starting point was even-aged conifer and even-aged mixed conifer-hardwood stands, 40–60 years of age in Oregon. The authors calculated the net asset value and found that the transformation option was associated with little economic loss in the short term but that there were significant cash flow advantages to clear-cutting immediately.

Pukkala et al. (2010) investigated the optimisation of structure and management of Scots pine and Norway spruce forests in Finland. Based on NPV, they found that uneven-aged management was more profitable than even-aged management in all cases, except for Norway spruce stands on fertile sites when a low discount rate of 1% was applied. They concluded that decreasing site productivity and increasing discount rate improved the relative financial profitability of uneven-aged management. These findings coincided with those from a study from Spain (Sánchez-Orois et al. 2004) that focused on the optimal residual growing stock and cutting cycle in uneven-aged maritime pine stands. Uneven-aged management was shown to be more profitable on poorer sites with even-aged management being favoured on fertile sites according to the land expectation value (LEV). Wikström

(2000) concluded, in a case study from Sweden, that even-aged management was more profitable than the uneven-aged alternative due to higher volume increment and higher net present value (NPV). However, he does point out that the NPV of the uneven-aged option was 90% of the even-aged NPV.

In summary, a number of key factors influence the outcomes of financial comparisons of even-aged forests with uneven-aged forests. First, natural regeneration is a key element of transformation and successful natural regeneration results in substantial savings in restocking costs. Helliwell and Wilson (2012) attributed the adoption of CCF by an increasing number of private estates in the UK to the need to avoid the substantial costs of restocking of clearfelled areas. Where underplanting is required this cost advantage is negated. Second, thinning used in the transformation process to CCF will be heavier and commence earlier than in comparable even-aged clearfell/replant management. The resulting earlier and larger revenues skew the financial advantages in favour of the transformation process, especially when high discount rates are used (Knoke and Plusczyk 2001). Third, it is often assumed that larger and more valuable trees will be produced in CCF systems. Certainly retaining trees longer, which is a feature of the transformation process, will result in large trees. However, there are concerns as to whether sawmills will be able to process large logs and whether markets will exist for them. For example, Andreassen and Øyen (2002) suggested that processing of large sized-logs in most modern sawmills in Norway would be more expensive and would not attract a premium price. Such a price premium for large and higher quality timber would be necessary to cover the cost of growing trees longer (Moore et al. 2012). Therefore, market demand for large quality logs and a sawmilling industry set-up capable of handling such products is vital. A sufficiently large production of larger logs would have to be secured to justify the investments in the sawmilling industry. In addition, operation costs may be higher in countries with no such sawmilling set-up since experienced staff that are able to harvest large trees will be required (Ireland 2007). Larger logs are not necessarily more valuable logs. For example, MacDonald et al. (2010) noted that growing trees to older ages (which will be a feature of CCF management) may result in them having big branches, particularly in the upper part of the stem, which will have negative consequences for wood quality. In particular the development of final crop trees that are tapered for stability reasons will also encourage greater branch growth, longer retention of branches (i.e. deeper living crowns), thus resulting in larger knots. To counteract these effects, pruning on selected frame trees may have to be considered if economically justifiable (Henman 1963). In Germany 85% of uneven-aged forests are pruned (Hanewinkel 2001).

Knoke et al. (2001) considered the volatility of timber prices as a risk in terms of forest management, concluding that the *continuity of income* in CCF management was crucial. In addition, they highlighted that the clear-cutting system can be far more influenced by timber prices, in contrast to the process of transformation to CCF which offers a much better distribution of the harvest over time. Knoke (2012) further argues that CCF delivers small and frequent profits that out-compete the large but infrequent profits yielded by clearfell. Furthermore, once an uneven-aged structure is achieved, forest owners have more flexible harvesting options owing to greater log size diversity; this contrasts with even-aged stands where no income will be earned for a long time after clear-felling. However, Hart (1995) raises the issue as to whether timber prices would be negatively affected by the range of assortments that are typically produced in the one harvesting operation in an uneven-aged stand.

Economic considerations also play a role in determining when transformation of a stand should be initiated. Price and Price (2006) found in their study of a 37-year-old Sitka spruce stand in Wales that the transformation to CCF should ideally begin earlier in such stands at 27 years of age as they found this to be the financially optimal age for initiating the transformation process. Knoke (2012) highlighted that from an economic perspective it was disadvantageous to transform a stand that has exceeded financial maturity claiming it may be better to clearfell the stand at the end of the rotation and engage in the transformation process in the newly-regenerated stand.

Climate change and CCF

The growing interest in CCF has been attributed in part to the need for greater forest resilience to the effects of climate change (Diaci et al. 2011). This is due to a belief that forests managed under CCF are better able to adapt to the changing climate due to their diversified structure and stability as well as their wider genetic diversity (e.g. Stokes and Kerr 2009, Küchli 2013). Evans and Perschel (2009) recommend inter alia the use of uneven-aged silvicultural systems to increase forests' resilience and ability to adapt to changing precipitation and temperature patterns. Lafond et al. (2013) also recommend the use of uneven-aged silvicultural practices, specifically group selection with gaps of 500 m^2 as a means of promoting forest resilience for climate change adaptation. Carbon sequestration has also been shown to be influenced by the silvicultural system used. For example, Seidl et al. (2007) showed that a Norway spruce stand under CCF management accumulated more carbon than an even-aged equivalent. Stokes and Kerr (2009) highlight that there are many gaps in knowledge regarding the response of trees under even-aged stand management or CCF to a changing climate. Nevertheless they outline that in the case of Scottish forests, CCF has the potential to adapt forests to some of the risks associated with climate change. Yet they stress that in stands being transformed, the response to climate change will depend on the stage of transformation.

Examples of CCF transformation

The process of transformation has been pursued for over a century in some parts of central Europe; however, it has more recently developed in other parts of the world (Cameron et al. 2001). There are examples of long-term transformation experiments in Europe, e.g. the transformation of pure stands of Norway spruce and Scots pine in the Black Forest, in Germany (Kenk and Guehne 2001). In Glentress, in southern Scotland, a transformation trial has been on-going since 1952 (Kerr et al. 2010, Kerr and Mackintosh 2012). The original stand composition included European larch, Scots pine, Douglas-fir, Sitka spruce, Japanese larch (*Larix kaempferi* (Lamb.) Carr.) and Corsican pine (*Pinus nigra* spp. *laricio* (Poir.) Maire). The main method of transformation in this forest has been group felling followed by regeneration.

Another long-term trial based in Faskally Forest, in Scotland, has been undergoing transformation for 60 years (Cameron and Hands 2010). The forest was originally a mixture of Norway spruce, Scots pine, European larch, Douglas-fir, and European beech planted at the beginning of the 20th century. Transformation into an irregular structure initially involved planting small groups of native and introduced conifer and broadleaf species within the existing stand. The latter stages of transformation have involved the application of the selection system.

Conclusions and practical implications

Interest in the application of CCF has been increasing, primarily prompted by the change in society's views on how forests should be managed with the current paradigm being sustainable multi-purpose forest management where structural and biological diversity, amenity and recreation values are considered alongside timber production. Consequently the process of transforming even-aged stands to CCF has commenced in a number of countries. There has been little research on this process and there is limited information and guidance available to foresters who wish to avail of this option. This review revealed that the small amount of work that has been conducted to date on CCF has focussed on the initial stages of the transformation process. If transformation is to be successful it is important that forest managers should already have a vision of the "type" of forest structure they wish to develop using this approach. Further research and guidance will be needed to help them achieve this objective. A considerable proportion of the literature on CCF has emanated from the UK and Central Europe. While the UK literature has provided a valuable starting point for those engaged in transforming stands in Ireland, there is a need for further research to develop country-specific guidelines on the stages of transformation.

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