Impacts of climate change on forests and forestry in Scotland

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Executive summary

There is now a very high level of certainty that global climate change is occurring as a result of human activity, particularly from the burning of fossil fuels. Although Scotland's climate may not change as much as in other parts of the world, there are likely to be impacts on Scotland's economy, environment, and society. The forest industry must now adapt to the challenge of a changing climate. The relatively long period between establishing young trees and utilising harvested wood means that forest practitioners must be aware of the likely changes in climate, its impact on site conditions, and the consequent changes in growth, forest ecology, and the ecology of pests and diseases. This report provides a preliminary discussion of the likely impacts of climate change for Scotland's forest industry. Although the process of adaptation must begin now, the recommendations will be refined as more research and new information becomes available.

Scotland's changing climate

1.1. Throughout Scotland, summers will become warmer, and winters will become milder.
1.2. The seasonal rainfall distribution will change: drier summers in eastern Scotland – particularly the eastern and south-eastern lowlands, and wetter winters generally throughout Scotland.
1.3. There will be an increased frequency of very dry summer periods in the future, leading to drought - depending on soil type and site conditions. This is likely to be most acute in south-eastern and eastern Scotland.
1.4. There will be an increase in the frequency of high intensity rainfall during storms.
1.5. Changes in the wind climate are less certain, but some reports suggest that increased wind speeds during winter storms are likely in the future climate.

Tree species suitability and growth

1.6. The growing season will lengthen for many species of tree, earlier bud burst, later bud set, and more lammas growth, where late summer conditions trigger new growth from a terminal bud.
1.7. Winter cold will lesson and frost days will decrease – winter hardening may suffer for some species.
1.8. With milder winters, some tree species may not enter full dormancy, and may become less hardy to winter cold.
1.9. Growth rate, as measured by yield class is likely to increase further (another 1 YC is likely) as a result of warmer summers and increased CO_2 .
1.10. The genetic diversity of forest material should be maintained or improved, use material from a as wide a range of families as possible.
1.11. Continental provenances tend to be unsuitable in Britain, and this will continue to be the case. Scotland's climate will continue to be dominated by the Atlantic Ocean – producing milder wetter winters and warmer and drier summers.
1.12. The choice of Sitka spruce provenance (QCI) should not be changed in Scotland.

1.13. Douglas fir provenance should be reviewed for Scotland, better suited material may currently be used from more southerly latitudes.

1.14. Several ‘new’ species might be suitable on specific site types in Scotland. These should be mixed with ‘known’ species on suitable sites.

1.15. In addition Forest Research must develop site suitability information for a wider range of species.

1.16. Initial investigations suggest climate change is unlikely to have a significant effect on the proportion of structural grade Sitka spruce timber in Scotland. It is likely that a number of pests and diseases will become more prevalent in Scotland.

1.17. Milder winters will allow bigger populations to overwinter, longer and warmer growing seasons will increase the number of lifecycles per year, and warmer conditions and higher CO_2 will provide more food – shortening time to maturity and increasing fecundity.

1.18. Opinion favours mixing tree species within stands to reduce the impact of pests and pathogens over an area.

Disturbance and adaptation management

1.19. Continuous cover forestry systems are probably more carbon efficient forest management systems – particularly where natural regeneration is the main recruitment method. However not all sites are suitable for a low impact silvicultural systems (LISS) – wind exposure and the risk of windthrow is probably the main constraint in Scotland.

1.20. LISS produces a less dramatic change to woodland micro-sites.

1.21. Mixing species in stands whether managed by LISS or a clearfell-restock system will help spread the risk associated with the impacts of climate and weather on trees.

1.22. Tree stability may become more critical with wetter winters and more frequent intense gales.

1.23. Summer drought stress will become more critical on imperfect or poorly draining soil types, as a result of restricted root development caused by more winter waterlogging.

1.24. Where appropriate use mixed species in plantation clearfell-restocking systems.

1.25. Managing stands to maintain a more continuous and even canopy roughness, would help reduce the risk of wind damage. Thinning interventions could start earlier and occur more frequently on risky sites.

1.26. Improved Sitka spruce should not be used on sites prone to wind damage. The material is more expensive to produce, grows more quickly and will suffer earlier damage including loss and damage to leaders on exposed sites.

1.27. Nursery operational working time will be reduced by the longer growing season and wetter winter conditions; this will require greater resources.

1.28. There will be a much greater need for irrigation systems in our easterly tree nurseries.

1.29. Back-end planting of bare-root spruce and larch will be reduced, but there will be an extension of the planting of containerised trees later into the autumn.

1.30. The spring planting time may be curtailed on drought risk eastern sites.

1.31. There will be more weed growth within the nursery and on planting sites to contend with.

1.32. For poorly and imperfectly draining soils mounding is likely to remain the most effective type of cultivation.

1.33. Scarification or direct planting is likely to remain appropriate on freely draining soils.

1.34. Better site and operations planning will be needed to maintain compliance with the Forestry Standard and related guidelines for sustainable forest management. This is particularly so when considering the management of water in and around operations. Soil damage and particularly rutting and erosion will be more difficult to control. It may be necessary to refrain from operations on sensitive sites in the winter months.

1.35. Contingency plans should be tested to ensure that the response to catastrophic wind damage, fire, and pest or disease outbreaks can be effectively managed.

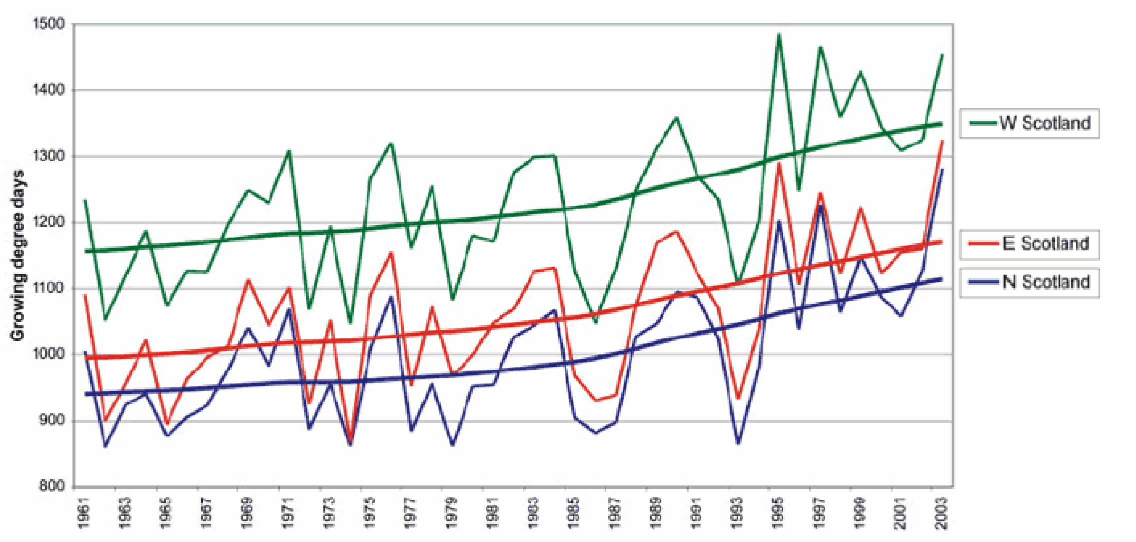
1.36. More decision support type guidance is required to help forest managers adapt and manage for climate change. DSS systems need to tackle the issues of spreading risk.

1. Climate change in Scotland

1.1. Temperature

Globally, the temperature of the earth's surface and lower atmosphere continues to increase as a result of the increased concentrations of CO_2 in the atmosphere. The mean annual temperature has increased significantly by about 1^0C across Scotland throughout the 20th century, the increases are most significant in spring and autumn over the country as a whole, and increases have been particularly noticeable since the beginning of the 1960s (Barnett et al., 2006). Figure 1 shows the accumulated temperature (AT) warmth index, in day.degress above 5^0C, calculated each year since 1961 as a regional average for north, east, and west Scotland.

Figure 1. The mean accumulated temperature (day.degrees over 5C) for north, east, and west Scotland from 1961 to 2004, with a running mean to show the trend, after (Barnett et al., 2006)



A recently published article (Smith et al., 2007) reports a new GCM capable of accurately predicting the natural variation through a decadal time frame. It suggests the circulation of the Atlantic Ocean and cooler water in the tropical Pacific Ocean has tended to offset greenhouse warming over the last decade. However, the model predicts that 50% of the 5 years following 2009 will be warmer than 1998 (the warmest year on record).

Impact

The increasing AT index is a climatic indicator of the improving potential for plant growth during a growing season. For tree species increasing warmth means higher productivity if water and nutrients are not limiting. The threshold of 1200 day.degrees is significant for growing high quality broadleaved species, although many conifers are very suited to lower thresholds of 1000 day.degrees (Pyatt et al., 2001). As the AT increases throughout this century, land which is more fertile and sheltered in the lowlands, and also at low elevation, on fertile soils of sheltered valleys of the uplands, will become better suited to growing broadleaved trees. The increasing warmth index will in addition stimulate higher yields for biomass production on better quality land over more areas of lowland Scotland (Ray and Grieve, 2006).

1.2. Frost

The number of frost days decreased sharply between 1961 and 2004, with an average reduction of 20 days during each winter. The Meteorological Office analysis (Barnett et al., 2006) showed that the coldest winters (lowest annual temperature) experienced the greatest number of frost days. Between 1961and 2004, the greatest reduction in frost days occurred during spring and autumn.

In the last 40 years, a 1.0^0C increase has occurred in the annual mean minimum daily temperature in all parts of the country, with the biggest increases in eastern Scotland. The minimum night-time temperatures have increased more in coastal regions than in the central, more continental parts of Scotland. Throughout the century the frequency of cold winter nights (-5^0C and below) will reduce from 15% of winter nights to about 4% of nights by 2080, and minimum winter temperatures are projected to increase more than minimum summer temperatures (Barnett et al., 2006).

Impact
Although the frequency of occurrence of winter frost has reduced in the last 40 years, and is projected to reduce further with climate change. The risk of frost damage will remain, particularly on flat ground and gentle slopes, and on sites more than 10 km away from the coast with southerly and easterly aspects.

1.3. Rainfall

A recent IPCC report (Anon, 2007) suggested that the climate of the UK will become 10% wetter in the winter months and 10-20% drier in the summer months by the end of this century. Projections suggest that heavy precipitation events will occur more frequently over most areas by 2090.

Regional variation in the total annual rainfall occurs between western and eastern Scotland. Between 1961 and 2004, Scotland experienced a significant 20% increase in precipitation, due to a large increase (50%) in the total winter precipitation, particularly in northern and western Scotland. Eastern Scotland has experienced a smaller 30% increase in winter precipitation.

The rainfall intensity is also projected (Hulme et al., 2002) to increase in all areas in the winter months, and the Barnett *et al* (2006) report indicates that a significant increase has already occurred in the number of days with 1mm of rainfall (or more) detectable, between 1961 and 2004. A small increase in the number of days experiencing very heavy rainfall has also occurred in the Scottish Borders, but this is not as great an increase as in the west of Scotland. The Barnett *et al* (2006) reports a significant 20% increase in maximum 5-day precipitation totals occurred between 1961 and 2004. Although the amount of rain has increased generally, it is most significant in eastern and western Scotland.

The UKCIP 2002 report (Hulme et al., 2002) simulations predict little change in the annual precipitation total for each of the 2050 and 2080 carbon emissions scenarios, but do suggest a shift in the seasonal distribution of rainfall (particularly in eastern Scotland) with significant increases in the winter, followed by drier summers. The UKCIP 2002 report simulations also predicts a 50% reduction in winter snowfall, particularly in northern and western Scotland, in the autumn and spring months.

Impact
A shift in the seasonal rainfall distribution to wetter winters and drier summers will have a profound impact on forests and their management. In the west of Scotland the predominantly wet gley and peaty gley forest soils will become seasonally wetter. This will tend to reduce the depth of rooting of shallowly rooting Sitka spruce (and other conifers) in the waterlogged anaerobic sub-soil horizons. Drier summers will exert an increased climatic moisture stress, on trees with shallower roots with a reduced rooting volume and lower available water capacity during the summer months. This effect will be most severe in the east of Scotland on soils which are indurated, which become waterlogged for longer periods in the winter, and drier for longer periods in the summer. Indurated horizons are slowly permeable to water movement but form a barrier to root penetration.

The winter is an important period for forest operations. With increased rainfall, many wet forest soils will become unworkable during and following periods of heavy rain. More careful planning of operations will be required, with a greater emphasis on monitoring weather conditions and the potential impact of soil damage by machinery on waterlogged soils.

1.4. Summer heat and drought

The moisture deficit calculated from UKCIP 2002 scenario simulations shows a marked regional change in Scotland (Figure 2). The data represent the average climate conditions over the 30 year period centered on the years 2050 and 2080 for high carbon emissions scenarios. The average climate data is constructed from a 30 year record. Assuming that the future climate will continue to feature year-to-year variability; future droughty summers will occur more frequently than now, in order to change the average moisture deficit by such a large amount. Figure 3 shows the year-to-year variability in moisture deficit between a wet summer –2004, an average summer – 2005, and a very dry summer – 2003.

Impact
Although warmer growing season temperatures will tend to increase the productivity of most tree species, this is only if soil moisture is non-limiting. Dry summers usually create high soil moisture deficits, causing stomata to remain closed, evapo-transpiration to reduce and after prolonged dry weather, moisture stress to develop in trees. Some tree species are more prone to drought stress than others. Drought damage can be physiological and/or secondary through increased susceptibility to pathogens. Therefore, on drought sensitive soils (e.g. freely draining) care should be taken in the choice of species for the future.

Figure 2. Changes in the distribution and extent of moisture deficit predicted in the mean climatic data for Scotland in the 21st century, for a high carbon emissions scenario centered on the years 2050 and 2080, and compared to MD for the baseline climate.

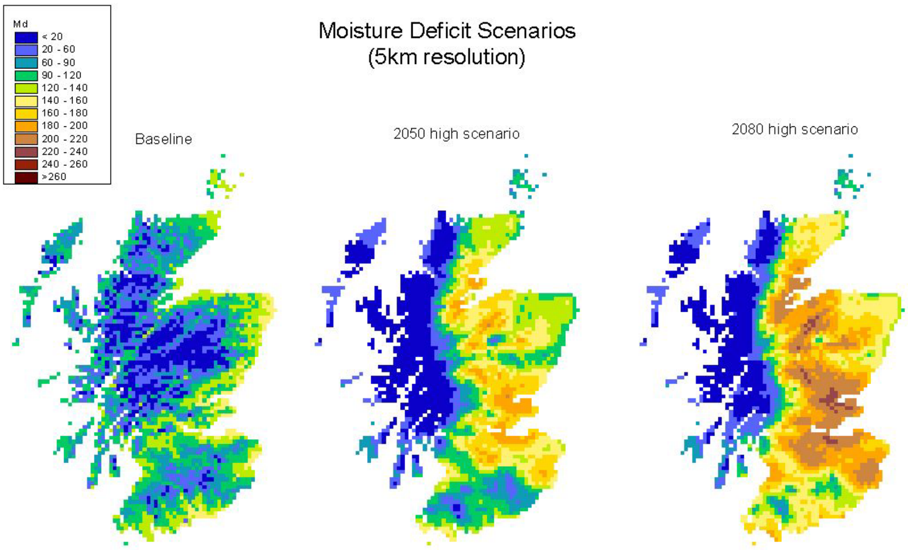
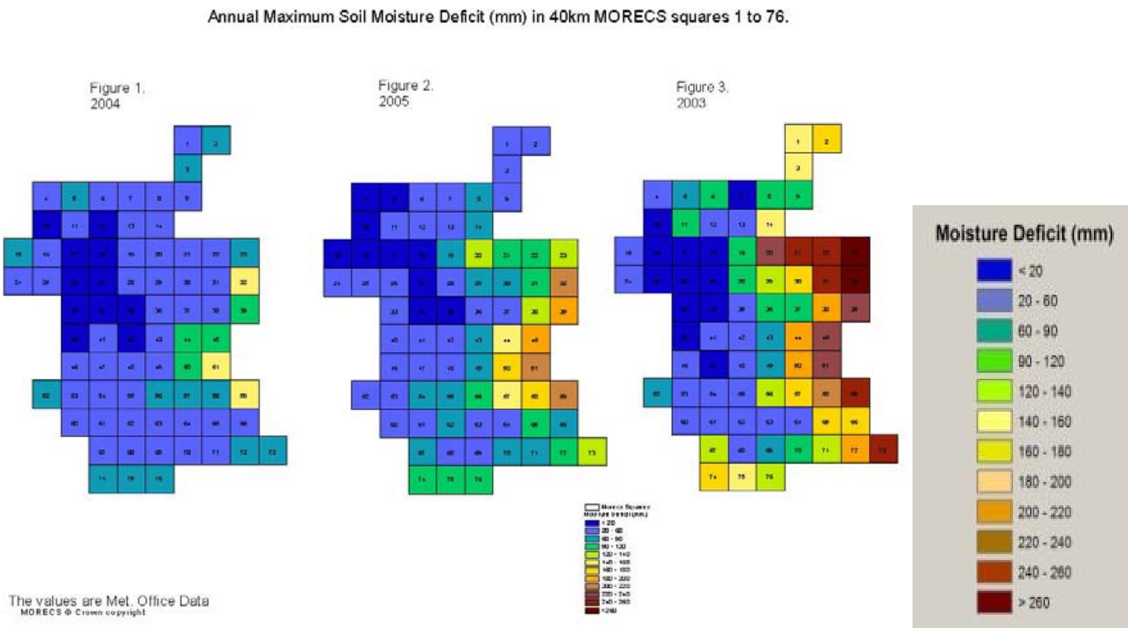


Figure 3. Comparison of moisture deficits in 2004 (wet summer), 2005 (average summer) and 2003 (dry summer) calculated for short grass by MORECS.



1.5. Wind

The UKCIP report and simulations do not provide information or evidence for a change in the wind climate of Scotland, other than projecting no change in the mean annual wind speed. These wind simulations have no effect on DAMS calculated for the future climate scenarios. There are references to a recent positive increase in the North Atlantic Oscillation Index (NAO – an oscillation in the pressure gradient between Iceland and the Azores) linked to human-induced warming. It has been shown that winter gales are more severe and more often westerly when the index is positive. The projected changes in the mean wind climate are not adequately covered by the Hadley GCM.

Impact

The trend of increasing severe winter gales from the Atlantic has continued for several years, and this is likely to cause greater disturbance on impeded soils in the wetter winter climate. As a result forest managers may have to adapt by concentrating timber production on more sheltered sites, and thereby spreading the risk of damage. Sheltered sites are often in lowland areas, and to increase woodland cover to 25% there will be greater land-use pressure on the more favoured agricultural land.

The introduction of more species, including a more widespread adoption of intimate mixtures on exposed and wetter land should help risk management. Self-thinning mixtures in particular may be very suitable for windthrow-prone sites resulting from wind exposure and/or wet soils. The self-thinning (competition- suppression) dynamics of the stand have been shown to maintain a more even canopy surface roughness through the competition phase, resulting in a reduced risk of premature windthrow (e.g. Birkley Wood - Kielder Forest District).

The management of thinning may need to be modified on risky sites. A key objective will be to try and maintain a similar canopy roughness over the age of the stand. This might be achieved by an earlier initial intervention and more frequent thinning thereafter, to allow time for trees to adapt to windy sites before the stand reaches a vulnerable size.

The DAMS threshold (19) for growing production stands of conifers may need to be reviewed. Any change in this threshold will have an impact on the area of productive forest in Scotland (Figure 4 and Table 1).

1.6. Conclusions

1. Our understanding of the future projected climate from UKCIP02 model simulations is currently incomplete. The forestry sector requires both climatic and weather event probabilities to assess the degree of risk in adapting species choice and management.
2. The Scottish climate will become warmer with milder winters and hotter summers
3. Rainfall amounts will increase in the winter and decrease in the summer.
4. Moisture deficits will increase generally in eastern and southern Scotland. It is also likely that the frequency of very dry (droughty) summers will increase in eastern Scotland.
5. The frequency of frost days will decrease in all parts of Scotland.
6. Projections of the wind climate are less uncertain, as current model simulations show little change in the mean wind speed. However an increase in wind disturbance is likely on forest soils with impeded drainage as a result of increased waterlogging (causing root damage) in the wetter winter climate.

Figure 4. The wind climate expressed as a DAMS score distribution across the forests of Scotland

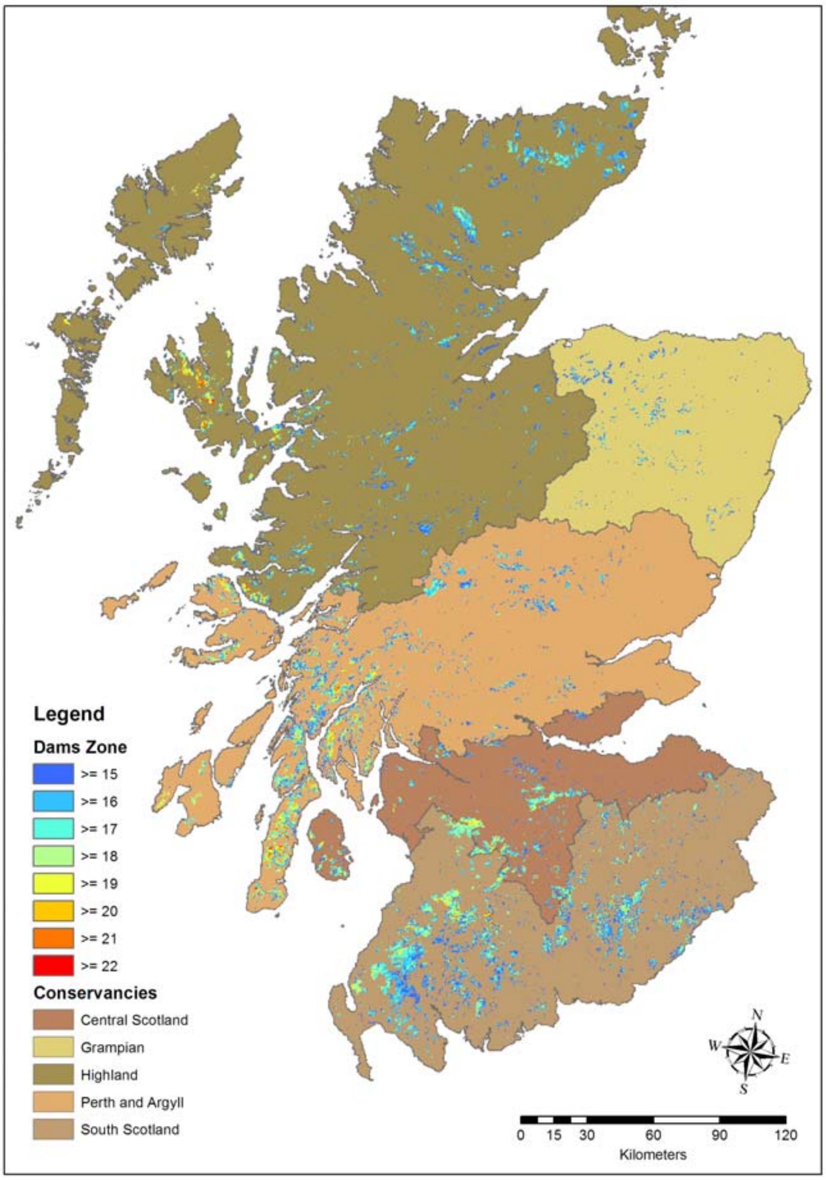


Table 1. The most exposed forest area (ha) expressed by DAMS score (Quine and White, 1993), split by conservancy area

	Central Scotland	*Grampian*	*Highland*	*Perth and Argyll*	*South Scotland*	*All Scotland*
DAMS 18	*5025*	*463*	*5400*	*7369*	*14356*	***32613***
DAMS 19	*2331*	*100*	*2631*	*6087*	*5269*	***16418***
DAMS 20	*938*	*18*	*2050*	*4019*	*1650*	***8675***
DAMS 21	*194*	*0*	*800*	*1775*	*600*	***3369***
DAMS 22	*25*	*0*	*675*	*537*	*262*	***1499***
Total	**8513**	**581**	**11556**	**19787**	**22137**	**62574**

2. Managing the impacts of climate on forests and tree species

2.1. Species and provenance choice

The overarching principal is to maintain a wide genetic base of material on risky sites.

2.1.1. Sitka spruce

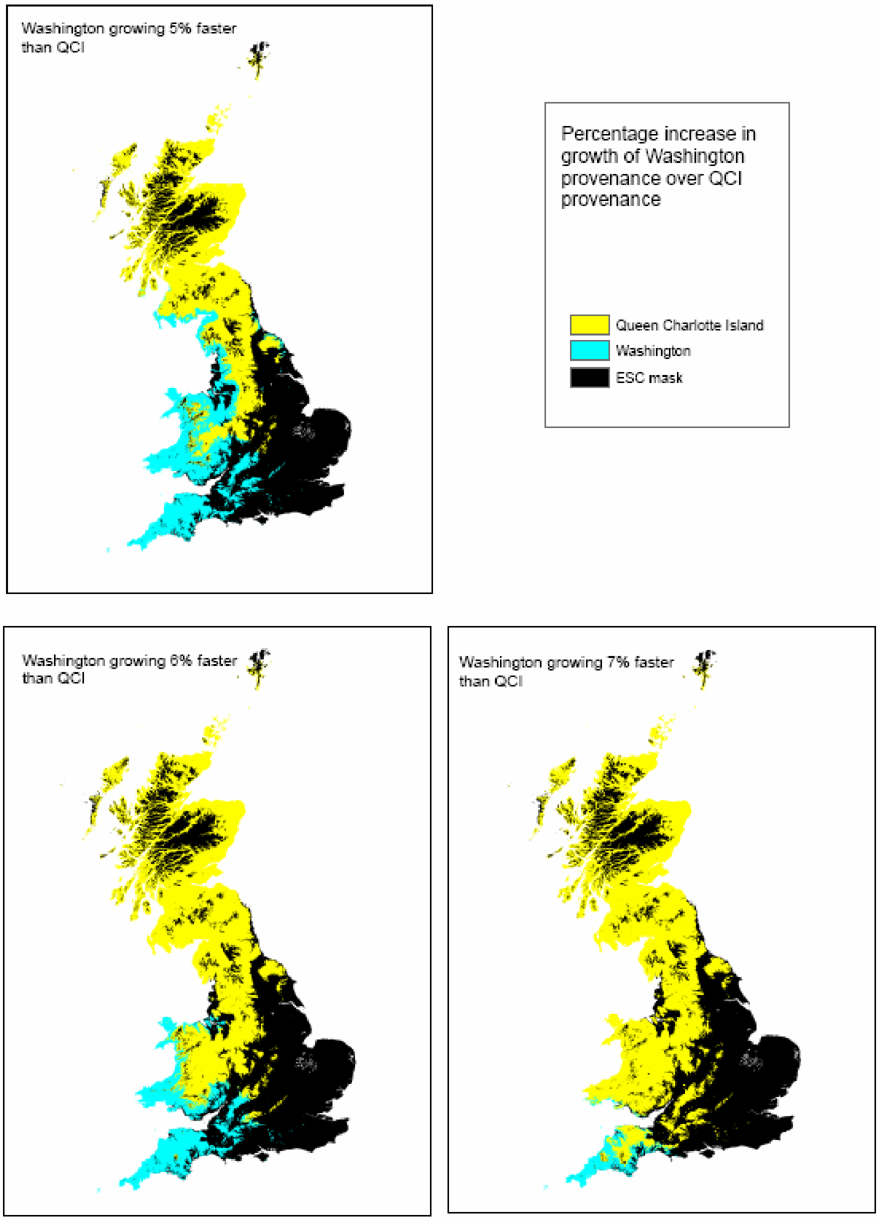
Sitka spruce breeding programme identifies 5 (possibly 6) levels of improved material, which may have a role in future production forests in a changed climate, the material in order of improved quality is:

1. Basic unimproved Sitka spruce stock, but of known provenance (e.g. QCI).
2. SS QCI seed stand material from the UK and shown to be well adapted to UK conditions.
3. Seed orchard material of improved QCI (iQCI) – progeny tested and shown to deliver a significant economic gain of 1 YC on most site types (e.g. YC 18 to YC20).
4. Vegetatively propagated material, demonstrating better timber quality attributes.
5. Full sib family material, in which both parents have been selected for economic gain.
6. Clonal material – not yet available.

In addition, there are alternative provenances of Sitka spruce from which to choose. However, it is well known that provenances of Sitka spruce from more southerly latitudes than the Queen Charlotte Islands (QCI at a latitude of 52 0N), for example Washington-SS and Oregon-SS, are available (though currently scarce) and can produce greater rates of growth than unimproved QCI-SS. However, due to a longer growing period causing later onset of dormancy, both Washington-SS and Oregon-SS are susceptible to frost damage in Scotland's climate in a more northerly latitudinal range. Forestry Commission Bulletin 127 (Samuel et al., 2007) provides indicative maps (Figure 5) on the likely extent of Washington-SS in Scotland (Oregon-SS is not suited to Scottish conditions). The suitable range for Washington-SS is within SW Scotland in an area confined to the coastal fringe, becoming unsuitable north of Ayrshire, Arran and Kintyre. Within the suitable range Washington-SS should only be selected on south-west facing no more than 10 km from the sea, on slopes of more than 5 degrees to avoid frost damage. In addition sheltered locations should be favoured to avoid leader breakage, leading to reduced timber quality.

From a commercial perspective, in Scotland the use of iQCI-SS is generally recommended, providing a whole yield class advantage over unimproved QCI-SS material, except on exposed sites, where there is likely to be no gain in improved yield or quality. iQCI has been observed to produce significant lammas growth, and this late season production of tender shoots can be damaged by early frosts. It is therefore important to have a clearer projection of the future likelihood of early frosts in different parts of Scotland, or failing that, avoid using iQCI on known frost prone sites.

Figure 5. Map showing the suitable distribution of the WSS provenance in Britain. In Scotland, the suitable zone extends only into the south western coastal fringe of Dumfries and Galloway.



Research is required to establish if and where there are sites that might improve for Washington-SS, and on such sites, whether Washington-SS is likely to be better than iQCI-SS.

Mixing provenance and iQCI on a site as a way of spreading the risk of damage is perhaps flawed, because selection pressure generally occurs very early on in the rotation (first 5-20 years) when young crops are also most susceptible to damage resulting from frost, drought, and waterlogging, and become suppressed prior to or through canopy closure. For conifers, the suitability of improved material or provenance material should be judged at the whole rotation scale and decisions on its continued use, or a change to better suited material, made as the end of the rotation. This logic would allow for early (pre-economic) felling if conditions dictate. However this model does not fit broadleaved species, due to the much longer rotation periods, unless there is a market opportunity for small diameter hardwood.

2.1.2. Douglas fir

Some work has been completed on Douglas fir provenance suitability. In France more southerly provenances of DF are used, and these may be suited to sites in England (and possibly Scotland) in the future. There is some scope therefore to recommend provenances of DF on Scottish sites from our knowledge of the natural range, the experience of growing different provenances in more southerly parts of Europe, and our ability to match future climates to current climatic conditions in Europe. The currently recommended DF provenance is from the border region between Washington and Oregon close to the Pacific end of the Columbia River.

2.1.3. Seed Origin

Current guidelines on using local origin seed for native species is based on an assumption that local material is the best adapted for local sites. With this assumption in mind, the UK Forestry Standard (Anon, 2004), and UKWAS (Anon, 2000) recommend the use of local material where possible. There is concern about the use of poorly adapted material, particularly regarding the offspring of interbreeding between local and introduced non-local material, having reduced fitness compared truly local genetic material. Recent information (Hubert and Cottrell, 2007) suggests that the scale at which local adaptation operates has been misinterpreted for many of Britain's native tree species, which are long-lived and open-pollinated, and likely to have become adapted to a wider range of biophysical conditions. Because of the history of management of the landscape and the longevity of trees, there is often no certainty that a local population has adapted to local conditions 'over many generations', nor that the population could adapt to changing climatic drivers within a single generation, even where the population does contain the genetic diversity necessary to adapt to change.

2.1.4. Genetic diversity of British populations

Research has shown that oak and ash re-colonised Britain from Spain following the retreat of the quaternary ice sheet, whereas beech and black poplar migrated from refugia in south-east Europe. The British populations are based on single lineages and are therefore likely to contain fewer genotypes and less genetic diversity than continental populations that have multiple lineages from different refugia. Scots pine re-colonised Britain from 2 refugia: SW Ireland and continental Europe, and native woodland conservationists have attempted to maintain the separate identity of these lineages. Two other key factors that must be considered are the degree of woodland fragmentation - leading to opportunities for seed and pollen flow, and the rate of climate change.

2.1.5. Provenance selection

Provenance trials of tree species have shown very little adaptive variation within Britain. Since the degree of change across biophysical gradients is small in Scotland, it suggests that local adaptedness within species is also small across the country for most species. Common-garden studies have shown that vigorous provenances tend to perform well across the climatic range within Britain, and that the degree of biophysical variation within Britain is small compared to the natural range of our native species.

Experiments have shown that when height growth is used as the focal trait, material from up to 2^o south of the growing site can outperform local provenances. However, height improvement is just one of many adaptation traits, and it is usually the extreme biophysical events that provide the selection pressure, and an adaptation quality measure of the provenance. In Scotland, we may currently look south as far as a line between the Rivers Humber and Mersey for suitable provenance material. Because of climate change this distance will increase, as climate matching studies show that some areas of Scotland may have a future climate that is similar to north-western France.

2.1.6. Seed zones and biophysical site matching

Areas which classify broad similarity across a range of biophysical variation can be thought of as seed zones. In Britain, the seed zones are small and conservative by comparison with other countries, reflecting the use of the system as an administrative tool for monitoring seed production rather than a scientific method of reducing the possibility of biophysical maladaptation. Ecological classification systems provide a more robust system for assessing the suitability of provenance and selecting material for a site.

2.1.7. Climate matching - selecting adapted

Climate and ecological site matching is a more reliable method of selecting provenance for the future climate. The assisted movement of material from areas currently experiencing biophysical conditions similar to those predicted for a site in the next 50-100 years is an important strategy for Britain generally. The rate of change in climatic factors projected for the 21st Century will far outpace the rate at which species might adapt through the sieve of natural selection.

Climate matching studies show that under the 2080 high carbon emissions scenario the climate of Kelty, in Fife, will be similar to the present climate of the Loire in France (Broadmeadow et al., 2005). Importantly, very high quality conifers and broadleaves grow in the Loire Valley. Climate matching studies are needed for all regions of Scotland, to help target suitable provenances of various species.

Scottish provenances seem to be conservatively adapted, and are currently rather sub-optimal for site and climatic conditions. Birch trials have shown that material from the Vale of York performs much better than local material at Craigvinean. It appears therefore that we should increase the genetic diversity of birch, particularly on risky sites, and in any case definitely not do anything to narrow the genetic diversity of stands.

2.1.8. Flushing date

Some species such as oak, show a linear flushing response to warmer springs and autumns, whereas the lack of intense winter chilling of ash in Scotland's maritime climate inhibits early flushing in warmer spring weather. Modelling studies suggest that for plants which respond to temperature change, the timing of spring flushing in Scotland is more sensitive to temperature cues than in any other part of Europe. An increase of 1^0C is predicted to advance the flushing date by 11 days in Scotland, and projections suggest a 3^0C temperature increase in Scotland. More northerly families of oak are more sensitive to temperature induced flushing than southern families, therefore it would seem prudent to introduce families into Scottish woodlands from northern and central England, that are well adapted to a similar site types.

2.1.9. Risk minimization

Woodland management is a long term process, with timber rotation periods of between 50 and 200 years, depending on species. Within this rotation range projections are for the climate to change significantly. Climate change impacts such as prolonged summer periods without rain leading to drought are likely to occur in southern and eastern

Scotland. Accompanying changes such as the increased seasonality of rainfall (leading to wetter winters, waterlogging and root death), warmer extended periods (supporting tree growth), and the changes in tree disease and pest ecology will all contribute to greater stress on woodlands.

Minimising risk is about adapting woodlands in a way which spreads the risk. If climate and site conditions allow, low impact silvicultural systems (LISS) would help spread risk, reduce extreme changes in the woodland microclimate, support mixed species woodland with structural diversity. If LISS is not feasible due to site conditions, then mixing species and provenance at restocking is an option. If stability is a main concern, then the use of self-thinning mixtures is an option.

2.1.10. Climate change adapted species

In addition to selecting suitable material and provenance from sites with a current climate similar to that predicted for the future forest, a range of less frequently used forest species will become better suited to the changing climate of Scotland. The list includes:

- *Pinus pinaster*
- *Pinus radiata*
- *Nothofagus nervosa*
- *Nothofagus obliqua*
- *Nothofagus pumilio*
- *Juglans regia*
- *Castanea sativa*

2.1.11. Conclusions

1. During the middle part of the 20th century there was a tendency to increase stand uniformity to improve timber quality, uniformity and utilization. Climate change may have a serious impact on stands managed in this way.
2. The emerging view is for greater variability and diversification from the genetic to the stand scale, including mixing tree species in stands and varying management systems and the timing of operations.
3. Diversity should provide some protection from climate impacts, by spreading the risks of management in a rather uncertain climate future.
4. A key issue is that species (and provenance) should be well suited to site conditions, and capable of absorbing and surviving more extreme weather with a potentially significant impact on forests.
5. Improved decision support tools (e.g. ESC and ForestGALES) for species choice in future climate scenarios will be required, and more research on the suitability of species and provenance from more southerly regions is required.

2.2. Timber quality

2.2.1. Timber quality criteria

Following the classification by MacDonald and Hubert (2002) the main timber quality criteria for construction grade timber are:

- Dimensions/size – the size (length and cross-section) of sawn timber is critical to its use in a particular situation. Logs need to be of sufficient diameter and length to make construction grade timber.
- Stiffness and strength – the bending stiffness/strength of all Scottish construction grade timber is determined by machine stress grading. The stiffness and strength are influenced by knot size and frequency, fibre grain angle, wood density and microfibril angle.
- Dimensional stability – differential shrinkage may lead to distortion of timber as the moisture content of the wood varies. Distortion is a function of the fibre grain angle, microfibril angle, the distribution of compression wood and the proportion of juvenile and mature wood.

2.2.2. Genetic Improvement and Silviculture

Although climate change will bring some changes to the growth rate and timber properties of British grown trees it needs to be remembered that these changes are likely to be much less important than the impact of genetic choice and forest management. Good choice of genetic material and appropriate silviculture can have a large and beneficial impact on maintaining and improving the quality of Scottish produced timber.

2.2.3. Site selection

A key factor in maintaining the quality of Scottish timber is to choose, wherever possible, the species or provenance best suited to the site type. In Sitka spruce cracking and ring shake in mature stands can result from water stress on droughty soils during dry summers in eastern Scotland. Conversely Scots pine can produce poor form and lower timber quality because of forking and heavy branching, on sites that are too wet, usually where winter water-logging is a problem.

Although eastern Scotland has been identified as potentially the area with the most serious risk of drought induced cracking in Sitka spruce, the problem may occur in parts of southern Scotland in the future. In the current climate, in southern and western Scotland, a 1 in 40 year drought (2 dry months) might be considered the limit of risk for a Sitka spruce site. However in the future, a shift in the seasonal distribution of rainfall is predicted, and 2 dry months will occur more frequently in the south and west of Scotland.

Micro-site assessment is also extremely important; frost hollows, aspect and slope should be considered in relation to the likelihood of drought or frost damage and its effect on the species being considered for the site.

2.2.4. Frost and winter cold

As the winter climate becomes milder over most of Scotland, some species may not enter dormancy until late in the winter, and the degree of winter hardening may be reduced. However, for the main conifer species day-length is the critical factor leading to trees beginning to enter dormancy. This is a function of provenance with northerly provenances entering dormancy earlier. With milder winters it will still be important to pay careful attention to provenance choice and use provenances not at risk from autumn frosts before the trees have entered dormancy.

The time of flushing in the spring is mainly controlled by temperature and there is less variation between provenances. Milder winters will encourage earlier flushing and make trees vulnerable to late spring frosts. Knowledge of the variation in temperature at a specific location and the correct species/provenance choice will be important for minimising the impact of any frost damage.

Many tree species are able to take advantage of warm late summer and autumn periods by producing lammas growth beyond the terminal bud set at the end of the main part of the growing season. Tender shoots formed in this way are especially vulnerable to early autumn frost, which could lead to stem forking. Additionally, the lammas apical shoots set a second whorl on the stem leading to increased knottiness in sawn timber.

2.2.5. Growth rate

The most important climatic variable for plant growth is temperature, and when water and nutrients are not limiting, most species will produce increased growth (height or diameter or both) in warmer growing seasons. It has been suggested that the rising CO_2 and climate warming will result in an increase in the general yield class of 1 unit for most species (e.g. from YC 6 to YC 8 for oak; YC 14 to YC 16 for Sitka spruce). Trees growing faster will tend to have larger heights, diameters and inter whorl distances.

Table 2. Comparison of Sitka spruce timber quality properties with yield class

		Yield Class		
Property	**Unit**	**14**	**16**	**18**
Average wood density (12% moisture content)	kg/m3	424.9	421.6	419.6
Average between whorl spacing	m	0.45	0.50	0.55
Average knot size for whorl with biggest branches	cm	3.40	3.65	3.90
Knot surface area ratio on outside of logs	none	0.01	0.01	0.01

With increasing growth rate there will be changes in the wood properties of importance for timber performance. Table 2 shows the change in 4 important criteria affecting timber strength as YC increases for Sitka spruce (holding site and tree spacing factors constant) as predicted by the FR timber quality model (A. Achim, personal communication). For a change of 1 yield class the model predicts a reduction in wood density by between 0.5-0.7%, an increase in whorl spacing of around 10%, a 7% increase in knot size and no change in the knot area ratio on the outside of logs

Research Information Note 212 (Maun, 1992) describes the sensitivity of the outturn of structural grade C24 Sitka spruce timber as a function of wood properties. A 10% increase in the surface area of knots in battens was predicted to reduce the number of battens qualifying as C24 by 3%, whereas a 10% increase in knot spacing would increase the number of qualifying battens by 4%. Finally, a reduction of the density of the wood by 10% was predicted to reduce the qualifying number of battens by 5%. Based on these results and those illustrated in Table 2 we can assess that climate change resulting in a 1YC increase in the growth rate of Sitka spruce will have no impact on the stress-graded batten recovery of British grown Sitka spruce.

Although conifers such as the spruces and firs tend to have reduced wood density with increased growth rate pines, larches and Douglas fir show little or no reduction in wood density with faster growth. Therefore, for these species there is also likely to be no change in the timber performance with increased growth rates resulting from climate change.

Hardwoods vary in response to increased rate of growth. The oaks, ash and elm are ‘ring porous’ producing harder and stronger timber when grown fast. In contrast, sycamore and birch are ‘diffuse porous’ and do not respond in this way. Chestnut and beech show an intermediate type of response.

2.2.6. Stem form

Stem form (straightness and taper) is a phenotypic attribute described as a function of the genotype combined with the biophysical factors of a site (environment). Scotland’s wind climate has an important influence on the loss of leaders during strong storms. Leader loss leads to crooked stems as one of the side-branches takes over apical dominance from the lost leader. This poorer stem form in turn leads to a lower recovery of desirable straight ‘green’ logs used in construction grade timber production. However, with time trees recover straightness as the initial bend following leader loss is subsumed within the tree and, therefore, increased rotation length can be an important factor in improving tree form.

Background wind loading can cause coniferous trees to produce compression wood and broadleaved trees to produce tension wood. Both these types of wood lead to increased difficulties in processing and poorer performance in service. In particular compression wood can lead to increased distortion and brash type failure under loading. Currently compression wood is not a serious problem in British grown conifers but attention needs to be taken in site selection in order to avoid the windiest sites if construction quality timber is desired.

2.2.7. Conclusions

1. Species choice, genetic selection and management system will have a bigger impact on the quality of future Scottish timber supplies than forecast climate change.
2. It is crucial to ensure the selection of the appropriate species, provenance and management for each site in order to maintain the quality of the Scottish timber supply
3. Forecast changes to the wood properties of the major Scottish timber species are predicted to have no measurable impact on the suitability of future sawn timber supplies to meet existing markets.
4. Climate change is predicted to increase the growth rate for most species. The impact of this increased growth will vary from species to species but is not expected to have an impact on the performance of Scottish timber.
5. Increased windiness may lead to poorer form on some sites due to increased leader loss. This can be mitigated by appropriate site choice and increased rotations.

2.3. Pests and diseases

2.3.1. General

Climate change will influence the distribution and abundance of many pests and pathogens. However, predicting the organisms likely to be affected, and whether climate change may lead to an increase in the frequency or intensity of damage is difficult to predict other than in very general terms, especially where complex interactions are involved. Nevertheless, a reasonable assessment can be made based on present knowledge of key pests and pathogens and the role played by environmental factors in their life cycle and population dynamics. For insect pests, one of the more general predictions for temperate regions of the northern hemisphere is that under climate change, ranges are likely to extend northwards and to increase in elevation. Pathogens on the other hand are often more widely distributed but within their range, disease severity can vary in relation to local climate. As for insect pests, climate may act directly on the pathogen or indirectly, for example, by affecting host resistance.

Temperature and rainfall are the two important aspects of climate change likely to affect forest pests and pathogens. For insects, simple responses to rising average temperatures include an increase in the development rate and in the number of generations per year. For example, semi-voltine insects (life-cycle taking more than one year) may become uni-voltine (a single generation per year), whereas those with a uni-voltine life-cycle have the potential to become multi-voltine. Other direct effects include the influence of winter temperatures on survival and of rainfall on mortality of vulnerable feeding stages. Examples of indirect effects include loss of phenological synchrony due to differential effects of temperature on host and insect development and the effects of drought or waterlogging on tree susceptibility.

Foliar pathogens which infect the leaves and needles of trees are likely to be most directly affected by climatic change and already show marked fluctuations each year depending on weather conditions. Overall however, there is a high probability that many pests and diseases will become more prevalent in Scotland under a climate with milder winters, and more frequent droughty summers. Milder conditions are particularly likely to present pathogens with longer periods of activity, closer to their optimum temperature for growth, while the increased frequency of drought will stress tree species not well suited to the site conditions, which in turn will encourage pest and pathogenic attack.

2.3.2. Insects

Likely effects of Climate Change are discussed in relation to the different ‘kinds’ of forest pest, characterised by life history and feeding ecology. There will be some generalised differences in the way these groups respond to climate change. For example, insects such as defoliators or aphids that are exposed on the surface of trees during feeding are more likely to be influenced by insolation and the vagaries of the weather whereas for those feeding in more ‘buffered’ environments within the tree such as bark beetles or shoot borers, indirect effects of the environment on the host should be relatively more important. Within each grouping there will be differences in the way individual species respond.

Bark beetles and weevils

Many bark beetles are ‘secondary’ pests, usually breeding in logs or windblown trees. A few species are primary pests and can breed in living trees, most commonly as part of a strategy of mass attack. The population dynamics of bark beetles will be influenced by factors such as drought stress of the host tree and by storms that increase the abundance of windblown timber in which they can breed and build up populations large enough to attack living trees. Bark beetles, some of which transmit fungal pathogens, and weevils are some of the most important forestry pests because of their ability to kill trees.

The spruce bark beetle, *Dendroctonus micans*, is solitary species and so is atypical of those able to attack living trees. An introduced species, it can cause significant damage and mortality when populations build up in infested stands. Initially restricted to Wales and the English border region by internal quarantine, it is now extending its range following relaxation of controls and is expected to spread to all spruce growing areas. Natural constraints on population growth in affected stands are the effects of an introduced predator, variation in resistance of spruce trees and a life cycle that often takes more than one year. Higher temperatures could increase the rate of spread into spruce growing areas and are likely to reduce development time and so increase the rate of population build up. The predicted increase in drought stress of spruce in eastern Scotland is likely to make trees more susceptibile to attack by *Dendroctonus*.

Another introduced bark beetle, *Ips cembrae*, attacks larch and occurs throughout eastern Scotland. Normally breeding in larch logs, populations can build up following silvicultural operations and damage the crowns of trees during maturation feeding. Beetles can attack standing trees when overmature or stressed and its association with a pathogenic blue-stain fungus, *Ceratocystis laricicola*, means that such attacks can lead to dieback and death of trees. Higher temperatures and disrupted rainfall patterns should increase tree susceptibility. Larch stands subject to windblow are likely to suffer increased damage by this bark beetle.

Populations of secondary bark beetles such as the pine shoot beetle, *Tomicus piniperda*, will also response to an increased availability of breeding material after windblow, and like *Ips cembrae*, can damage standing trees through feeding in the tree crown. Pine shoot beetle can be particularly damaging when associated with outbreaks of pine looper moth as discussed below.

The pine weevil, *Hylobius abietis*, is a significant pest of spruce and pine throughout the UK. A ‘silvicultural’ pest, population densities and consequent damage levels are determined mainly by the availability of stumps and associated roots of newly felled conifers in which the weevils breed. Pine weevil is a particular problem in areas with intensive clearfelling and replanting programmes. In Scotland, the life-cycle on spruce is exclusively semi-voltine and one consequence of this is that emergence from root-stumps can occur in two or more consecutive years. Transplants are therefore vulnerable to attack over a extended period. Under climate change, the life cycle of *Hylobius* is likely to shortened so that in Scotland, the main reduction in impact will be a through a reduced fallow period. Damage levels, are likely to decline under continuous cover management.

Defoliators (Lepidoptera and sawflies)

Defoliators can cause extensive outbreaks in both broadleaved and conifer forests. The main economic effect is through growth loss but in conifers, this depends on which age class of needles is affected and the seasonal timing of attack. Simultaneous outbreaks two of species of defoliator attacking different age classes of needles are particularly damaging. Some defoliators have cyclic population dynamics.

The pine beauty moth, *Panolis flammea*, and the pine looper moth, *Bupalus piniaria*, are two of the most significant defoliating Lepidoptera and both are a particular problem in Scotland. For both defoliators, climate and site-related factors are thought to contribute to the development of outbreaks. As a pest of lodgepole pine, *Panolis flammea*, is particularly damaging because, unusually, a single complete defoliation can kill trees. The gradual replacement of lodgepole pine plantations is likely to solve the problem of *Panolis* in the medium term as this native insect occurs only at endemic levels on Scots pine. *Bupalus*, which defoliates more mature trees, causes growth loss but defoliated trees may be attacked and killed by *Tomicus*. Populations of *Bupalus* show cyclic changes in density and there have been several damaging outbreaks in Tentsmuir forest. Eastern Scotland could become more vulnerable to outbreaks of this defoliator. Recent outbreaks of *Bupalus* on lodgepole pine in Sutherland in which trees were killed by a single defoliation without the intervention of *Tomicus* are very unusual and may be indicative of effects under climate change.

Several species form a defoliating complex associated with broadleaved trees such as oak and birch, including species such as the winter moths, *Operophtera brumata* and *O. fagata*, the oak leaf roller moth, *Tortrix viridana*, and the autumnal moth, *Epirrita autumnata*. Their pest status is illustrated by periodic defoliation of trees and the extension of the host range of *O. brumata* onto Sitka spruce where it can cause significant damage. In general, synchrony of egg hatch with host flushing in the spring in these early season feeders is important for larval survival and can influence population levels from year to year. Differential effects of climate change on host and insect development has the potential to affect this synchrony and so influence population dynamics. Effects are difficult to predict with the present state of knowledge but the 'host-shifting' observed in *O. brumata*, appears to be opportunistic rather than an effect of climate change.

Conifer sawflies have occasionally produced spectacular outbreaks in the UK and in some species, climatic and sites factors seem to play an important role. Outbreaks of introduced species such as the web-spinning larch sawfly, *Cephalcia lariciphila*, and the European spruce sawfly, *Gilpinia hercyniae*, have been confined to the southern half of Britain. A northward extension of their range under climate change seems likely but the occurrence of outbreaks is difficult to predict. Extensive overlap in the ranges of *Cephalcia lariciphila* and *Ips cembrae* could pose a threat to Scottish larch populations.

The pine sawfly, *Neodiprion sertifer*, is one of the most important defoliators of Scots pine in northern Europe. In cold northern regions, warmer winters are predicted to increase damage by reducing overwintering egg mortality. In Scotland, low winter temperatures are unlikely to be a limiting factor in population dynamics.

Aphids, scale insects and adelgids
This group of sucking insects has a number of significant pests. Adelgids tend to be a particular problem on Christmas trees and are only mentioned here for completeness. Aphids are noted for their parthenogenetic reproduction and multi-voltine development. Because of this, aphid populations are likely to respond strongly to favourable weather conditions. They would however be more vulnerable to weather-induced mortality factors such as heavy rainfall or unseasonal frosts.

Outbreaks of the spruce aphid, *Elatobium abietinum*, cause significant defoliation of Sitka spruce at any stage during the rotation, resulting in loss of annual increment. Temperature has an important influence on the population dynamics of this aphid. But so can natural enemies and the resistance and nutritional quality of the host, making it difficult to predict the net effect of climate change on population dynamics. *Elatobium* can reproduce throughout the year. During the spring to autumn period, the duration and seasonal timing of optimal host nutritional quality and prevailing temperature have a large influence on reproductive rate. Populations are likely to benefit from the increased incidence of drought stress of spruce which is predicted to be more frequent in eastern Scotland. The aphids are vulnerable to low winter temperatures which can cause widespread mortality so the predicted warmer winters in Scotland should increase overwintering populations. High overwinter populations and favourable conditions during the growing season can lead to outbreaks, which in the current climate occur approximately every 5-8 years. The mean abundance of *Elatobium* populations seem certain to rise in a warming climate resulting in a general increase in the impact on the growth of spruce. However, with the current state of knowledge and the complexity of interactions, climate-induced effects on the frequency and intensity of outbreaks cannot be predicted with any certainty.

Drought-stressed trees attacked by *Elatobium* are likely to be much more susceptible to bark beetles. Future widespread overlap in the distributions of *Elatobium* and *Dendroctonus* in eastern Scotland will increase the threat of significant pest damage on drought-prone sites.

In southern England, beech plantations have been affected by beech bark disease which can cause significant mortality. The beech scale insect, *Cryptococcus fagisuga*, plays a key role in predisposing trees to a pathogenic fungus that colonises and kills bark on the trunks of trees that have very high scale insect populations. Within stands, populations of the scale insect build up relatively slowly and climatic factors do not seem to play a key role, although high rainfall can cause significant mortality. Beech, which is predicted to become a more significant component of Scottish broadleaved woodland under climate change, is unlikely to be at high risk from beech bark disease.

2.3.3. Pathogens

Foliar pathogens

Red band needle blight is currently one of the most commercially significant and damaging foliar diseases. It affects more than 60 species of pine; the most susceptible include radiata, lodgepole and Corsican pine, and is occasionally found on Scots pine. Other conifers such as European larch, Norway spruce, Sitka spruce and Douglas fir have also been reported as hosts. The disease is caused by the fungus *Dothistroma septosporum* (also called *Mycosphaerella pini*) which is of unknown origin although both the Himalayas and high altitude rain forests in South America have been suggested as the native range of this pathogen. In the 1950s and 1960s the disease was reported on Corsican and ponderosa pine at Wareham nursery in Dorset. Since 1990 it has become more widespread in Britain, and is now causing serious damage in East Anglia on Corsican pine possibly as a result of local climatic change. The fungus requires high humidity, and temperatures between 12 -180C for successful infection and over the past 30 years East Anglia has seen a trend towards an increased number of consecutive days with rain where the maximum temperature is at least 180C. Results of annual monitoring in East Anglia FD showed that in 2006 a total of 11,241 ha (81% of the

Corsican pine crop) was affected by the disease, and the percentage of stands where mortality is present has also escalated from 1% of stands in 2003 to 18% in 2006. Recently, the disease has been confirmed on Scots pine in central Scotland and lodgepole pine in western and northeastern Scotland.

The warmer wetter springs predicted by climate change are likely to encourage greater activity by this pathogen. In British Columbia, the marked increase in the severity of this disease appears to be strongly associated with changes in climate and species conversion (changes to more susceptible species such as lodgepole and loss of more resistant genera such as fir). The disease has been observed to be most severe in dense unthinned stands of pine. There is evidence to suggest that practices such as pruning and thinning which improve the airflow within a stand and reduce canopy humidity, make conditions less favourable for the pathogen.

Root pathogens

Phytophthoras are a mainly introduced group of pathogens. Many species are now widespread and often highly destructive, especially those that attack the roots and root collars of woody plants. They require moist soil conditions (even periods of flooding) for infection and spread, but the damage they cause tends to be most visible in the summer especially if trees are drought stressed. A build up of *Phytophthora* results in the death of fine feeder roots, even root and stem girdling, so trees may die suddenly when under water stress or show signs of marked decline. Current evidence suggests that episodes of oak decline are correlated with *Phytophthora* activity and this also predisposes trees to attack by secondary organisms such as *Armillaria* or bark beetles. Many species of *Phytophthora* can over-winter in soil through mild winters. The predicted warmer climate will result in milder winters in Scotland, and so may provide more suitable conditions for many root attacking *Phytophthoras*.

One of the most destructive species of *Phytophthora*, *P. cinnamomi*, has been associated with the decline of several forestry, ornamental, and fruit industries as well as over 900 woody perennial plant species. It is most damaging at temperatures of 25^{o}C or above and its present activity and distribution in the UK is therefore constrained by climatic conditions. Soil with a poor drainage, high clay content, high water table, hard pan, clay pan or where water pools after irrigation or rainfall have been associated with sites where *P. cinnamomi* is severe. It is likely that in the field, the combination of heavy rainfalls leading to occasional waterlogging, and summer droughts, acting in combination will predispose oak and other broadleaf genera to infection by *P. cinnamomi*. As *P. cinnamomi* is most pathogenic at temperatures of 25°C and above and does not survive freezing conditions in the soil, CLIMEX models have been used to assess how its activity in Europe could alter as a result of climate change. With the currently predicted moderate climatic warming up to the year 2050, activity of *P. cinnamomi* is likely to increase significantly in the Mediterranean region and in maritime climates such as that of coastal western Britain, but not in central Europe. The extent of the pathogen’s activity will also depend upon availability of suitable hosts and other ecological factors. Preventative measures and chemical application are the typical forms of control for this species. There are no eradication methods available to combat this species.

A much more recently introduced *Phytophthora, P. alni*, which infects alder is also likely to show an increase in activity in response to climate change. The pathogen is present in Scottish river systems particularly in the east, and apparently infects trees during flooding episodes. Recent modelling of the factors that increase risk of infection suggest that increased water temperatures and more episodes of flooding are both likely to contribute to more frequent episodes of infection.

Latent / endophytic pathogens

Endophytic pathogens infect trees years, even decades, before disease symptoms become apparent in the infected hosts. Perhaps one of the best known examples is sooty bark disease of sycamore caused by the fungal pathogen *Cryptostroma corticale*. This pathogen can remain quiescent and undetected in healthy trees unless they are put under stress of many consecutive days of high temperatures. When at least one summer month has a mean maximum temperature of 23°C, then there is a likelihood of sooty bark disease developing, and the more months that reach this mean maximum temperature, the greater the likelihood of more trees becoming affected and showing disease symptoms in the following year. Hot dry summers trigger the rapid development of this pathogen within the wood and subsequently the bark, causing death of branches and even entire trees, and in so doing liberating black, powdery spore mass within the bark tissues.

Other latent pathogens which cause disease linked to drought stress include species of *Biscogniauxia* and *Hypoxylon*. Two species, *B. mediterranea* and *B. nummularia*, cause strip cankers on oak and beech, although the former is largely limited to warmer European countries. *B. nummularia*, however, is common in southern Britain where it causes strip cankers on beech particularly after 'double-drought' years, but it is found as far north as southern Scandinavia. Increased summer temperatures and drought episodes are expected to shift the range of both these pathogens, and make their occurrence more frequent in Scotland.

Facultative pathogens

Increased climatic stress will also increase the susceptibility of trees to faculative or 'opportunist' pathogens. This includes weak pathogens such as the less pathogenic species of I(e.g. *A. gallica*) or canker causing fungi, which appear to be almost entirely dependent on host stress to impair host resistance before they can infect.

2.3.4. Alien pests and pathogens

In the medium term, one of the most important effects of climate change for pest management is likely to be an increase in the threat of introduction of exotic pests and pathogens that are able to survive in regions that were previously inhospitable or at least suboptimal. Models such as CLIMEX can be used to predict the likely 'favourableness' of climate for specific pests and are a useful aid in pest risk analysis (PRA).

The European spruce bark beetle, *Ips typographus,* is a moderately aggressive mass-attack species that can kill living spruce trees during outbreaks in Continental Europe. It would be a significant threat to spruce forests if it became established here. This bark beetle is regularly trapped at UK ports where it originates from imports of infested timber. It has also been caught in wood processing areas inland but apparently without becoming established. In a warmer climate with increased areas of drought-affected spruce and an increased frequency of windblow, the prospects for its establishment would be significantly increased.

Recently introduced species such as the oak processionary moth, *Thaumetopoea processionea* and the gypsy moth, *Lymantria dispar* are presently confined to the south of England and are unlikely to pose a threat in Scotland in the foreseeable future.

2.3.5. Changing management and structure in response to climate change

Suggested changes in forest management as a response to climate change such as planting new species or provenances or changing the species composition of forests have the potential to influence the frequency or spatial extent of pest or pathogen outbreaks. Forest monocultures are often stated to be more susceptible to pests and pathogens than more 'natural' mixed forests. The evidence that outbreaks or damage in mixed species forests will be less than that in monocultures is equivocal. Although some experiments do appear to show that the abundance or damage caused by insects can be higher in single than in mixed-species stands, the opposite can sometime be the case. For example, pathogens or species of adelgids that require an alternative host, may cause more damage where plantations contain both primary and secondary hosts. While mixed forests are likely to be more diverse than monocultures, and this may be an important objective of forest management, overall, there is no strong evidence that mixed species forests are inherently more 'resistant' to pests and pathogens.

Where new tree species such as maritime pine are being considered as part of the adaptation strategy, PRA methods should be used to determine risk from pest species already present in the area of introduction. Experience with lodgepole pine has emphasised the importance of trial plantings on a range of sites to assess likely susceptibility to local pests and diseases.

2.3.6. Abiotic factors

Fire

The predicted increase in fire frequency in Scotland could result in increased insect damage to trees. A number of studies have shown that fires severe enough to damage trees, even in fire-tolerant conifers, scorching of the bole can increase susceptibility to bark beetle attack.

Windblow - salvage and long-term storage

The proposed development of disaster management contingency plans would need to incorporate guidelines on salvaging and storing timber to prevent degrade by pests and pathogens. Effective storage is also important for preventing areas of windblow from acting as outbreak foci for bark beetles, resulting in damage over an even larger area. Storage of logs in stacks on dry land under sprinkler systems is a practical solution that has been used successfully on a number of occasions to store timber for several years.

2.3.7. Spreading risk

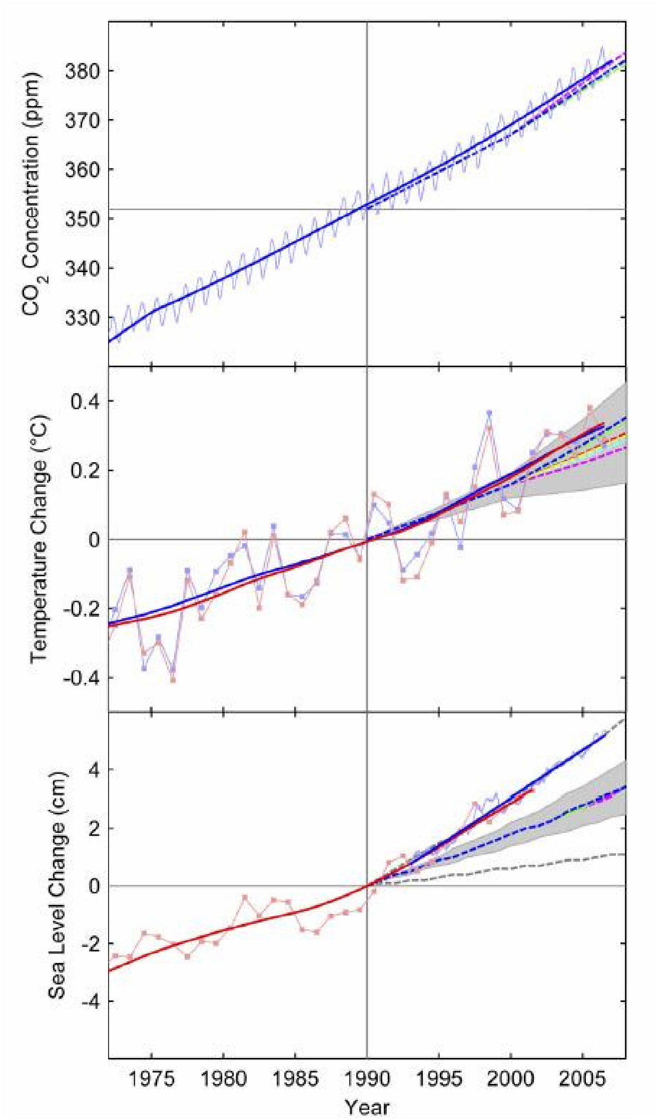
Adapting forests to the future climate means spreading the risk in different ways. Adjusting species to match future site conditions, encouraging woodland management towards mixed species woodlands and managing for mixed aged classes, are some possibilities. Continuous cover systems are considered to produce probably the most resilient woodland ecosystems. Unfortunately over large areas of Scotland on wet soils and exposed sites, continuous cover systems are not feasible. Nevertheless, there should be an attempt to spread the risk of pest and disease attack by encouraging the natural regeneration of more broadleaved species on wet site types; birch, alder and willow may be suitable. The main production species should also be reviewed carefully to select trees which are less prone to drought stress on sites likely to cause problems.

2.3.8. Conclusions

1. The damage caused by bark and ambrosia beetles will largely depend on the availability of breeding resources such as windblown trees or host susceptibility induced by, for example, drought stress. Damage is likely to increase under climate change. The length of fallow period needed to minimise damage by pine weevil on restock sites is likely to reduce under climate change.
2. There is a history of significant defoliator outbreaks in Scotland causing both tree mortality and growth loss. Responses to climate change on population dynamics are likely to be species specific and difficult to predict. Replacement of lodgepole pine will reduce of damage by *Panolis* in the medium term.
3. Aphids and other sucking insects cause damage that is largely sublethal. In a warmer climate, background levels of feeding damage are likely to increase. The frequency of outbreaks of *Elatobium*, during which significant growth loss occurs, is influenced by a range of factors and consequently difficult to predict. Drought-stressed spruce in eastern Scotland would be more vulnerable to damage.
4. The warmer wetter springs predicted from the climate change scenario simulations are likely to encourage greater activity of foliar pathogens on both broadleaves and conifers.
5. Increased spring rainfall together with periods of drought in summer will increase damage by *Phytophthora* pathogens on the more susceptible species such as *Abies, Betula, Fagus* and *Picea*.
6. Hot dry periods are likely to exacerbate problems of latent pathogens, with a northward shift in distribution and impact. The risk of invasion by alien pests and pathogens is likely to increase.

2.4. Flooding from sea level change

Figure 6. Changing concentrations of CO2 on global temperature, and a comparison of the predicted impact of different SRES CO2 emissions scenarios (dashed lines) and the measured change in sea level (solid line) (Rahmstorf, 2007)



Climate change, and in particular rising mean annual temperature, is thought will cause the sea level to rise globally. The two main reasons are reduced volumes of terrestrial and sea ice on earth, and the increased volume of warmer water in the oceans. Figure 6, from the IPCC SRES report (Anon, 2007) demonstrates a 3 cm rise in the mean sea level since 1990. The report predicts that global temperatures are likely to rise by 4.5^0C by 2100. Satellite images taken in 2006 have shown that the Greenland Ice sheet is melting three times faster than predicted in 2001. SRES predict a global rise in sea level of between 0.25-0.50 m by the end of the century, but these estimates are considered very conservative, as the contribution to rising sea levels from the melting ice sheets of Greenland and Antarctica is largely unknown. Many climate change scientists believe that a sea level rise of about 1m is likely by the end of the century (Rahmstorf, 2007). The worst case scenario would be all of the ice on earth melting; causing the sea level to rise by at least 6m (not including thermal expansion). A rise of 1m (which is possible in 90 years time) will flood 2,853ha of woodland in Scotland. Although very unlikely in the medium term, a rise of 6m would inundate 11,700ha of woodland, including all of Tentsmuir and Culbin forest.

3. Silviculture and stand management

3.1. Low impact silvicultural systems (LISS)

Low impact silvicultural systems (LISS), alternatives to clearfell (ATC), or continuous cover forestry (CCF) systems, are likely to afford the most carbon efficient means of forest management, especially where natural regeneration is the preferred method of seedling recruitment. Transformation to LISS is often driven by landscape and public access issues, and any consideration of site suitability is secondary. However the opportunity and likelihood of success are largely constrained by:

- biophysical characteristics of the site
- stand structure and species components
- management objectives

These three components should determine if LISS is possible, and if so, which silvicultural system is best suited.

The Forestry Commission Information Note 40 (revised) (Mason and Kerr, 2004) discusses the approach of transforming even-aged conifer stands in Britain, using ESC, ForestGALES and a transformation decision support tree. However, it doesn't describe or assess how climate scenarios may impact on that process, by constraining the range of suitable sites or by affecting successful establishment, sound management, high timber quality, and minimum wind damage within transformation and climate change scenarios of the future.

3.1.1. Site requirements

Many forest plans consider LISS as a way of improving landscape, amenity and recreational use of the forest, but these objectives are not always compatible. For example if windthrow is a risk, then by opening up the stand there could be danger and inconvenience to the public, and additional expense incurred in clearing paths and making safe hanging or unstable trees.

Most transformation to LISS is on freely draining soils and on brown earths in particular for which there are more species options, SS, EL, HL, SP, DF etc. In addition, most LISS stands are in the eastern part of Scotland or in sheltered valleys to the west. For example in: Perthshire e.g. Tay FD and Atholl Estates, Aberfoyle FD; Scottish Borders e.g. Borders FD, Buccleuch Estates and others; the Moray coast; the Dee and Don valleys.

3.1.2. Wind exposure threshold

Instability is unacceptable for LISS except perhaps where planning a gradual PAWS restoration or gradual conversion from conifer to broadleaved native woodland. Sites where the DAMS score is greater than about 15 will, in general, be unsuitable for LISS. In Scotland, areas on which bracken has expanded, usually indicates a freely, or at worst, imperfectly draining soil, and therefore a site capable of supporting native woodland, with oak-birch woods being particularly suitable. Bracken control would often be necessary for regeneration or restocking.

3.1.3. Climate change and adaptation

Suitability needs to be tested in the current baseline climate, but also in the climatic scenarios of 2050 for conifers, and 2080 for broadleaved species, as UKCIP global circulation modelling project rapid changes to the Scottish climate within the next 1-2 rotations. Maps showing the changing suitability of a range of species are available on www.forestresearch.gov.uk/climatechangescotland . The climate impacts in 40-150 years time must be considered when embarking upon a transformation plan. In addition, the extremes of weather should be taken into consideration, remembering that the extreme events associated with an average climate will constrain options.

3.1.4. Introducing new species

Sometimes the wrong species, or a limited selection of suitable species are on a site, and this might constrain the options for LISS. Fortunately, LISS can include replanting to broaden or change the species mix. Examples of the wrong species on a site, which are intolerant of a site predicted to become droughty, include European larch, Japanese larch and Sitka spruce on potentially droughty freely draining soil. On such sites it would be necessary to introduce Douglas fir and/or Scots pine, according to site fertility. To accomplish this, different stand intervention thinnings should be planned and implemented at an early stage, depending on whether the introduced species is shade tolerant or light demanding. Some Sitka, larch and pine sites are being transformed to native woodland, but most often LISS is being employed on sites with a bigger range of species, probably to take advantage of design plan objectives and establishment costs.

3.1.5. Impact of drought and/or waterlogging

On droughty sites, flowering and regeneration is often very successful, and for some species the frequency of good seed years will increase. But dry summers will cause high mortality of young seedlings and droughts often have a major impact on older trees of particular species, causing stress and opening opportunities for pathogens. The expected higher growing season temperatures will also increase the rate of respiration in plants, and this will tend to exacerbate the loss of naturally regenerating seedlings.

The impact of the change in seasonality of rainfall will cause more sever and prolonged waterlogging in winter. This will be critical for the root systems of some species, particularly when compounded by later and incomplete dormancy. Of course the problem is compounded further on many soils during a dry summer. With shallower root plates, trees will come under greater drought stress in dry summers. This will lead to a greater incidence of drought cracking and increased mortality of mature stands on some site types. However this requires more research, to assess properly the interactions between sites and species. For example we are not sure if drought stress kills fine roots and in which species.

3.1.6. Soil damage

The high level of intervention required with LISS might be constrained by a change in the weather patterns of the future climate. Heavier winter rainfall is likely to make sites, which can currently be worked with heavy machinery (in an average winter), too wet and soft, and more sensitive to compaction, rutting and erosion. The problem may be compounded by the fact that LISS tends to provide less brash to reduce trafficking damage for harvesting machinery, and a shorter time between operations in which sites can recover. To avoid damaging soil during interventions, it will become more important to reduce forest operations in the winter months, and program work for late summer, maintaining careful adherence to the guidelines of sustainable forestry.

3.1.7. Spreading risk

Generally there is a greater frequency of intervention associated with LISS than in clearfell-restock (CR) systems. In addition, there must be greater monitoring of the stand as it transforms, to ensure that intervention is both well timed and produces the intended change. On sites suitable for this type of management, we think LISS can offer the best forest management opportunity for spreading risks associated with climate change, and help produce managed woodlands which are well adapted and resilient to climate change.

3.1.8. Conclusions

1. LISS is now considered to have major advantages over fell-restock systems.
2. LISS management aims to maintain woodland conditions throughout the harvesting regeneration cycle. In particular it provides a management system which encourages species and structural diversity in forests.
3. It is thought that LISS can maintain and improve woodland habitat with major benefits to woodland biodiversity.
4. From a climate change adaptation perspective, LISS is very likely to maintain the type of species and structural diversity important for the resilience of woodland ecosystems to external pressure such as climate change.
5. LISS should favour processes such as recruitment through more successful regeneration and establishment in less harsh site conditions than occur in fell-restock systems.
6. The challenges of adopting LISS include avoiding windthrow in transforming even-aged stands, selecting suitable species for the site, and ensuring that species choice is viable for the management system selected.
7. Considerable information is available to assess stands suitable for LISS, and then provide guidance for their transformation and long-term management.

3.2. Clearfell-restock systems (CRS)

In addition to ensuring the right species are selected for a particular site, an assessment of the likelihood of problems associated with water stress and wind damage are key to understanding and managing forests using CRS silviculture. For CRS, the crop species and stand structure are relatively simple in comparison to LISS. Additionally, on some CRS sites, the frequency of intervention might also be less. CRS currently concentrate on single species stands, with forest plans and design plans updated on a 5 year cycle.

3.2.1. Site requirements

The relatively simple silviculture of CRS compared to LISS lends itself to a slightly greater range of sites compared with LISS. In particular, wetter and windier sites have been managed very successfully using CRS where LISS would inevitably fail. When considering species suitability for CRS silviculture, it was only necessary to assess a single species, or occasionally two species, over the range of site types within a coupe.

3.2.2. Timing operations to reduce soil damage

The Forests and Water Guidelines (Anon, 2003) were developed to protect water and riparian areas from forest operations. On imperfectly and poorly draining types of soil in particular, good forestry practice is designed to protect soil, prevent rutting, soil erosion and compaction damage, and by doing this prevent soil material entering watercourses as a result of forest operations. Under current climatic conditions the frequency and intensity of winter rainfall in the uplands requires forest harvesting machinery to use brash mats, as a primary means of preventing soil damage. The canopy of Sitka spruce can supply sufficient material for matting on clearfell sites, but often not for thinning. Where thinning occurs (e.g. more shelter, steeper slopes, loamier soil) operations may have to be carried out earlier, in the autumn or late summer, before soils become too wet for operations. This requires another stage of planning operations, to ensure availability of machinery at the right time for operations, and to ensure that managers have the authority and confidence to stop operations before the soil begins to rut and cause erosion.

3.2.3. Increased warmth and adaptation

A warmer and longer growing season, coupled with longer frost-free period may encourage managers to use faster growing provenances of Sitka spruce. Currently QCI (material originally from the Queen Charlotte Islands) is recommended in Scotland. The climate scenarios suggest areas of south-west Scotland close to the Irish sea where the Washington provenance of Sitka spruce may become suitable. However Washington provenance is risky in most of Scotland, and is likely to remain so. It has a longer growing season and is susceptible to frost damage in the autumn due to later hardening-off. In any case there may not be an advantage to planting Washington when compared to genetically improved QCI. The differences in yield and suitability for a range of sites still need to be properly tested. However other species and provenances better suited to a warmer climate could be considered.

3.2.4. Adaptation and managing risk

The climate change factors which will improve the growth of most species are increasing warmth during and extending the growing season and increasing concentrations of CO_2 in the atmosphere. The big climate change unknown which is likely to exert a negative impact on CRS management is the changing wind climate.

Current forest policy tends to promote and favour the management of stands to maturity, and favours contiguous areas of woodland for more efficient management with fewer staff. Both policies run the risk of increased damage in the future climate, and of financial loss to the industry. Forest policy should be more flexible to encourage short rotation silviculture, for example for woodfuel. Owners should be encouraged through incentives, to geographically broaden their estate, and spread the risk of growing timber over wider areas and a bigger range of biophysical site conditions.

Disaster management contingency planning should also be developed and implemented. Recent storms in France, Sweden and Germany caused millions of hectares of damage. A similar big storm across western or southern Scotland would severely interrupt the production plans for decades. The plans should firstly identify the resources required to clear up following a storm, fire or pest outbreak. The plans should deal with the logistics of getting staff and plant to the right places quickly, and to quickly halt the felling programme to deal with the emergency.

3.2.5. Conclusions

1. Fell-restock systems provide options for forest and woodland management on sites that are not favorable for LISS.
2. Particular climate change risks associated with fell-restock systems, mainly relate to extreme events, but also to changes in the ecology of pests and pathogens from climatic trends.
3. Extreme events such as intense rainfall can quickly erode soil on harvesting sites, while droughty seasons may cause widespread failure of new plants.
4. Interactions between wetter winters and the wind climate may cause increasing wind disturbance.

5. Opinion favours the diversification of stands managed in this way, particularly in the range of species planted, and additionally in the genetic variability within a species.
6. The timing and frequency of interventions should be adjusted to improve the windfirmness of stands. Early and frequent thinning may help avoid periods of high wind risk, through the maintenance of more even canopy roughness throughout the rotation.
7. Existing DSS tools such as ESC, Forest Yield and Forest GALES have been developed to help managers undertake site suitability assessments, and test the objectives and risks for CRS silviculture. These tools must now be extended to assess the impact of future climate scenarios, and extreme weather patterns on CRS silviculture on a range of site types.
8. Contingency planning will help prepare the sector to deal with catastrophic damage, and plans should be tested and be capable of halting normal operations quickly, to attend to urgent requirements within the sector.

3.3. Nursery and establishment systems (NES)

3.3.1. Establishment Silviculture

Overall acceptable planting windows will be reduced by a shift in the timing of bud-burst and set. Changes will be made to current establishment practices, include a reduction in back-end planting of bare-root spruce and larch trees on warm and intermediate sites. The planting of containerised trees will need to occur later in the autumn, as soils begin to re-wet. There will also be a reduction in the acceptable spring planting dates on eastern ‘droughty’ sites, and a general reduction in access to many sites experiencing high winter rainfall events in late-autumn, winter, and early spring.

There is insufficient evidence, to date, on the effects of minimal cultivation, fertilisation, and weed control on the overall green house gas (GHG) balance of reforested sites. The techniques do, however, exist to investigate the carbon cost of different establishment methods.

For poorly draining soils, the use of mounds will continue to be the most appropriate establishment method. However, seasonal waterlogging may restrict site access in the winter months. Of particular importance is the use of a well-designed brash mat to minimise soil disturbance.

On imperfectly draining soils, mounding is likely to remain the most appropriate establishment method, although for these types of soil alternatives will become more common. For example, there may be some potential on non-waterlogged sites of ‘mound inversion (i.e. mound back in the hole’) to reduce carbon losses at establishment.

On freely draining soils scarification (or direct planting) will continue to be the most appropriate establishment method.

Ecological Site Classification DSS, run in conjunction with Sniffer/UKCIP scenarios, will allow the identification of areas within Scotland where climatic change is likely to be most acute. Tree species can be modelled to illustrate the effects of changes in temperature and water availability upon species suitability. The Establishment Management Information System (EMIS) DSS will allow guidance on changes in establishment practice (nurseries, species and sites) to be readily available. The new UKCIP scenarios will allow probabilistic risk (of a particular event) to be identified.

3.3.2. Nurseries

The increasing incidence of wetter winter soils, warmer soils and an increase in summer drought will require targeted weed control, more irrigation and the potential inclusion of water/nutrient retentive soil additives and amendments. Access for winter operations (lifting) may be restricted.

There will be a greatly reduced plant dormancy period with a knock-on effect on reducing the lifting and storage windows. This could have a detrimental effect on the total nursery productivity. In order to adapt nurseries may have to invest in more efficient mechanised processes, or greater numbers of staff to complete operations at key seasonal periods.

The warmer climate will create conditions ideal for an increase in the type and number of outbreaks of pest and pathogens in nurseries.

4. Native woodlands

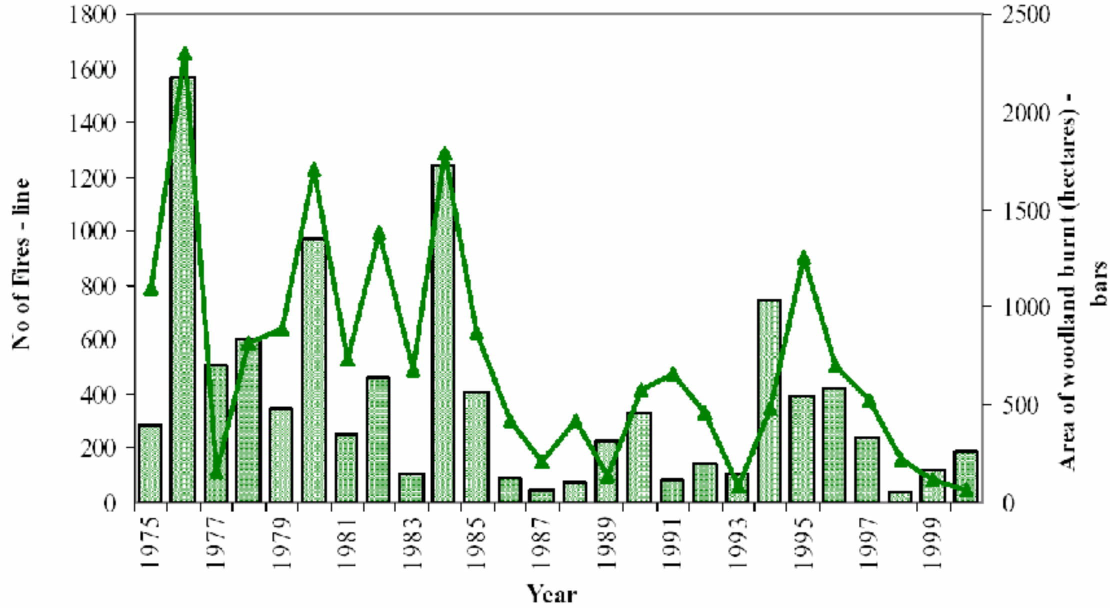
4.1. Native pinewoods

Summer drought is likely to select for drier sub-communities in the west and central highlands. Warmer summers will encourage colonisation of broadleaved species, as well as vascular plants not currently associated with a pinewood community. For example there may be greater colonisation of oak, birch, and rowan into woodlands once dominated by Scots pine; and an increase in the colonisation of vascular plants such as blaeberry, bracken, and grasses into pinewood communities. Where land-use and grazing pressure allows, there may be a tendency for an increase in scrub above the current treeline and a broadening of the upper scrubby edge of pinewoods. Juniper and montane willows may establish at higher elevation on suitable sites in the complex montane soil mosaic.

There is likely to be an increase in the frequency of natural disturbance from fire and wind in all woodlands including pinewoods. Fire frequency and annual area of forest burnt both increase in drought years (Figure 7), and the future climate will feature a greater frequency of dry summers.

Deer numbers are also very likely to increase in pinewoods and other native woodlands. Milder winters, fewer frost days, will reduce winter mortality, improve fecundity, and increase browsing damage. The scrub and more extensive areas of natural regeneration following fire and wind damage will provide more secure cover for deer.

Figure 7. Increase in the number of forest fires, and of the area of woodland burnt in dry summers



4.2. Atlantic oakwoods

The western seaboard climate projections are for milder winters, more severe winter gales, and warmer summers with more frequent drought (but not as frequent as in eastern Scotland). Atlantic oakwoods are likely to be affected by more frequent gales, causing damage to branches, the blowing over of trees with less firm root systems. Many stands will have frequent gap openings, allowing colonisation of oak, birch, hazel and rowan, producing a more 'scrubby' woodland ecosystem if the light conditions allow, and rigorous deer management systems are maintained. The milder winters springs and autumns will also allow wider range of broadleaved species to colonise. Beech is likely to become more frequent components of many Atlantic oak woods, and sycamore may become a more frequent colonist of oakwoods in eastern Scotland.

4.3. Upland birchwoods

Birchwoods are likely to expand as a result of more by damaging storms, allowing the colonising birch species to expand within existing woodlands. In the central and eastern highlands, and in eastern Scotland, birch and oak may be encouraged and expanded for shelter and shade as a more extensive semi-natural woodland type within agri-environment schemes. A major issue for upland birchwoods is their ability to regenerate as vegetation communities change and become more competitive. There are many upland birchwoods created anthropogenically, as opposed to natural climax communities, and in the present climate many of these woods are tending to change. It may be necessary to seed more competitive species such as oak and hazel into birchwoods where seed sources don't exist so that they may change in response to the climate, soil and vegetation changes.

4.4. Mixed broadleaved woodlands

This type of woodland is confined mainly to the fertile loamy to clayey soils of the lowlands. On heavier soils, the frequency of natural disturbance through damage in winter storms will increase. Some woods will become shrubby where soils are frequently waterlogged. Other sites will tend to be sheltered and the increased frequency of 'damaging' winds may do no more than reduce the amount of old trees in such woodlands. Most of these woodlands are quite old, and in a warmer climate, bramble will become rank and more dominant. Fire damage may become more widespread. Although there is little history of fire in the broadleaved woodlands of central France, largely because the amount of fuel is comparatively low. However in Scotland, the combination of summer drought and people will cause more frequent outbreaks. The frequency of sycamore and beech will increase in mixed broadleaved woodlands, as beech seed viability improves in the warmer climate, and as sycamore is able to out-compete oak, ash and elm. Eventually, beech and sycamore must be accepted as naturalised species in the mixed broadleaved woodlands of Scotland.

4.5. Upland ashwoods

Occur on freely draining but slowly percolating, fertile heavy soils. In west Scotland, as for oakwoods, more frequent natural disturbance events are likely to occur, creating canopy openings with colonisation of a greater range of plants. Ash is very shade tolerant as a seedling and young sapling, and can regenerate and compete successfully in the intense shade of dense woodland. The tree species composition may change in the warmer climate, but perhaps more slowly than other woodland types, even though the age structure will broaden in response to more frequent disturbance.

4.6. Wet woodlands

The range of wet woodlands can be dominated by species of alder, willow, birch, with the proportion being dependent on biophysical conditions, including climatic warmth, soil wetness and fertility.

Wet woodlands are a significant feature of the lower floodplains of many of the river systems of eastern Scotland. These woodlands are a representation of the natural tendency of major river networks to periodically flood, particularly in the spring, autumn and winter months. The projections suggest that rainfall will be more seasonal in the future climate, with drier summer months, slightly more rain at other times of the year falling in more intense storm events. The climatic conditions for wet woodland would appear set to provide the plentiful groundwater/high water table at times of the year other than the summer. It must also be remembered that wet woodlands in the lower reaches of major catchments are much dependent on rainfall occurring in the headwater tributaries, often in the central highlands.

There will be an increasing role for wet woodland management in many river systems, as a natural defence against flooding.

5. Key information needs from research

Foresters need more relevant information to better understand management and climate change interactions in general. In particular, the site requirements suitable for LISS, the choice of LISS systems offered by sites in relation to objectives, and most importantly the constraints and opportunities of a site in relation to future climate change, must be researched and presented in an accessible user-friendly way. A decision support tool which links LISS opportunities to climate change interactions is vital to support this type of forest management. The two big climate change unknowns are the future wind climate and the changing soil quality.

Spreading risk involves predicting and managing risk in a methodical way. ForestGALES currently identifies the risk of wind damage for spruce crops with different cultivation, spacing and yield combinations. The decision support application must be adapted for use in future climates by embracing an element of sensitivity testing, to enable managers assess the risk of intervention in an uncertain wind climate, on sites more prone to winter waterlogging. For this more research is urgently needed. In addition the wind climate-LISS interactions must be incorporated into a new version of ForestGALES, so that the timing of intervention can be more carefully planned in response to changing gale magnitude and frequency, on a range of different sites. ForestGALES should include sensitivity analysis features which adjust the wind speed – return period distribution by 5-20%, and adjust the rooting depth of trees according to one SMR class.

On many sites, soil quality will change with the climate, becoming wetter in the winter and drier in the summer, leading to shallower rooting, water stress, and nutrient deficiencies for some species. The ESC-DSS must be upgraded to supply information to help identify these sites, and provide information to help foresters adapt. Climate change adaptation options are available for LISS silviculture, but of major concern between LISS management and fell-restock systems is the planning, with a much greater need for good planning and silviculture in transforming to LISS systems. For example, in areas where winter waterlogging and/or spring drought is predicted, indices for species susceptibility and better guidance on appropriate silviculture are required.

Research could help develop contingency plans for dealing with widespread storm damage. GIS modelling might help identify pinch points in plans from modelled storm damage scenarios.

Risk analyses are required, to assess the policy of managing forest in high risk areas, assess how much forest is at risk, estimate where changes, and the type of change, needed to reduce risk. Assess the financial implications of the risk management. This represents a type of cost-benefit analysis of risk, which would assess options against lost production.

6. Discussion and conclusions

The projections of Scotland's climate in the short term (1-3 rotations), through the remainder of this century, remain relatively uncertain. The UKCIP has produced a range of climate simulations from scenarios that reflect possible global carbon emissions outcomes resulting from the complex economic and social systems globally. The current trajectory of carbon emissions remains high and our best estimate of the impact of climate change, even with increasing carbon emissions control, is likely to be the A2 medium-high scenario.

The UKCIP carbon emission scenario simulations published in 1998 and 2002 show the change in a set of climatic variables at a gridded resolution of 5 square km on the ground, and these have been statistically downscaled from a global circulation model (GCM) that simulate changes in the atmosphere and ocean at 50 square km resolution. It is therefore important to recognise that apparently high resolution maps showing changes in climate across Scotland do include a large amount of uncertainty. It is also important to recognise that the climatic factors described and modelled are average values from a 30-year climatic period. The variability of annual weather patterns must be considered in relation to the trend suggested by the 30-year period averages. This is vital in linking the effect of a changing climate on seasonal or annual extremes which will cause the climatic limitations and changes to species suitability and forest operations in Scotland. In 2008, UKCIP will release new climate simulations which will include daily (weather generator) simulations of certain variables. This will help us better translate the extreme events of climate change in terms of their impact on forests and their management in Scotland.

With the limitations of the climate simulations and their accuracy in mind, this report indicates that climate change is likely to have a significant impact on forests and forest management in the future. Forestry is a relatively long term land-use, and over centuries woodlands have remained - and are expected to remain - part of the landscape. This places a large expectation on forest managers and policy makers to understand the potential impacts of climate change on forests, and make robust plans to adapt their management to maintain resilient ecosystems capable of maintaining multiple benefits and uses in the future.

The climate simulations from UKCIP02 provide an indication of the likely changes, and allow us to see how forest sites may be affected, so that we may begin advising forest policy on adaptation strategies. In addition, the report provides a source of information for forest practitioners in the sector. It is hoped that this will help to raise awareness of climate change, and the possible consequences on the forestry sector based on current evidence, knowledge and climate projections. Future climate projections (UKCIP 2008) are likely to provide more valuable simulations to improve our understanding of impacts and useful adaptation strategies.

The concepts of risk minimisation, spreading risk, effective monitoring, and contingency planning, are central to the requirement for adaptation of forests to climate change. Risk minimisation is a key component of species choice, in which species well suited to similar biophysical conditions are chosen for the predicted future conditions of a site. Spreading risk is a central theme of moving to mixed species and provenance stands, a ‘no regrets’ type of planning in which one accepts that some impact is likely through future extreme events, but one is unsure of the outcome. This idea also runs through the management for pests and diseases, with a proviso that some pests may profit from a mixed species forest model. In these circumstances it would be important to understand the degree of risk and use alternate tree species that are more tolerant of the perceived risk. Effective monitoring and adaptive management is key to the sustainable management of forest operations. Effective monitoring should help provide information required to halt machinery working on site, to prevent soil damage and the sedimentation of streams in extreme wet weather; or re-schedule spring planting if the soil is too dry and the long term weather forecast does not suggest rain.

Contingency planning is required for the Scottish forest industry. It is likely that the occurrence of potentially damaging extreme events will increase for some climatic factors, such as storminess (extreme wind speeds), drought, and fire. The industry must be well prepared to deal effectively and quickly with the impact of various scenarios and its disruption to the industry and the national economy.

There are positive outcomes for forests resulting from climate change. Assuming good species choice for site conditions, the warmer climate will produce greater timber yields. A wider choice of species will be possible across a greater area of Scotland. This will help underpin expansion of the use of locally grown quality timber for products (including construction) with benefits from the added value that these products bring to local and regional economies.

The specific outcomes of species suitability modelling in future climate scenarios are presented on the web pages (www.forestresearch.gov.uk/climatechangescotland), and these analyses and map outputs will provide some pointers to develop adaptation plans as part of the implementation process of the Scottish Forestry Strategy. As the UKCIP 2008 simulations (and beyond) unfold and our expectation of future climate conditions becomes more certain, the plans will require updating and refining. However we cannot continue to wait for news of certainty of our climatic future. Forestry investment is long term and we don't have the luxury of time on our side. Our best estimates for planning should be implemented quickly, and modifications and adjustments made as more research and information becomes available.

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