Forest Research

The evidence supporting the use of CCF in adapting Scotland's forests to the risks of climate change

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Contents

Executive summary

1. The aim of this report is to answer the question: what evidence exists to support the use of Continuous Cover Forestry as part of the strategy to adapt Scotland's forests to the risks of climate change?

2. Continuous Cover Forestry (CCF) is an approach to forest management that results in diverse forests: a range of structures is possible, depending on the combination of site and species, and generally there is more than one species in the stand. CCF is therefore not a single entity that can easily be compared with even-aged management, the main silvicultural system presently used to manage forests in Scotland.

3. To facilitate the comparison of CCF with even-aged management we have identified three broad categories of CCF: simple structures (consisting of one or two canopy strata of trees); complex structures (consisting of three or more canopy strata) and stands undergoing transformation to CCF. One of the findings of the review is that the ability of CCF to help mitigate risks of future climate change varies with the type of structure.

4. Climate change is a term used to describe how regional or local climate is affected by changes in the global climate as a result of anthropogenic emissions of greenhouse gases. It is now generally accepted that climate change is taking place but the magnitude and speed with which changes will occur are less certain. Climate change predictions for Scotland indicate that there will be warmer and drier summers, particularly in the south and east of Scotland, while winters will be milder and wetter with fewer frost days. There is likely to be more winter rainfall with more heavy events; mean wind speed may not change but strong winds may be more frequent. All of these changes will affect forests and may necessitate changes in forest management.

5. The main method of conducting the review has been to examine the scientific literature and then discuss the main findings with a range of experts in Forest Research. The subject of the review is complex and there is an enormous amount of written material on climate change and continuous cover forestry (but not both, see below). We hope that the review is comprehensive but we acknowledge that with the time available the coverage of some areas may be better than others.

6. Climate change and continuous cover forestry are both subjects about which there is significant uncertainty. With climate change, as mentioned above, the main uncertainty concerns what aspects of the climate will change and the magnitude, speed and geographic distribution of the changes. With continuous cover forestry there is uncertainty about how it will be applied and whether or not the skills base of forest managers is good enough to put it into practice.

7. The risks posed by climate change to Scottish forests can be categorised into primary risks, resulting directly from the future climate and extreme weather conditions that may be experienced; and secondary risks, due to biological interactions, ecological responses and other factors. For each of these factors we have rated the potential impact (high/medium/low) on Scottish forests and made a judgement, based on the available evidence, about how CCF can help mitigate the risks (positive/neutral/negative). Finally, we have rated the evidence on which the judgement was based (good/moderate/poor).

8. There have been few direct scientific comparisons of the benefits of CCF and even-aged management for many of the risks considered in this report. In fact it quickly became apparent that our knowledge and understanding of the response of even-aged stands is limited for many of the factors considered. However, we have found a limited amount of information comparing CCF and even-aged management for some of the factors considered. Where evidence from direct comparisons does not exist we have based our findings on other appropriate scientific data, knowledge and understanding.

9. The main finding of this report is that CCF has potential to help adapt the forests in Scotland to some of the risks of future climate change (Table 1, page 6). The report has identified 5 primary risks and of these 3 could be mitigated using CCF. A further 9 secondary risks were considered and again 3 could be mitigated through the use of CCF. Importantly, of all fourteen risks considered only 2 rated the use of CCF as negative; 3 were rated as neutral and 3 as unknown. The evidence base used to make these judgements varied between poor (for 4 risks), moderate (6) and good (4).

10. Detailed consideration for each factor will be important when making site specific decisions. For example, on drought prone sites the ability of CCF to help mitigate future risks is unclear and it would be wise to concentrate on getting the species choice correct, whereas in another area enhancement of biodiversity may be a primary management objective and CCF could have a positive contribution to make.

11. At the strategic level, CCF should be viewed as an approach to forest management that seeks to create more diverse forests, both structurally and in terms of species composition. The development of more diverse forests is a sensible way to reduce the risks posed by future changes in the climate. However, this could be achieved using both even-aged management and CCF. Large areas of upland forests have been diversified since the 1980s using the process of 'restructuring' and there is potential for this to be extended; for example, by increased planting of species mixtures. It is clear from this review that CCF also has a role to play and can diversify risks in a different way compared with even-aged management. For example, in a simple CCF structure if a storm affects the overstorey, there is a good chance the understorey can replace it. In a complex CCF structure if a pest or disease affects one species occupying 30% of the stand then the growth of the other species would compensate.

12. In terms of positioning Scotland's forest estate to minimise the risks of future climate change the best way forward is to use an appropriate combination of even-aged management and CCF. Unfortunately there is no easy answer to the question: what is the optimum combination of the two approaches to management? At present FC Scotland has the following policy objective for CCF:

> 'Areas should be designated for continuous cover management within Forest Design Plans where this approach is considered the best way of delivering key pre-determined management objectives, or where the cost-effectiveness of this designation can be readily demonstrated over conventional practice.'

This policy enables forest managers who are confident and interested in CCF to use it wherever they perceive it as the best way of delivering management objectives. This is likely to result in a patchy distribution of the use of CCF in the short to medium term. In terms of mitigating the risks from climate change a more even distribution of uptake is required and a revised policy about CCF may be required to achieve this.

Table 1: Summary of risks of climate change to Scottish forests and potential effects of CCF

Risk to forests in Scotland	Rating of potential impact*	Effect of CCF management (positive/neutral/ negative)	Evidence base for judgement**
Primary risks			
Increased incidence of strong storms	High	Neutral-Positive	Good
Increased incidence of heavy winter rainfall	Medium	Positive	Moderate
Changing growth rates due to increased CO_2	Medium	Neutral	Good
Increased temperatures and incidence of drought	Medium	Unknown	Poor
Reduced incidence and changed timing of frosts	Low	Positive	Good
Secondary risks			
Attack by pests and diseases - general	High	Positive	Moderate
Pine weevil	High	Positive	Moderate
Green spruce aphid	High	Unknown	Moderate
Heterobasidion annosum	High	Neutral	Poor
Red band needle blight	High	Neutral	Poor
Implications for *in-situ* carbon storage	High	Positive	Moderate
Impact on biodiversity	High	Positive	Good
Changing tree species suitability	Medium	Negative	Moderate
Increased deer damage	Medium	Neutral	Poor
Changes in timber quality	Medium	Neutral	Moderate
Changes in weed competition	Medium	Unknown	Poor
Changing phenology of natural regeneration	Low	Unknown	Poor
Forest fires	Low	Negative	Moderate

* Impact ratings are:

Low – there will be an impact but it is unlikely to be significant
Medium – there will be a significant impact on a narrow range of economic, social and environmental factors on a limited area
High – there will be a significant impact on a broad range of economic, social and environmental factors on a wide area

**The evidence base ratings are:

Poor - small amount of evidence, poor understanding of factors
Moderate - reasonable evidence base but no direct studies of CCF versus even-aged management
Good - sound evidence base that includes scientific studies of CCF versus even-aged management

1.0 Introduction

1.1 What is CCF?

Continuous Cover Forestry (CCF) is an approach to forest management that results in the development of diverse forests with a range of different structures and often a variety of species (Mason et al., 1999). For the purposes of this report, three broad categories of CCF stands are considered: simple structures (consisting of one or two canopy strata of trees); complex structures (consisting of three or more canopy strata) and stands undergoing transformation (Mason and Kerr, 2004). Transformation stands are those that currently have only one stratum of trees but are being managed using CCF with the intention of developing a simple or complex structure.

Transformation stands are likely to constitute a large proportion of the 'CCF stands' in Scotland over the next few decades. The majority are likely to be thinned using crown thinning to improve the chances of securing natural regeneration, with the intention of forming a second canopy stratum to achieve a simple structure (Mason and Kerr, 2004). The risks of climate change to transformation stands and their possible benefits and drawbacks will depend upon the stage of transformation and stand structure. In some aspects, early transformation stands are similar to even-aged stands and will have similar responses to climate change.

1.2 What is climate change?

Anthropogenic factors, in particular the burning of fossil fuels, have been increasing the atmospheric concentration of 'greenhouse gasses' such as carbon dioxide for over 100 years (IPCC, 2001). As a consequence, a larger proportion of radiant energy is trapped within the Earth's atmosphere, resulting in gradually increasing temperatures and associated changes in other dependent climatic variables such as humidity, rainfall and windspeed. Weather patterns and seasonality of weather may also be affected (Broadmeadow and Ray, 2005). Although it is clear that climate change is taking place, the severity, speed and geographic distribution with which changes will occur are less certain. Climate change predictions for Scotland are less severe than in some parts of the world but will still impact on forests.

The UK climate change projections released in 2002 (Hulme et al., 2002; UKCIP02) have recently been revised by DEFRA (Murphy et al., 2009; UKCP09). Although the projections are broadly similar, it should be noted that the most recent UKCP09 projections are for greater temperature changes, less extreme summer drought, and less intense winter rainfall than were predicted in 2002. We have based our judgements of the potential of CCF to mitigate impacts of climate change on the current UKCP09 projections.

In general the effects of climate change in Scotland will most likely lead to warmer summers and less severe winters with fewer frost days. Summer rainfall will decrease, particularly in the eastern and south-eastern lowlands, with summer drought becoming increasingly frequent in these parts (Green and Ray, 2009). Winters will be wetter throughout Scotland with an increase in high-intensity storm rainfall events. Windspeeds during winter storms may increase. A more detailed summary of climate change predictions for Scotland can be found in Ray et al. (2008).

1.3 CCF and climate change risks to Scottish forests

There is growing recognition that forests are vulnerable to the complex effects and spatial and temporal interactions of climate change, due to the long life-span of trees and slow development to maturity. Forest managers and policy makers must develop adaptive strategies to reduce the adverse effects and take advantage of the benefits of climate change (Spittlehouse and Stewart, 2003; Ohlson et al., 2005). This requires evaluation of the specific hazards and detailed risk analysis, followed by scenario modelling to anticipate forest management outcomes in a systematic way (von Gadow, 2000). The slow development of forests means that anticipation of and planning for future site conditions provides an opportunity for managers to start to create forests now that will be successful and productive in the future. The main aim of this report is to summarise the evidence supporting the use of CCF in adapting Scotland's forests to the risks of climate change.

The risks posed by climate change to Scottish forests can be categorised into primary risks, resulting directly from the future climate and extreme weather conditions that may be experienced; and secondary risks, due to biological interactions, ecological responses and other factors. A summary of each of these risks and the evidence supporting or opposing the use of CCF to mitigate against the risks of climate change forms the main part of this report. The potential impact of each of the identified risks, as well as the quality and quantity of the evidence base, is summarised in Table 1 on page 6. In addition, after consideration of the evidence we have made a judgement of whether CCF is on balance positive, neutral or negative in helping Scotland's forests adapt to the risks of climate change. An underlying assumption of the report is that whenever CCF is used it will be well applied, based on a good knowledge of the silviculture of the species involved, an understanding of the site and how to achieve the desired end result. With the current skills base and lack of confidence with CCF there is a significant risk that this assumption may not be valid.

Figure 1: CCF is relatively new in Britain and practice is developing

2.0 Primary risks of climate change

2.1 Increased incidence of strong storms

Definition of the risk

The severe wind climate of the UK has meant that forest management, particularly in upland regions, has developed to tolerate strong winds. Current climate change predictions about wind speed are very uncertain (Murphy et al., 2009) but there have been some indications that although there may be little change in mean wind speed in Scotland, there may be more severe storms, particularly from the west (Hulme and Jenkins, 1998).

Scientific evidence

Many silvicultural texts have claimed that complex CCF structures are inherently more stable than even-aged structures (Kostler, 1956; Smith, 1962; Nyland, 1996). However, much of the evidence for this, summarised by Mason (2002), comes from studies carried out in Europe after severe storms; there is often no proper comparison with even-aged systems, soil types may differ and sites may have experienced different windspeeds and contrasting management histories. Most CCF stands in Britain have rarely been managed as such for long periods of time and are generally in the transformation phase. It is difficult to compare transformation stands with complex CCF structures as the conditions under which the trees develop and grow are quite different and this will affect stability.

A review of the stability of complex CCF stands and even-aged stands by Mason (2002) indicates that the main difference between them is the lower (i.e. more stable) height-diameter ratio of dominant trees in the former. This growth response is attributed to the higher wind loading on dominant trees in complex CCF structures. A second part of the study used the ForestGALES wind risk model (Gardiner et al., 2004) to evaluate the stability of complex CCF, thinned even-aged and unthinned even-aged stands, all of Sitka spruce. The study found little difference between these on sheltered sites but increased stability of complex CCF stands on moderately exposed sites with good rooting. On exposed sites the most stable option was the unthinned stand but the complex CCF was marginally more resistant to stem breakage. However, Mason notes that even on moderately exposed sites late transformation to CCF can be difficult as the dominant trees have not developed under high wind loading conditions.

Gardiner et al. (2005) have also demonstrated that complex CCF structures can reduce wind loading on the dominant trees by using model trees in a wind tunnel. They showed that in the presence of smaller sub-canopy trees, a complex structure reduced the wind loading on the largest trees in the stand compared with a simple structure or a stand in transformation. This is due to a sheltering effect within the canopy as little difference in mean wind speed and turbulence above the canopy was found between the different stand structures tested. The beneficial sheltering effect of the understorey has also been demonstrated in an experiment at Kyloe, Northumberland by Wellpott (2008). Wind-loading and turbulence characteristics were recorded in two similar stands that were adjacent, one with and one without an understorey. Reduced momentum transfer to the overstorey was recorded in the stand with an understorey, supporting the theory that complex CCF structures can be more stable than even-aged stands.

Although few studies have been carried out, no differences in root architecture or depth have been found between different silvicultural systems where soil type remained constant (Mitscherlich, 1963; Schütz, 1997, both on Norway spruce). In an even-aged stand of Sitka spruce, Nicoll and Ray (1996) found that the most exposed trees had higher root-shoot ratios and larger buttress roots than less exposed trees in the same stand. Although not observed, it might be expected that exposed trees in complex CCF stands have better developed root structures and hence greater stability.

Can using CCF help Scottish forests adapt to a higher incidence of winter gales?

There is some evidence that on moderately exposed sites, stands managed using CCF may be more windfirm than even-aged stands, particularly if the structure is complex. CCF also has the added benefit that if wind damage to the overstorey does occur, if natural regeneration is present and, if this can respond to the change, the stand would be able to recover more quickly than an even-aged stand. However, stands undergoing transformation to CCF will be as vulnerable to wind damage as even-aged stands, particularly if the transformation is late, and careful thinning is required.

2.2 Increased incidence of heavy winter rainfall

Definition of the risk

Winter rainfall in Scotland is likely to increase with climate change, with more heavy rainfall/precipitation events (Barnett et al., 2006; Anon, 2007; Murphy et al., 2009). This could have a negative effect firstly by increasing the risk of flooding and secondly by increasing the risk of nitrate leaching and surface water acidification (Nisbet, 2002).

Scientific evidence

a) Flooding

We have been unable to find any scientific studies examining the impact of CCF compared with even-aged management on flooding in Britain. However, there is clear evidence that forests intercept more water than other vegetation types due to the size of their canopies and dense, layered nature of foliage. Although variable, annual canopy interception rates of over 45% have been recorded in the UK (Calder et al., 2003). This can clearly help to reduce flooding by preventing rainwater reaching the ground, particularly in comparison with clearfelled sites. It has long been recognised that interception rates are higher for conifer forests than broadleaved forests (Ovington, 1954; Calder et al., 2003) particularly for winter rainfall, when deciduous canopies have no foliage. Interception rates decrease during prolonged heavy rainfall events as the canopy eventually becomes saturated.

It is also known that due to their high organic matter content and open structure, forest soils have a high capacity to absorb and retain water compared with other soil types (Shoenholtz et al., 2000). This is particularly true during summer when soils are dry due to high water usage by trees. In winter, when soils are already wet, and heavy rainfall is more likely, the ability to retain high volumes of additional water is reduced.

At the stand level, forestry practices such as cultivation (Worrell, 1996), clearfelling (Rosén, 1984; Roberts and Crane, 1997) and drainage (Bergquist et al., 1984; Iritz et al., 1994) have all been shown to increase the rate of surface water run-off, due to both the removal of intercepting vegetation, and compaction and rutting of soil by machinery. In general, CCF has a lower intensity of these types of operation compared with even-aged management and therefore it has often been assumed that CCF has lower levels of ground disturbance. However, we have been unable to find any published studies comparing ground disturbance of CCF and even-aged stands. Recent assessments of ground disturbance by harvester and forwarder by Forest Research during final overstorey removal of a simple structure in Sitka spruce have shown that very little ground disturbance is caused, provided felling and extraction are carefully planned (D. Ireland, pers. comm.). This suggests that at the stand scale, CCF with the avoidance of clearfelling and reduced soil disturbance should increase interception of heavy rainfall events and reduce or slow run-off, helping to reduce flooding. Once again we have been unable to find any research to demonstrate this or examine the relative interception rates of different CCF structures.

Although individual forestry practices can affect peak flows at the stand level or within small headwater catchments, the effects are not necessarily seen lower down the catchment where flooding tends to occur and there is often less forest cover. Many studies have shown that in large catchments, the amount of forestry and the management practices employed high in the catchment do not affect flooding lower down the catchment (FAO, 2005).

There is also an implication for tree stability of higher rainfall in the winter due to fine root death in anaerobic waterlogged soils (Ray and Nicoll, 1998).

In summary, while CCF management and avoidance of clearfelling has the potential to reduce the impact of heavy rainfall and prevent flooding within and near to the stand, it does not appear likely that it would reduce flooding lower down the catchment.

b) Nitrate leaching and surface water acidification

The recent policy shift away from patch clearfelling as the main silvicultural system for the management of National Assembly woodlands in Wales (Forestry Commission, 2001 and 2009) has resulted in a review of the effects of continuous cover forestry on the implications for surface water acidification in the uplands of Britain (Reynolds, 2004). This makes the point that it is difficult to predict the likely consequences because: (1) there is uncertainty about how CCF will be implemented in upland spruce; (2) there have been no direct studies of CCF with patch clearfelling and effects have to be inferred from other work designed to answer different questions; (3) previous studies have been undertaken in a pollution climate which differs from that which is likely over the next decade or so. However, the conclusions of the review are valuable and can be summarised by the following points for acidic and acid sensitive sites.

1. Any move away from large scale patch clearfelling is likely to have benefits in terms of reduced nitrate leaching and reduced stream acidification. High levels of leaching and acidification

caused by heavy rainfall on clearfelled sites have been reported by many scientific studies (Adamson and Hornung, 1990; Titus and Malcolm, 1992; Roberts and Crane, 1997; Kubin, 1998; Reynolds and Stevens, 1998; Moffat et al., 2006)

2. CCF will maintain vegetation cover on sites so that nitrogen and base cations continue to be taken up by the soil-plant system (see also Sverdrup and Rosen, 1998).

3. The use of a greater range of species in CCF may encourage exploitation of base cation reserves (which buffer increases in acidity) deeper in the soil profile and recycle them to the more acidic surface horizons via litter fall and canopy leaching.

4. The canopy structure of CCF stands, generally more open than even-aged stand with deeper crowns, may enhance atmospheric deposition of nitrogen and sulphur compounds and have undesirable consequences in the long-term through soil acidification and nitrogen enrichment. There is good evidence that trees with deeper crowns on gaps and edges can increase deposition rates by up to three times compared with even-aged management (Lindberg and Owens, 1993, Environment Agency, 1998).

5. The introduction of species with greater potential to retain nitrogen (i.e. broadleaves) deposited from the atmosphere should be beneficial on acid sensitive sites.

One of the other conclusions of Reynolds (2004) was that if CCF results in a smaller proportion of mature Sitka spruce forest (greater than 30-40 years old), this will reduce nitrate leaching on well drained acid soils. However, in our view this is unlikely; CCF will probably increase the proportion of older trees because of the use of natural regeneration. The nitrate release from older trees tends to be higher (Emmett et al., 1995), this may increase the risks of acidification of the site.

In summary, although there are no direct studies of the effects of CCF and even-aged management in this area, on balance CCF has a number of advantages and could help reduce nitrate leaching and surface water acidification. This seems likely in general as well as for the specific scenario of heavy winter rainfall/precipitation events.

Can using CCF help Scottish forests adapt to increased risks of heavy winter rainfall/precipitation events?

It is clear that the presence of forest increases interception of rainwater compared with clearfelled areas, and that flooding, nutrient losses and acidification can occur during heavy rainfall events in clearfelled areas. Although there are few, if any, direct comparisons between CCF and even-aged stands it seems likely that the avoidance of clearfelling and use of CCF will reduce the negative effects of increased winter rainfall. Rainfall interception may be particularly high in complex stands due to their canopy structure; in the early stages of transformation interception will be little different to that of an even-aged stand. However, while there may be benefits at the stand level, there may be little effect at the larger catchment scale, and use of CCF alone is not a reliable method by which to address flood-risk areas.

2.3 Changing growth rates due to increased carbon dioxide (CO_2) concentration

Effects of increased CO_2

The continuing increase in atmospheric concentrations of greenhouse gasses such as carbon dioxide, methane, nitrous oxide and ozone (IPCC, 2007) will have an ongoing direct impact on forests. Rates of carbon uptake will increase, although in some circumstances nutrient and moisture limitations will modify the increased growth rates. There will be an increase in tree leaf area index, affecting rainfall interception, snow loading, soil moisture, light environment and wind resistance. Experiments on young trees and saplings indicate that a doubling of atmospheric CO_2 can increase biomass by 50% (ECOCRAFT, 1999; Broadmeadow and Randall, 2002). However, it is unclear how this level of increase will translate to mature forests; some authorities have suggested it may be in the order of 1-2 yield classes for productive conifers in Scotland (Broadmeadow, 2000).

Scientific evidence

Increased atmospheric concentration of CO_2 has the effect of directly increasing photosynthetic enzyme activity and hence plant growth rates. Increased CO_2 can also reduce stomatal apertures, which contributes to increased water use efficiency. Although much research has been carried out into the effects of this on agricultural crops, little is known about how trees of different species and ages will respond, or how forest structure may be affected (Körner et al., 2005). One study that demonstrated the complexity of the relationship between light environment in a CCF structure, elevated CO_2 concentrations and tree growth was conducted by Hättenschwiler and Körner (2000). Their results showed that growth response of seedlings of six European temperate forest species (beech, sycamore, pedunculate oak, yew, European silver fir, Scots pine) to elevated CO_2 concentrations was strongly dependent on the light environment and density of the overstorey canopy. Some species (beech and yew) were able to respond to elevated CO_2 concentrations only when grown in low light conditions (0.8% of full sunlight, in shady understorey positions), while other species (silver fir, oak and sycamore) responded only when growing in higher light positions (4.8% of full sunlight, in canopy gaps). Therefore, small variations in light environment completely changed the response of some species to elevated atmospheric CO_2 concentration, leading to the conclusion that there is likely to be a shift in species composition of natural regeneration that will be highly dependent on overstorey structure and local light environment.

There is some evidence that growth rates of mature trees are also changing due to increased carbon dioxide concentration (Karnosky et al., 2007). Changes have been shown for a range of species and are largely, but not exclusively, positive (Becker et al., 1995; IPCC, 1995; Hulme and Jenkins, 1998; Rolland et al., 1998). At the forest scale the majority of forests in Northern Europe are growing faster than in the early 20th century. Observations of growth rates in Sitka spruce in Britain planted in the 1930s and the 1970s show a 20-40% increase (Cannell, 2002). It is currently unclear whether the increase in growth rates is due largely to improved forest management practices (with limited room for further improvement), nitrogen deposition (which is not expected to rise much further), increased atmospheric CO_2 concentration (which is likely to continue to rise for some time) or a combination of these and other factors. However, recent work suggests that the combined impacts of nitrogen deposition and increased temperature may be largely responsible for increased forest growth rates (de Vries, 2009).

The relative productivity of even-aged and complex CCF stands is a frequently debated topic in silviculture and forestry. Nearly all previous comparisons have been empirical growth studies, simulations of stand growth, or economic analyses based on differences in stem volume production. Both even-aged and CCF stands are highly variable and the large number of factors involved and assumptions made makes any comparison difficult. One notable study by O'Hara and Nagel (2006) synthesized a series of studies with the aim of developing a better understanding of the relative stemwood productivity of CCF and even-aged stands. The study focussed on ponderosa pine growing on water limited sites in western USA. They concluded that CCF stands were either as efficient or slightly more efficient at converting light energy to volume growth than even-aged stands. Even-aged stands experienced a higher level of mid-summer water stress than CCF stands. They suggested that reduced photosynthesis in even-aged stands is a possible cause for a slightly lower level of productivity. However, the differences in productivity they found were small and operationally insignificant. It is also important to note that ponderosa pine sites are primarily water-limited and these results may not apply to more light-limited systems.

Can using CCF help Scottish forests to take advantage of increased growth rates?

Increased growth rates present little risk to Scotland's forests *per se*, and could in fact be generally beneficial to the forest industry. We currently know very little about how different species and age-classes of trees will respond to this or whether particular management practices may offer benefits. There is no clear evidence that CCF stands are more efficient at converting light energy into volume growth compared with even-aged stands but it seems unlikely that the factors associated with climate change will shift this balance. However, one effect of increased growth rates of saplings and young trees may be that the time taken for transformation from even-aged stands to CCF may be slightly reduced. In conclusion, there is little evidence that CCF can help Scottish forests take advantage of the opportunities of increased rates of tree growth.

2.4 Increased temperatures and incidence of drought

Definition of the risk

Climate change will bring warmer, drier conditions to Scotland, particularly in spring and autumn, and in eastern and south-eastern Scotland (Barnett et al., 2006). High summer temperatures will increase photosynthetic rates, particularly as global CO_2 concentrations will continue to rise. In combination with the longer growing season, this will allow increased growth (see section 2.3). However, summer droughts are also predicted to increase in frequency and severity, increasing vapour pressure deficit and reducing stomatal conductance. This is likely to have a counteracting effect on growth rates and in some cases cause mortality.

Scientific evidence

For photosynthesis to occur the stomatal pores on the leaves must remain open to allow carbon dioxide into the leaf and to allow cooling by evaporation of water from the leaf. It is likely that winter waterlogging of poorly drained soils will restrict root growth (Coutts and Philipson, 1978; Xu et al., 1997) and hence there will be reduced capacity to replace lost water during summer drought when vapour pressure deficits are high. Therefore, under drought situations it is likely that stomatal pores on the leaves will close to regulate water loss, preventing photosynthesis and production, and perhaps causing high-temperature damage to leaves (Breda et al., 2006). Thinning of overstorey canopies has been shown to increase temperature and vapour pressure deficit in the canopy, potentially increasing stomatal closure under these conditions (Rambo and North, 2009). However, as thinning also increases throughfall and soil moisture availability it is unknown how these factors will interact in forests (Jiminez et al., 2008). Analysis of tree ring data and growth of Alaskan white spruce over the past 90 years shows that radial growth has consistently decreased with increasing temperature due to temperature-induced drought stress (Barber et al., 2000).

Therefore high temperatures will increase growth except during drought periods. In extreme droughts mortality will increase (Renaud and Nageleisen, 2004). Mortality may not be immediate or directly due to low water availability, and may occur in subsequent years, for example due to a reduction in leaf area index (Le Dantec et al., 2000). Young trees and seedlings produced by natural regeneration are particularly susceptible to high temperatures and drought especially as seedling root structures may only penetrate into the quick-drying leaf litter and organic surface soil (Koppenaal et al., 1991). Drought and water stress have also been shown to increase susceptibility to pests and pathogens (Green and Ray, 2009) (see section 3.1).

It should be clear from the above that the effects of light, temperature and water availability on tree growth and survival in even-aged stands are complex and difficult to predict for trees at any stage of development (Dulamsuren et al., 2009) Responses will vary widely for different species growing on different sites. The presence of a canopy in a CCF stand will further add to the complexity of the interacting factors and there is little evidence available on which to base any judgement of the likely effects. However, the following statements can be made with some certainty based on existing knowledge.

1. If a drought is severe on a vulnerable species/site combination then there is a high risk that young trees planted in an even-aged woodland could suffer a high rate of death. In an equivalent situation with CCF the risks would be lower because: (1) the young trees will be growing in a wider range of environmental conditions (Leiffers et al., 1999; Page et al., 2001; Hale, 2004), and (2) some of the species in the mix may be less vulnerable to drought stress compared with the main species.

2. If a drought is severe on a vulnerable species/site combination then there is a risk that established trees in an even-aged woodland could die; although it should be noted that relative to young trees this risk is much lower. In an equivalent situation with CCF the risks could be higher if the understorey is more developed than in the even-aged stand as this has been shown to reduce the water availability for canopy trees (Nambiar and Sands, 1993; Castro et al., 2004). However, other effects are much more difficult to predict because of the complexity of the factors involved.

3. In all situations the effects of drought can be counteracted by effective vegetation management; we have good understanding and information about this for even-aged stands but it is limited for CCF (see section 3.7).

In both of the situations described above the risks for CCF stands would be higher for transformation stands and simple structures compared with complex structures.

Can using CCF help Scottish forests adapt to increased temperatures and drought?

Evidence is weak in this area and it is not possible to make any firm conclusions about how CCF could help forests in Scotland to adapt to increased temperatures and drought.

2.5 Reduced incidence and changed timing of frosts

Definition of the risk

Climate change predictions (Murphy et al., 2009) indicate that there will be an increase in mean temperature across the UK in all seasons, including a reduction in the number of frost days and in the diurnal temperature range in winter. This is likely to advance budbreak date but reduce frost damage in spring (Cannell and Smith, 1986; Murray et al., 1994). However, in autumn although frosts will occur less frequently, they may cause more damage due to generally warmer temperatures and later hardening of shoots. Therefore in general frost will decrease as a problem (Redfern and Hendry, 2002).

Scientific evidence

The maritime climate of Britain has encouraged the commercial use of many non-native species such as lodgepole pine, Sitka spruce and Corsican pine. These commercial species are generally more prone to cold and frost damage than they would be in their native environment, particularly when growing away from the coast. Currently, many commercial species, particularly non-native species, in Britain are affected by cold weather and frost (Redfern and Hendry, 2002). Variation in the native ranges of many of these species provides the opportunity to minimise frost risks by provenance selection.

There is a large body of evidence demonstrating that the presence of an overstorey can reduce frost damage compared to open sites (Nilson et al., 2006; Erefur et al., 2008). Studies have shown that near-ground temperature can be several degrees higher under a shelterwood than in open exposed sites on clear calm nights, reducing frost damage to regenerating seedlings and underplanted trees (Groot and Carlson, 1996; Langvall and Örlander, 2001). In areas where unseasonal frosts may cause damage to young trees, CCF has the potential to reduce damage on young trees, particularly for the more frost susceptible species which may become desirable in future climates.

Population dynamics and infection rates of pests and pathogens are also strongly affected by temperatures, particularly in winter, with frost often being a controlling factor (see section 3.1). Winter chilling and frost are also necessary to break seed dormancy prior to germination in some conifers (see section 3.8).

Can using CCF help Scottish forests adapt to reduced incidence and changed timing of frosts?

Although frosts will decrease in frequency and severity, earlier frosts in autumn may cause increased damage to unhardened non-native species. If these species remain commercially desirable, regeneration (whether by planting or naturally) under a canopy as in CCF will offer an opportunity to minimise frost damage.

Figure 2: the ability of CCF to help mitigate risks of future climate change will depend on the type of structure

3.0 Secondary risks of climate change

3.1 Attack by pests and diseases

Definition of the risk

There is a high probability that climate change will cause an increase in the frequency and severity of attack by pests and diseases (Straw, 1995; Evans et al., 2002; Broadmeadow and Ray, 2005). In particular, warmer winters are likely to increase the period of activity for many pathogens, while in summer trees under drought stress are likely to be more susceptible to attack

(Ray et al., 2008). Wind and storm damage also increase the likelihood of attack by fungal and insect pests by increasing the availability of breeding material in broken and deadwood increases (Schroeder and Eidmann, 1993).

The range of pests and pathogens that affect or have the potential to affect Scottish forests is very wide. In this report we focus on two major pests *Hylobius abietis* (pine weevil) and *Elatobium abietinum* (green spruce aphid), and on two major pathogens, *Heterobasidion annosum* (formerly *Fomes*; butt rot) and *Dothistroma septosporum* (red band needle blight). We also examine the risk of new pests and diseases that may become more prevalent in Scotland under climate change conditions.

Scientific evidence

Hylobius

In Scotland, *Hylobius* reproduce over a two-year life cycle. Under climate change conditions this is likely to shorten, so that weevils emerge and attack transplants during only one season, reducing the fallow period necessary after clearfelling. However, damage rates during this period may be high, as most insects are more active when temperatures are higher.

As the majority of *Hylobius* damage occurs when the adult insects emerge from cut stumps to feed on newly establishing young trees, it is logical that the avoidance of clearfelling should reduce the amount and density of cut stumps available, reduce the availability of planted seedlings and therefore limit *Hylobius* populations and damage. There is evidence from studies in Scandinavia to support this hypothesis (Lof and Madsen, 2000; Pitkanen et al., 2005; Pitkanen et al., 2008). Work currently in progress by Forest Research's Centre for Forestry and Climate Change indicates that *Hylobius* damage levels are reduced in Sitka spruce being transformed to CCF due to a reduction in the number of felled stumps, where the insects develop, and the presence of alternative food resources for the adult weevils (Mason et al., 2004).

Elatobium

Elatobium is the most important defoliator of Sitka spruce, and to a lesser extent Norway spruce, in Britain and populations are limited by a combination of cold winter temperatures and natural predators. Therefore it seems highly likely that populations and damage levels are likely to increase in Scotland due to generally warmer temperatures and fewer winter frosts (Straw, 1995; Day et al., 1998; Evans et al., 2002; Westgarth-Smith et al., 2007). Drought stress is likely to increase susceptibility to *Elatobium* particularly in eastern Scotland, resulting in increased defoliation and reduced volume increment. However, changes in nutritional quality and resistance of spruce foliage and interactions with predators mean that the timing and severity of outbreaks will be difficult to predict. High densities of *Elatobium* and severe defoliation during outbreaks are expected to lead to a progressive decline in the productivity of Sitka spruce (Straw, 1995).

After clearfelling an even-aged stand the cycle of attack by *Elatobium* is broken until transplants are colonised and attacks recommence, particularly after canopy closure. Attacks then continue in 3-5 year cycles with the severity of the attack being closely related to the climate in the preceding year. There is little information on which to base a judgement about how the use of CCF will change this. However, these are some of the factors that will be involved and take account of emerging work in Forest Research's Forestry and Climate Change Centre (N. Straw, pers. comm.):

1. In CCF tree crowns are likely to be more isolated and overwinter populations of *Elatobuim* could be subject to greater mortality caused by wind and low temperatures.

2. In more developed structures, such as a complex structure, the overwinter populations of *Elatobium* may be protected from extremes of temperature in lower canopy strata.

3. In more developed structures, such as a complex structure, there is a greater variety of habitats to maintain populations of natural predators. This may reduce the amplitude of the boom-bust population cycle of *Elatobium*.

4. Recent work has shown that there is a direct relationship between tree age and the density of *Elatobium*; i.e. the older the tree the more aphids. This could be important for CCF as this will use more trees of a greater age compared with even-aged management.

5. There is strong observational evidence that *Elatobium* can cause serious damage to natural regeneration of spruce under an overstorey.

At present it is unclear what the result of these interacting factors will be. However, a rigorous scientific approach is being taken to the study of the likely impacts of CCF on *Elatobium* in Forest Research.

Heterobasidion

Heterobasidion annosum currently causes significant economic damage to British conifer plantation forests (Pratt, 2003). The fungal spores can colonise the freshly cut stumps of most coniferous species and are then able to spread downwards into the root system. Where there is contact with the living roots of neighbouring trees the fungus can transfer and spread to other trees that are not infected. The disease causes severe decay, a reduction in increment and, in some circumstances, death. Both the levels of infection and rate of dissemination throughout a stand are most severe at locations with a warm, dry climate and well-drained soils (Redfern et al., 2001). Cool, wet sites with poorly-drained soils have lower infection rates and on these sites Sitka spruce stump treatment is currently not considered necessary. Predicted temperature increases and drier summers indicate that the risk of *Heterobasidion* infection and spread on cool, wet sites is likely to increase; infection rates will also increase on sites that are currently high risk. Conversely, it is possible that heavy rainfall and water-logging of soils during winter may help to reduce infection rates on some sites.

While there are chemical and biological stump treatment methods that can be applied to uniform stands undergoing pre-commercial thinning, methods of preventing infection during clearing-saw respacing of natural regeneration have not yet been developed and this could affect the success of respacing of saplings in CCF stands. Current FC guidance (UM2) stipulates that all cut stumps of 2.5 cm diameter or over should be treated, although no suitable application method is suggested for such small stems. Research into self-thinning of dense Sitka spruce regeneration suggests that respacing may not always be necessary in CCF managed stands, potentially reducing the risk of *Heterobasidion* infection (Mason, 2008). However, in practice most CCF stands with dense regeneration will be respaced for operational and health and safety reasons.

No published experimental studies could be found comparing *Heterobasidion* infection rates in even-aged management and CCF. However, it seems logical that using CCF would increase infection rates as cut stumps, of both overstorey and regeneration, exist in close proximity to living trees. However, the environmental conditions in CCF understories may also remain cooler and moister than on clearfell-restock sites, helping to prevent infection. CCF management may also help to reduce infection rates where mixed species stands are developed. For example, Peri et al. (1990) reported lower *Heterobasidion* infection rates in mixed stands (with birch and pine) compared with pure stands of Norway spruce. However, as there is no clearfell stage in CCF management there is no opportunity to remove stumps if infection does occur, although this practice is restricted to a small number of locations in Britain at present.

The impact of climate change on *Heterobasidion* is likely to be significant and further research on this potentially devastating pathogen is required, particularly in light of changing silvicultural practice and the increased use of CCF.

Dothistroma

In Britain, red band needle blight is caused by the fungus *Dothistroma septosporum* and in recent years has become an economically important disease, primarily of pine species. The disease results in premature needle defoliation and reduced growth rates, and in Corsican and lodgepole pine this can cause mortality. It is thought that the recent increase in the disease is due to wetter spring and summer conditions in Britain in combination with warmer springs (Brown and Webber, 2008). Many coniferous species grown in Scotland are affected but evidence suggests that host species growing outside their natural range may be worst affected (Gibson, 1972). Predicted future climatic conditions suggest that infection rates may worsen; susceptible species such as Corsican pine and lodgepole pine may become unsuitable for commercial use in Britain.

Silvicultural practices that increase air movement within the canopy, such as heavy thinning, pruning and use of lower basal areas are thought to reduce infection rates but the evidence for this is not strong (Gadgill, 1984; Brown, unpublished data). These practices are part of CCF and if used with a wider range of tolerant species this could reduce the impact of red band needle blight. CCF management by underplanting with groups of resistant species may be an effective way of diversifying stands to improve robustness. With even-aged management, if stands are badly affected they could be heavily thinned or clearfelled and replanted with a mixture of resistant species. Therefore, on balance the use of CCF does not have any clear advantages for the future control of this disease compared with even-aged management.

New pests and diseases

As well as changing susceptibility to current British pests and pathogens, climate change brings the risk of new organisms affecting forests. Some of these may be severely damaging. One example of particular is chestnut blight (*Cryophonectria parasitica*). Following its introduction into North America at the end of the nineteenth century, chestnut blight spread within the next five decades throughout all the main chestnut areas and virtually destroyed all mature chestnut trees. It is now present in southern France and still expanding northwards, with new records of the chestnut blight disease occurring yearly, especially in northwest (Brittany) (Denman et al., 2009). Another group of particular concern are the bark beetles, which respond positively to increased temperatures and trees under physiological stress (Anderbrant, 1986). The reduction in the number of frost days in Scotland is likely to improve conditions for the development of pests that have not previously been able to establish, if they are successful in colonising.

Can using CCF help Scottish forests adapt to increased attack by pests and diseases?

The continued use of single species, even-aged stands increases the future risks posed by pests and diseases, particularly under climate change conditions when trees may be more susceptible to attack due to other stresses. Mixed species stands are more robust because they spread the risk of attack; if one species is severely damaged other species may be able to compensate and occupy the vacant space. The increased use of CCF will lead to more diverse forest stands, both in terms of species and structural diversity, and will help mitigate future risks (Gottschalk, 1995; Ray et al., 2008). It follows that complex CCF structures are therefore probably more robust than simple structures, while early-stage transformation stands may be no more robust than even-aged stands. Mixed species, even-aged stands can also be developed; however, the disadvantages compared with complex CCF stands are that (1) a single species stand can only be changed into a mixed species stand by clearfelling and then restocking, and (2) the structural diversity of the stand is lower.

3.2 Implications for *in-situ* carbon storage

Definition of the risk

Forest ecosystems and timber can potentially play a large part in removing CO_2 from the atmosphere and storing it as carbon. Forest management practices have a large impact on stored carbon, in both trees and the soil, through afforestation/deforestation, ground preparation, species choice, thinning and silvicultural system. The carbon impact of any change in management, which is seeking to mitigate the risks of climate change, must be considered before implementation.

Scientific evidence

The maximum potential for carbon accumulation in British forests is approximately 200 tC ha^{-1} (Broadmeadow and Matthews, 2003). This figure represents the carbon reservoir of an 'old-growth' stand of trees in which the canopy is dominated by very old trees (i.e. not CCF). The equivalent figure for even-aged woodlands is approximately half of this, averaged over a series of rotations. Few studies have examined the effects of different approaches to CCF on carbon sequestration at the stand level. However, from the small number of studies that have been carried out there is some evidence that CCF has the potential to accumulate more carbon than an even-aged woodland but less than an 'old-growth' stand. For example, Seidl et al. (2007) investigated the carbon accumulation of a range of silvicultural systems in Norway spruce stands and showed that the highest carbon stocks occurred in an old-growth stand, followed by a complex CCF stand, with the lowest carbon stocks in an even-aged stand. Another study by the same research group investigated the effects of transformation of even-aged stands to CCF under the current climate and two transient climate change scenarios (Seidl et al., 2008). The results demonstrated that transformation to CCF increased carbon stocks by between 45.4 and 74.0 tC ha^{-1} for all climate scenarios over a 100 year period. From this it seems logical that for the CCF scenarios considered in this report the carbon stocks would decrease as follows: complex>simple>even-aged management=transformation stand.

The carbon stock of any woodland must also be considered along with the potential to sequester carbon in the longer term (Jandl et al., 2006). In general if trees are growing at their maximum rate of growth they will also be accumulating carbon at a similar relative rate. Because of this even-aged management could be considered to have an advantage over CCF because trees are generally grown during their period of fastest growth, up to the point where mean annual volume increment peaks (at the stand level). After this the trees are felled and replanted and the next generation of trees continue to sequester carbon at a high rate. In general our understanding of CCF is that although it may have a larger store of carbon on site for a long period of time, the potential to sequester further carbon after maturity is reduced as some trees remain on site past their rate of maximum growth and therefore sequestration. This is likely to be correct for simple structures where stands are managed for uniformity and in order to achieve successful regeneration trees will be maintained on site beyond the time at which (stand) mean annual volume increment peaks. However, recent work by Poore and Kerr (2009) has suggested that the situation may be very different for complex CCF structures. In these the focus of management shifts from the average tree of a stand to individual trees, and the objective is to concentrate increment on the best trees. Their data show that individual trees continue to grow at high rates of growth well beyond the time at which an equivalent 'mean tree' in an even-aged stand has peaked.

Forest soils, particularly peat soils, can also contain a large amount of carbon, sometimes more than is contained in the trees themselves (Milne, 2001). Soil carbon stocks are a balance of input and incorporation from dead biomass, and losses due to respiration and decay. These processes are all strongly affected by changes in temperature and moisture, as well as disturbances from forest operations or natural events. In general CCF reduces or removes the need for operations that disturb forest soils and therefore it is logical that this should help to maximize forest soil carbon stocks. However, the criteria of Mason and Kerr (2004) to assess the likelihood of success of CCF rate low carbon mineral soils much higher than high-carbon soils, such as peats and peaty gleys. The main reason for this is that the potential for natural regeneration is considered to be higher for mineral soils, see Figure 4.3 of Nixon and Worrell (1999). This suggests that most of our early efforts at CCF will be focussed on mineral soils, which have relatively low forest soils carbon stocks compared with other types of forest soil (Morison et al., 2009).

An interesting approach to the use of CCF on peat and peaty gley soils is currently being trialled at Cwm Berwyn, one of the Forestry Commission's National Network Sites for CCF (Ireland, 2006). Sitka spruce is being managed with a range of silvicultural systems, all of which use natural regeneration with little or no soil disturbance. In addition, innovative methods of forming access racks with deadwood and brash have been developed to minimise ground disturbance (Ireland, 2006). This example of trying to develop forests that have a high stock of carbon on soils with a large reservoir of carbon is worthy of further investigation.

Can using CCF help Scottish forests increase *in-situ* carbon storage?

Although very difficult to assess in field experiments, evidence suggests that on suitable sites CCF has the potential to increase in situ carbon stocks compared with even-aged management. The structure of the resulting stand will have a large impact on the extent of carbon accumulation, with complex structures offering greatest benefit. As CCF management generally reduces site disturbance it is also likely that carbon losses from the soil will be less than in even-aged management, although careful management of brash will be necessary to avoid soil damage during thinning.

3.3 Impact on biodiversity

Definition of the risk

A large proportion of the species contributing to the flora and fauna of woodlands and forests have a limited ability to respond to rapid changes in environmental conditions. The biodiversity of Scotland's native woodlands and plantation forests is at risk from climate change (Petty et al., 1995; Summers et al., 1999; Humphrey et al., 2002; Berry et al., 2003; Woodcock et al., 2003).

Scientific evidence

The increased use of CCF in plantation forests is likely to lead to: (1) extended rotation lengths and older trees; (2) a more diverse range of vertical structures; (3) a greater mixture of species, and (4) increased spatial heterogeneity at the landscape scale if harvesting occurs at a range of scales. There is good evidence that these changes will help to maintain and enhance the biodiversity of forests in Scotland (Ratcliffe, 1993; Spellerberg and Sawyer, 1993 and 1996; Kerr, 1999; Humphrey, 2005). The benefits will depend on the nature of the woodland where the changes occur and its position within the landscape. For example, they would be very different for a single stand in a large forest compared with one that is connecting isolated patches of semi-natural woodland (Hossell et al., 2000; Peterken, 2003). If a CCF structure can be developed that supports higher levels of biodiversity there is also good evidence to suggest that such structures can be managed to maintain it. For example, selective thinning has been found to be non-detrimental to biodiversity in old-growth stands in Norway (Storaunet et al., 2000) and Alaska (Deal et al., 2002).

The situation with native woodlands in Scotland is quite different. Since the policy changes in the mid-1980s (Forestry Commission, 1985) the use of clearfelling in native woodlands has largely disappeared and the management advocated in the Forestry Commission Practice Guides could be considered as very similar to CCF. The main effect of CCF on native woodlands is therefore that the concept could act as a stimulus for bringing unmanaged native woodlands into management, including some element of proofing against the future risks of climate change. However, considering other factors such as economics, ownership and access that are often attributed to native woodlands not being managed, this seems unlikely.

Can using CCF help to maintain and improve biodiversity of Scottish forests?

There is strong evidence that the increased use of CCF can help to maintain and enhance the biodiversity of forests in Scotland. However, the changes need to be planned at the landscape scale in order to maximise benefits; the Forest Design Planning process is the ideal vehicle to drive this forward in publicly owned forests.

3.4 Changing tree species suitability

Definition of the risk

The predicted changes in climate and environmental conditions will result in ongoing changes in species suitability across Scotland. While growth rates will tend to increase due to rising atmospheric CO_2 concentrations and generally warmer temperatures, there will be other weather events such as spring and autumn frosts, summer drought and localised flooding that will limit growth and survival of some species on some sites. Growth rates of these stands may slow before the end of the current rotation and stress and mortality will increase, leaving stands susceptible to attack by pests and disease.

Scientific evidence

Several reviews of species suitability under climate change conditions in Scotland and in Britain have been carried out describing likely changes in different regions (Broadmeadow and Ray, 2005; Broadmeadow et al., 2005; Ray, 2008; Jinks, 2009). Various methods of assessing adaptability of forest species to climate change are being investigated by Tene et al. (2009) and will help to clarify the links between site, future climatic conditions and species suitability, which are currently uncertain.

The risk of forest-wide loss of production due to unsuitability of species can be mitigated by converting stands to a mixture of tolerant species suitable for future conditions. This objective can be achieved using even-aged management and CCF but there are risks and opportunities with both. CCF is an appropriate method by which stands can be gradually transformed to a suitable species mixture. However, any attempt to steer the stand to a different mix of species will mean that the forest manager will have to exercise control over the regeneration phase. With natural regeneration, this can be difficult unless there is evidence that desirable species have previously regenerated in the area. If the change was to be made using planting then the choice of species may be constrained by how the canopy could be opened. With even-aged management the forest manager can select when to fell the existing stand and what species to use in the restocking operation. The species would need to be chosen to tolerate current climatic conditions as well as predicted future changes (Ray et al., 2008). There is also the added flexibility that if the decision is not optimal then the stand can be harvested on a short rotation and a different species mixture used. The main disadvantage of this is cultural in that our previous experience of using mixtures in British silviculture has not always been positive (Kerr et al., 1992; Mason, 2006). However, they have been successfully used in other parts of the world (Kelty, 2006).

Can using CCF help Scottish forests adapt to changing tree species suitability?

Changes in species suitability are likely to occur gradually and with some uncertainty. Both CCF and even-aged management can be used to change the species composition of any stand that is vulnerable or shows signs that growth has slowed due to the changing climate. However, on balance even-aged management has advantages over CCF as it allows the forest manager to control the rate and nature of the change in species; with CCF the change may be difficult or expensive to achieve.

3.5 Increased deer damage

Definition of the risk

Populations of deer are adversely affected by cold, wet weather, through reduced food availability and increased mortality. Predicted climate change is therefore likely to result in increased population densities and ranges if appropriate control measures are not put in place; this could result in more damage to a wider area of forest (Sparks and Gill, 2002). Deer in Scotland are the most likely to benefit from future changes to the climate compared with those further south (Irvine et al., 2007)

Scientific evidence

It is generally agreed that one of the main factors determining the population size of deer species in Britain is the timing, availability and quality of food (Gill, 1992; Fuller and Gill, 2001). In even-aged stands the amount of food available depends on the stage of development of the stand, the species and how it is managed (Gill et al., 1996). In general, young stands before canopy closure, light demanding species and stands that are regularly thinned will be the best sources of food (Halls and Alcaniz, 1968). In CCF stands the amount of food available will be influenced by the structure of the woodland, species and how the canopy is managed. In general terms the basal areas used in CCF will be lower than equivalent even-aged stands, either as gaps for complex structures or spread evenly in simple structures, which will increase the amount of food available to deer. Hence the main differences between CCF and even-aged management are: (1) CCF does not have the flush of vegetation that follows clearfelling, and (2) CCF may provide more food due to generally lower basal areas. We have not been able to locate much work that directly compares even-aged stands and CCF in terms of the availability and quality of food for deer. However, there is a strong body of information on factors determining habitat suitability of deer in temperate landscapes, most of which suggest that one of the primary drivers is the mix of agricultural and forest land rather than the structure of the forests (Crawford and Marchinton, 1989; Boroski et al., 1996).

Climate also directly influences deer in Britain, with the most pronounced effects in winter and spring. Lower temperatures, wind and rain increase the rate of heat loss, which can be particularly important for calves in spring; snow can hamper mobility and increase the amount of energy expended for feeding. A reduction in the frequency or severity of cold winters would therefore have the effect of maintaining higher over-wintering populations of deer that could have a sustained impact on forests (Sparks and Gill, 2002). In the same way that it is difficult to compare even-aged management with CCF in terms of food availability, it is also difficult to do this for general climate factors. There are differences between CCF and even-aged stands in terms of the environment in the stands that are discussed elsewhere in the report. However, there is no evidence to suggest that these would counteract the main climate factors influencing deer populations.

It should be clear from the above that there are complex interactions between climate, forest management and the physiology of deer. It is therefore not surprising that there is little evidence on which to base a judgement about the ability of CCF to help in this area. One study by Vospernik and Reimoser (2008) attempted to do this for roe deer in the Gleinalm, a heavily forested area at the eastern end of the Alps in Austria. Their findings suggest that CCF stands support lower densities of roe deer than even-aged stands and also that there is less browsing of young trees in continuous cover forests than in clear-cut forests. However, the paper has two main weaknesses: (1) the models used are sensitive to the assumptions made, and (2) the context of the study is large forests and the findings may not be applicable to fragmented forest/agricultural landscapes in Scotland.

The differences between CCF and even-aged management in terms of population control and the costs of protecting young trees also need to be considered. However, once again little evidence is available from scientific or economic studies. In terms of the ability to control populations, even-aged management would seem to offer some benefits as the process of regeneration, clearfelling followed by restocking, creates the type of habitat in which it is much easier to control deer. However, exponents of CCF would argue that control of deer is still possible through the intelligent use of open areas within the design of the forest. In terms of the costs of protecting young trees there are no differences between CCF and even-aged management if planting is used as the main method of regeneration. However, if CCF management can operate with the reliable formation of dense regeneration, for example with Sitka spruce in simple structures, there is an opportunity for a reduction in costs.

Can using CCF help to reduce deer damage in Scottish forests?

There is little evidence that increased use of CCF will have any effect on the increased population densities and ranges of deer that are likely to occur due to climate change. The use of CCF is a fundamental change to the balance between the availability of food and the impact on regenerating trees compared with even-aged management, which has not been rigorously evaluated for conditions in British forests. Where CCF is used in combination with the ability to secure dense natural regeneration there may be some benefits in decreased costs of protection but these may be offset by increased costs of population control.

3.6 Changes in timber quality

Definition of the risk

The primary risks of climate change to the forests of Scotland will cause species or provenances to be sub-optimal and this will lead to a reduction in timber quality.

Scientific evidence

We have not been able to find much evidence that CCF would help mitigate this risk compared with even-aged management. However, during the process of producing this report we have found evidence that some people involved in forest management believe that the use of CCF will lead to an overall reduction in the quality of timber. We have therefore taken the opportunity to examine this in more detail. Fortunately, a recent review by Macdonald et al. (2009) has provided timely and useful information. Their work consisted of a wide ranging literature review and a modelling simulation of the effects of different transformation scenarios on the timber quality of Sitka spruce. The main findings of the work were:-

- Retaining trees to older ages can produce higher quality timber with improved mechanical properties.
- Regular selective thinning and increased use of crown thinning will improve timber quality, but timing is critical to avoid producing highly tapered trees with heavy branches.
- Creating gaps in a uniform canopy will generally have a negative impact on the timber quality of the trees around the gap edges.
- Increased variation in tree age, size, spacing and species will result in greater variation in log quality and wood properties.
- Using natural regeneration reduces the opportunities for improved growth and timber quality offered by selectively bred planting stock but can deliver good-quality timber if the characteristics of the original stand are suitable and adequate stocking is achieved.

The main conclusion of the review was that transformation to CCF will not lead to a significant reduction or improvement in the quality of timber being produced in forests in the UK. The main effect will probably be to increase the variation of log sizes and wood properties that are available in the market. This confirms other work such as that by Ridley-Ellis et al. (2008) that large old trees can have improved timber properties compared with those from even-aged stands. They found that structural timber from the outer part of logs from an 83-year-old stand of Sitka spruce had greatly increased strength, indicating the performance gain that may be achieved by extending the rotation length beyond the normal period. In addition, a comparison of logs from even-aged and complex CCF stands of *Pinus taeda* reported reduced knot sizes and better grade logs from the latter, probably due to the greater age of the tree for a given log size (Guldin and Fitzpatrick, 1991).

Can using CCF help Scottish forests adapt to changes in timber quality?

We have found little evidence that CCF can help mitigate the risks to timber quality posed by climate change. Increased use of CCF will not lead to a significant reduction or improvement in the quality of timber being produced in Britain, assuming it is consistently and well applied. The main effect will probably be an increase in the variation of log sizes and wood properties available in the market.

3.7 Changes in weed competition

Definition of the risk

Increases in atmospheric CO_2 concentration and temperature, and changes in rainfall and other environmental conditions will change competition between trees and weed species (Bazzaz and McConnaughay, 1992). Some weed species may become more aggressively competitive, affecting growth and survival of young trees, particularly where soil moisture is limited.

Scientific evidence

Although few scientific studies have been carried out on the interactions between weeds and tree species under climate change conditions, more is known about weed species in agricultural situations. Ziska and Bunce (2006) reviewed competitiveness of weed species with agricultural crops and demonstrated that interactions were affected by increased levels of atmospheric CO_2. Weed-crop interactions are also influenced by many other factors such as increased temperatures and dry summers; it is likely that these responses also apply to trees and forest weed species. For example, Fotelli et al. (2005) carried out experiments on naturally regenerated beech seedlings growing with bramble, and found that under conditions of high light and high temperatures bramble became significantly more competitive, while nitrogen acquisition of beech seedlings was impaired.

One of the areas where some work has been carried out is in relation to shade tolerant understorey species and their response to climate change (de Groot and Ketner, 1994). This work showed that Holly (*Ilex aquifolium*) and ivy (*Hedera helix*) are predicted to increase in abundance in northwest Europe and may have deleterious effects on forests. Both of these species were found much further north than at present during the last inter-glacial period. The distribution of ivy in particular is thought to be strongly related to temperature and may become much more abundant under a warmer climate, particularly in the north.

Another area is in relation to how climate change may affect the efficacy of herbicides on target vegetation. Ziska et al. (1999) demonstrated that when grown at elevated concentrations of CO_2, some weed species can become more tolerant of herbicides such as glyphosate, reducing efficacy. However, the efficacy of glyphosate in controlling some other species was not reduced by high CO_2 concentration, indicating that different weed species may become dominant. Efficacy of many herbicides could be affected by climate change due to anatomical, physiological and morphological changes in plants grown under different conditions.

Weed control is a significant challenge in many establishment situations. In even-aged management the main method of regeneration is by restocking in prepared ground which is often quickly colonised by dense competitive weed growth. Weed control is usually considered necessary on most sites for between 1-5 years for effective establishment and we have developed good techniques to achieve this (Willoughby et al., 2004). However, there is strong pressure to reduce the use of pesticides use in forestry (UKWAS, 2006). Careful management of the overstorey in CCF can potentially reduce or avoid the need for weeding during regeneration (Willoughby et al., 2004). CCF therefore offers an opportunity to address the requirement of reducing chemical use but there can also be problems. For example, natural regeneration may not be successful, the window of opportunity on nutrient rich sites is limited and if success is uneven some weed control will be required but we have limited knowledge of how to achieve successful weed control in close proximity to natural regeneration. Much work is required on the use of forest canopies to achieve vegetation management and how to achieve effective weed control in close proximity to natural regeneration.

Can using CCF help Scottish forests adapt to changes in weed competition?

Little is known about how climate change will affect the competitive balance between trees and other vegetation. The area where CCF has potential to help is through a reduction in herbicide use during regeneration, firstly by avoiding creating open, prepared sites which are heavily colonised by weed growth, and secondly by using the canopy to control competing vegetation. However, knowledge and understanding in this area is limited and any potential will not be harnessed without further research and development.

3.8 Changing phenology and effects on natural regeneration

Definition of the risk

Many changes in phenological timing have been observed in recent decades due to the impact of changing temperatures, particularly in spring. Changes are larger in the UK than in the rest of northern Europe (Roetzer and Chmielewski, 2000) and affect plants, invertebrates, vertebrates and the interactions between them. There has been a general advancement of budbreak, lengthening of the growing season and advancement of flowering time for many woodland plants and trees (Sparks et al., 2000). These changes are expected to continue and could affect natural regeneration.

Scientific evidence

Little is known about the impacts of climate change on regeneration processes such as pollination and seed development but it is likely that they will be affected (Price et al., 2001). In Denmark, the peak birch pollen season advanced by about 14 days between 1977 and 2000 (Rasmussen, 2002). Seed production is strongly related to temperature and rainfall in the preceding growing season (Matthews, 1963; LaBastide and Vredenburch, 1970) and to atmospheric carbon dioxide concentration (LaDeau and Clarke, 2001). However, species will respond differently to changing climatic conditions, affecting relative competitiveness (Curtis and Wang, 1998).

Seed germination of most conifers requires a period of chilling to break dormancy, and occurs predominantly, but not exclusively, in the spring and summer following dispersal (Clarke, 1992; Nixon and Worrell, 1999; Kerr et al., 2008). It is thought that under climate change conditions with warmer winters, some species may not receive the critical chilling requirements, affecting germination rates (Price et al., 2001). Cannell and Smith (1986) have also suggested that warm winters may delay flowering and reduce pollination rates. Seeds also require moisture for germination and early survival, largely during the spring/summer period (Nixon and Worrell, 1999; Gosling et al., 2003), suggesting that drier summers may lead to lower germination rates and reduced survival, although this may be less of a problem under the shade of a canopy.

One study that demonstrates how little is known in this area has been described by Gosling (2009), who investigated the effects of climate change on the dormancy and germination characteristics of common alder seed. In the present climate, the dormancy and germination characteristics of alder minimise autumn germination and stimulate early and synchronous emergence over a wider range of temperatures. If climate change brings about longer, warmer autumns then Gosling's results suggest that more seeds are likely to germinate before winter, and if the winter is also warmer, shorter or both then these seedlings will thrive into the next spring. But even if a spell of sub-zero winter temperatures kills the delicate seedlings, there will always be a few seeds that remain dormant into the winter, benefit from the cold snap and emerge later in the spring.

Can using CCF help Scottish forests adapt to changing phenology of natural regeneration?

Most even-aged forests are regenerated artificially and therefore will not be affected by these changes; it is much more likely to affect forests managed using CCF as natural regeneration will be commonly used. However, little is known about the effects of climate change on many of the processes involved in natural regeneration and it is therefore difficult to draw any firm conclusions. Even if changes were deleterious and some species became more difficult to regenerate naturally in Britain, this would not reduce the utility of CCF as underplanting could be used.

3.9 Forest fires

Definition of the risk

Forest fires can be natural or anthropogenic (e.g. loss of control during burning of grouse moor or arson) but the majority of forest fires in Britain start in open ground (grassland or moorland) and spread to forests. Although currently low, there is evidence that the combination of drier summers and higher temperatures is likely to increase the incidence of forest fires (Broadmeadow and Ray, 2005).

Scientific evidence

Little research has been carried out comparing the relative flammability of CCF and even-aged stands in Britain. However, inferences can be made based on current knowledge of forest fires.

Forest fires can be ground-fires (e.g. burn in peat), surface fires (burn litter and ground vegetation) or crown fires (burn in the tree canopy), with most starting as surface fires. In even-aged stands there is generally little in the way of ground vegetation to act as ‘ladder fuel’ enabling a surface fire to gain access to the canopy. Although some damage to bark and roots can be sustained, surface fires rarely cause severe damage to even-aged stands in Britain. Fires have been recorded in thinned even-aged pine stands and in larch stands in Britain where ground conditions are similar to what may be expected under CCF management (I. Murgatroyd, pers. comm.).

In CCF it is likely that the stand will be more open, with more ground vegetation and natural regeneration present (some of which may be dead) and more than one canopy stratum.

Therefore it seems logical that this type of structure may provide more ladder fuel and enable a surface fire to reach the canopy and cause damage. Evidence to support this comes from the finding that fire intensity is higher under tree canopies due to the increased litter depth and drier fuel due to rainfall interception (Varner et al., 2005; Hille and Stephens, 2005).

In a review of fire behaviour in boreal forest systems, Ryan (2002) noted that stands with a high, open crown and little understorey are more likely to have surface fires due to the increased sunlight and wind penetrating the forest but have been shown by many authors to have low crown fire potential due to the low amount of 'ladder fuel' and height of the crown (Stocks et al., 1989; Grishin, 1997; Kunkel, 2001; Scott and Reinhardt, 2001). Stands with a large amount of understorey vegetation and natural regeneration are more likely to have crown fires due to the vertical continuity of fuel, with crown fires spreading more easily in dense canopies compared with patchy canopies where the crowns are more isolated (Finney, 1998 and 1999; Van Wagner, 1993). Complex stands with high connectivity between the multiple canopy strata may allow fire access to the canopy more easily than in simple structures; however, once in the canopy, the isolation of the crowns may reduce horizontal spread of the fire compared to simple structures.

A post-fire study of a ponderosa pine stand that had received experimental shelterwood and seed tree overstorey treatments 20 years previously demonstrates these differences (Lezberg et al., 2008). Despite severe crown fires through the surrounding uniform forest, the shelterwood and seed tree treatments within the experimental plots were less severely despite the two decades since thinning. Within the experimental area, average burn severity was greater in areas where there had been a high density of saplings and under the denser shelterwood treatment than under the seed tree treatment (Lezberg et al., 2008).

Can using CCF help Scottish forests adapt to increased risk of fire?

Although an outbreak of fire is no more likely in CCF than in an even-aged stand, the presence of ladder-fuel in CCF stands may increase the likelihood of a surface fire reaching the canopy and causing damage. However, it should be noted that although the fire risk in Scotland may increase slightly with climate change, the risk is not expected to become high.

4.0 Conclusions

1. Climate change and continuous cover forestry are both subjects about which there is significant uncertainty. With climate change, the main uncertainty concerns what aspects of the climate will change, and the magnitude and speed of the adjustment and its geographic distribution. With continuous cover forestry there is uncertainty about how it will be applied and whether or not the skills base of forest managers is good enough to put it into practice.

2. There are still many gaps in our knowledge about the responses of trees, forests and ecosystems to climate change. This is true for even-aged management and also, to a greater extent, for CCF. This review has not been able to find many direct scientific comparisons of the benefits of CCF and even-aged management for many of the risks considered. In order to conduct the review we have therefore had to carefully use existing knowledge and understanding and apply it in a logical way to examine the benefits and drawbacks of CCF and even-aged management to mitigate the risks of climate change.

3. The main finding of this report is that CCF has potential to help adapt the forests in Scotland to some of the risks of future climate change (Table 1, page 6). The report has identified 5 primary risks and of these 3 could be mitigated using CCF. A further 9 secondary risks were considered and again 3 could be mitigated through the use of CCF. Importantly, of all fourteen risks considered only 2 rated the use of CCF as negative; 3 were rated as neutral and 3 as unknown. The evidence base used to make these judgements varied between poor (for 4 risks), moderate (6) and good (4).

4. Detailed consideration for each factor will be important when making site specific decisions. For example, on drought prone sites the ability of CCF to help mitigate future risks is unclear and it would be wise to concentrate on getting the species mix correct. In another area enhancement of biodiversity may be a primary management objective and CCF could have a positive contribution to make.

5. At the strategic level, CCF should be viewed as an approach to forest management that seeks to create more diverse forests, both structurally and in terms of species composition. The development of more diverse forests is a sensible way to reduce the risks posed by future changes in the climate. However, this could be achieved using both even-aged management and CCF. Large areas of upland forests have been diversified since the 1980s using the process of 'restructuring' and there is potential for this to be extended; for example, by increased planting of species mixtures. It is clear from this review that CCF also has a role to play and can diversify risks in a different

way compared with even-aged management. For example, in a simple CCF structure if something such as a severe storm affects the overstorey, there is a good chance the understorey can replace it. In a complex CCF structure if a pest or disease affects one species occupying 30% of the stand then the growth of the other species would compensate.

6. In terms of positioning Scotland's forest estate to minimise the risks of future climate change the best way forward is to use an appropriate combination of even-aged management and CCF. Unfortunately there is no easy answer to the question: what is the optimum combination of the two approaches to management? At present FC Scotland has the following policy objective for CCF (Kerr, 2008):

'Areas should be designated for continuous cover management within Forest Design Plans where this approach is considered the best way of delivering key pre-determined management objectives, or where the cost-effectiveness of this designation can be readily demonstrated over conventional practice.'

This policy enables forest managers who are confident and interested in CCF to use it wherever they perceive it as the best way of delivering management objectives. This is likely to result in a patchy distribution of the use of CCF in the short to medium term. In terms of mitigating the risks of climate change a more even distribution of uptake is required and a revised policy about CCF may be required to achieve this.

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Figure 3: CCF is a significant challenge for many aspects of forest science

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