Silvicultural strategies for adapting planted forests to climate change: from theory to practice

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ABSTRACT: Adapting forests to climate change involves silvicultural measures such as use of a range of species and the fostering of mixed stands. We tested these in a Sitka spruce forest in southern Scotland, employing the Ecological Site Classification to match suitability of 24 species to six climatic and edaphic variables under values of accumulated temperature and moisture deficit projected for a medium emissions scenario for the present century. Both median and 90th percentile values were contrasted. In the first case there was a small change in species suitability with Sitka spruce, noble fir, downy birch, sycamore and aspen being the most suitable species. When the 90th percentile values were employed, the suitability of Sitka spruce and similar conifers had declined by the 2050's due to soil moisture deficits. The actual performance of a range of species in a long-term experiment on a similar, warmer site showed several productive conifers including Sitka spruce that maintained reasonable growth when planted in mixture. Mixed plots were developing into pure stands of the most productive species. Species diversification was the most practical adaptation measure for this forest and should concentrate on areas of the greatest risk like south-facing slopes with free-draining soils.

Keywords: climate change; silviculture; adaptive management; species choice; species mixtures

The last two decades have seen increasing awareness of the potential impacts of projected climate change upon terrestrial ecosystems including forests. In Europe, the mean annual temperature has risen by more than 1.1°C compared with conditions before the Industrial Revolution (IPCC 2007). The effect of a warming climate is likely to influence the distribution and growth of important tree species and to affect the range of ecosystem services provided by forests (Lindner et al. 2010). In recent years there has been an increasing number of reports of drought induced dieback and mortality in many parts of the world (Allen et al. 2010). European examples include the dieback of Scots pine (*Pinus sylvestris* L.) forests in the Southern Alps (Gonthier et al. 2010), increased mortality of several tree species in France after the 2003 heat wave (Bréda et al. 2006), and damage and tree death in Sitka spruce (*Picea sitchensis* Bong. Carr.) plantations in eastern Scotland (Green et al. 2008). The frequency and intensity of other extreme weather events such as wind storms may also change (Gardiner et al. 2010), thus risking disruption to timber supplies and a loss of carbon stocks. In Scandinavia, windthrow in the 2005 Gudrun storm resulted in a carbon sink reduction of around 3 million tonnes carbon, while the larger Lothar storm of 1999 may have resulted in losses of 16 million tonnes carbon (Lindroth et al. 2009). Increased winter rainfall in Atlantic regions of Europe could increase soil wetness and result in reduced tree stability in annual gales and storms (Ray 2008). Climate change may also result in a higher incidence of damage due to biotic pests and pathogens. For example the spread of *Dothistroma* needle blight worldwide is thought to be linked to a combination of management practices and climate change favouring the spread of this pathogen (Woods et al. 2005; Watt et al. 2009). The impact of this pathogen in pine plantations in Great Britain has been considerable, resulting in a moratorium on the planting of Corsican (*Pinus nigra* ssp *laricio*) and lodgepole (*Pinus contorta* Dougl.) pines (Brown, Webber 2008). Battisti et al. (2005) were able to link the northwards range expansion of the pine processionary moth (*Thaumetopoea pityocampa)* in western Europe to an increased winter survival due to warming temperatures. However, climate change may also result in faster growth and higher productivity of European forests, particularly in northern and western regions where the length of the growing season is predicted to increase without limitations imposed by summer moisture stress (Magnani et al. 2007; Broadmeadow et al. 2009; Pussinen et al. 2009).

One inevitable consequence of the growing awareness of climate change and its potential impacts on forests is uncertainty among forest managers about the most appropriate silvicultural measures to be deployed to maintain forest vitality and productivity. While foresters have been aware of the potential impacts of abiotic and biotic risks for many decades (e.g. Schelhass et al. 2003 on the historic impacts of storms), their decision making has implicitly assumed that the occurrence of such extreme events took place within the framework of long-term climatic stability and that responses could be based upon accumulated experience (Bolte et al. 2009). However, this assumption is no longer tenable and the need for effective strategic, tactical, and operational adaptation planning is urgent, not least because the young trees planted or regenerated in contemporary forests will have to cope with a rapidly changing climate over the course of this century. The challenges posed by climate change require solutions that may be outside the scope of institutional experience and have led to proposals that future forest management should be based upon principles of "adaptive management" involving a cycle of planning, implementation, monitoring, and evaluation (Lawrence, Gillett 2011). Other authors have proposed a framework of adaptation concepts with supporting actions that should allow managers to manipulate forests to enhance their resistance and resilience to climate change (Spittlehouse, Stewart 2003; Millar et al. 2007). Such actions can be seen as part of a risk management strategy linked to the principles of sustainable forest management. These ideas have been developed by Bolte et al. (2009) to propose three different strategies for the future management of forest stands in central Europe. The first is termed "conservation of forest structures" which seeks to maintain stand structures against increasing environmental pressures. This option is favoured in older stands of high economic value and good structure, located in regions where impacts of climate change are anticipated to be low, and where there is a good likelihood of silvicultural intervention improving the stand. The second option is called "active adaptation" wherein a range of silvicultural tools such as thinning, respacing, and choice of alternative species are used to develop a stand structure that is more resilient to the impacts of climate change. This approach is proposed for stands in areas with a higher probability of climate change impacts and where the species or structures are thought to be particularly exposed to hazards such as windthrow. The third approach is known as "passive adaptation" and relies primarily upon natural processes such as succession to increase the fitness of a stand for future conditions. It would be used where the stands are of limited economic or ecological value and where there are no cost-effective measures that can be implemented to increase adaptive capacity.

Kolstrom et al. (2011) recently reviewed stand level adaptation measures reported by 19 European countries; most of them appear to involve aspects of an active adaptation strategy such as increasing genetic and species diversity, fostering mixed stands of well adapted species, and introducing alternative silvicultural regimes such as continuous cover forestry (Pommerening, Murphy 2004). For example, at least ten non-native tree species could be considered for planting in north-eastern Germany (Bolte et al. 2009) while over 20 alternative species have been proposed as part of a climate change adaptation strategy in Wales (Anonymous 2010). Thus, there is an emerging view that an appropriate way of spreading the risk of climate change impacts is to increase the species and structural diversity of forests. This belief may, in part, be influenced by the traditional ecological theory that "diversity begets stability", although the universality of this proposition may be open to question (Bodin, Wiman 2007).

However, given that an active adaptation strategy is currently the favoured policy for adapting forests to climate change, an important issue is deciding which of the measures embraced by the strategy is the most suited to a particular forest or region and how these measures might be implemented on the ground. This involves taking the general principles of an adaptation strategy and applying them at an operational or tactical level in a specific forest. The need to bridge the gap between the theory of adaptation and the practice and realities of forest management is recognised by other authors (Ogden, Innes 2007; Janowiak et al. 2011). A particular need is to see how adaptation measures might be implemented in planted forests which are expected to supply an increasing proportion of the world's timber supply in the current century (Paquette, Messier 2010) and whose simple stand structures composed of a few tree species might be expected to make them particularly vulnerable to the impacts of climate change.

This paper presents a case study showing how climate change impacts might affect a planted forest in Scotland dominated by Sitka spruce: this is a forest type of major significance for timber production in Atlantic Europe (Mason, Perks 2011) and where species diversification and 'close-to-nature' management are currently proposed to increase adaptive capacity (Mason, Meredieu 2011). We explore how an active adaptation strategy might be developed for this forest with a focus on species diversification and consideration of the possible role of species mixtures. The feasibility of various silvicultural measures is illustrated using evidence accruing from relevant long-term experimental trials. The results are used to show how the application of general silvicultural principles needs to be tested against site factors if forests are to be effectively adapted to the impacts of climate change.

Fig. 1. Map showing the location of Craik forest and an inset showing the general outline of the forest

MATERIALS AND METHODS

Case study

Craik forest is located in the southern uplands of Scotland (55°21'N, 3°2'W) and covers an area of 4,729 ha at elevations from 175 to 425 m a.s.l. (Fig. 1). Average rainfall is 1,380 mm and the average temperature is 7.1°C. Until the 1930's, the area had been managed for several centuries for sheep grazing, but thereafter the land was progressively afforested using primarily a range of non-native conifer species. In 2010, around 19% of the forest was classed as permanent open space or was felled awaiting replanting. The forest was dominated by stands of Sitka spruce representing 80% of the forest area (Table 1) with broadleaves being about 5%. The dominance of Sitka spruce can be explained by the higher productivity provided by this species (Table 1), plus the access to higher yielding strains provided through tree breeding (Lee, Matthews 2004). The structure and species composition of the forest are typical of the extensive plantations created in upland Britain since 1945 (Mason 2007). In 2010, about 85% of the stands were managed under a patch clear felling system (Matthews 1989) on a rotation of 35–50 years, about 14% was managed on longer rotations with a mixture of species ("combined objective forestry"; Mason, Meredieu 2011), while the remainder was maintained as non-intervention areas with little management.

Table 1. Species distribution at Craik forest in 2010 and average productivity

Species	Forested area (%)	Productivity ($m^3 \cdot ha^{-1} \cdot year^{-1}$)
Picea sitchensis	80.3	16
Picea abies	7.0	13
Mixed broadleaves[1]	4.8	2
Larix spp.[2]	3.6	11
Pinus contorta	2.5	6
Pinus sylvestris	1.1	6
Others[3]	0.7	9

[1]mixed broadleaves denotes mixed plantings of species such as *Quercus robur*, *Q. petraea*, *Betula pendula*, *B. pubescens*, *Prunus avium*, *Populus tremula*, planted at wide spacing for amenity and conservation purposes, [2]*Larix kaempferi* and *Larix × marschlinsii*, [3]*Fagus sylvatica, Alnus glutinosa, Pseudotsuga menziesii, Abies grandis, A. procera, Nothofagus obliqua, Pinus strobus,* and *Tsuga heterophylla*

Table 2. Main soil types present at Craik forest

Soil type	Proportion (%)
Surface water gley	32.0
Peaty gleys	18.0
Unflushed deep peat	14.6
Brown earths	14.4
Ironpan soils	10.1
Other soils	9.0
Unknown	2.0

The relatively infertile soils are mainly wet and acidic which impose important limitations on root development (Table 2). Only the freely draining brown earth and ironpan soils (about 25% of the total) are likely to provide the better root development necessary for tree and stand stability. The shallow rooting on the wet soils coupled with the exposed wind climate typical of upland Britain means that the risk of windthrow is a serious constraint to management (Quine et al. 1995). At present, about 70% of the forest stands have been designated for management on a non-thin regime to limit the anticipated impacts of windthrow.

Potential climate change impacts

To explore the probability of future climate change affecting Craik forest, we used the latest probabilistic climate projections available for the UK (UKCP09; Murphy et al. 2009). The dataset used for the assessment of potential climate impacts in Craik forest was the weather generator (WG) provided by UKCP09 (Jones et al. 2009). The WG data were used to analyse the climate in three time periods; the baseline (1961–1990) and two future time periods, 2050's and 2080's, where each period represented information for 30 years. Since Craik is in a part of Scotland that is not projected to be vulnerable to climate change in the near future (Ray 2008), only the medium emissions scenario (equivalent to the A1B scenario of Nakicenovic, Swart 2000) has been used for the analysis presented in this paper. Data were downloaded from UKCP09 website for Craik forest and required time periods. Based on the formulae used to support the Ecological Site Classification (ESC; Pyatt et al. 2001), customized Python™ script was written to calculate accumulated temperature [the sum of degrees in days > 5°C (day degrees); AT] and moisture deficit (mm; MD). These are the climatic parameters where change is thought most likely to affect species performance during this century (Ray 2008). The final outputs provided AT and MD values representing the median and the 90th percentile over the three 30-year periods (i.e. baseline, 2050's, 2080's). The use of the 90th percentile was as a means to show the level of climate change uncertainty and to explore the potential impact of extreme events.

Species suitability and performance

We explored the impact of the baseline, 2050, and 2080 climates upon species suitability at Craik using the climate matching approach embodied in ESC (Pyatt et al. 2001). In brief, this classification relates survival and growth of a number of conifer and broadleaved species to four climatic (accumulated temperature, moisture deficit, exposure, and continentality) and two edaphic (soil nutrient regime arranged in six classes of increasing fertility and soil moisture regime with eight classes of soil wetness varying from dry to wet) factors. In this study the edaphic factors of soil fertility and soil wetness were derived by converting soil types mapped at high resolution (one soil survey point every hectare) to provide a detailed soil map at a scale of 1:10,000. The climate matching approach has been previously used to explore the impact of projected climate change upon the long-term performance of broadleaved species in Britain (Broadmeadow et al. 2005). Species suitability is graded into three categories: "very suitable" indicates that the species should be capable of growing to biological maturity and in the higher third band of productivity expected of that species; "suitable" indicates a lesser rate of productivity; while "unsuitable" indicates a high risk of damage from biotic or abiotic factors and the likelihood that the species will not close canopy. The actual calculations were based on version 2.0 of the ESC-DSS (Anonymous 2011) which provides suitability predictions for 24 tree species of importance in British forestry. We examined the potential suitability of each species using information for Craik from the Forestry Commission sub-compartment database (Dewar 1986) to calculate the factors influencing the species performance. We scored the three ESC "suitability" categories from 1 to 3 ("very suitable" to "unsuitable") and calculated an average score for each species across the whole forest. Thus an average score of 2 or less would indicate a species that was well suited to the climate over much of the forest, while a score > 2 would indicate a species that was only suited to limited areas of the forest. The ESC suitability calculations were carried out in two stages, first relying solely on the four climatic factors and then expanded by incorporating the two soil-based edaphic factors.

Experimental validation

We reviewed Forest Research's portfolio of long-term experiments (Mason et al. 2008) to see if we could find any extant trials on similar soils and in relevant climatic regions planted with an extensive range of species. The most useful match was with an experiment established in 1956 on a surface water gley soil in Rosedale forest in northern England (54°21'N; 0°44'W). The Rosedale site had similar soil nutrient and soil moisture regimes to those found at Craik, but the baseline data from ESC suggested that the former experienced 35% less rainfall, 20% higher accumulated temperature and 84% greater moisture deficit. The site could therefore provide helpful information on the response of a range of tree species to a warmer climate, and, in particular the estimated moisture deficits were in excess of 120 mm and so could be expected to limit the growth of Sitka spruce (Pyatt et al. 2001).

The experiment contained pure plots of European larch (*Larix decidua* Mill.), Japanese larch (*Larix kaempferi* Lamb. Carr.), Scots pine (*Pinus sylvestris* L.), Corsican pine (*Pinus nigra* ssp. *laricio* Maire), birch (*Betula pendula* Roth. and *B. pubescens* Ehrh.), sycamore (*Acer pseudoplatanus* L.), and red oak (*Quercus rubra* L.). There were also plots of Sitka spruce, Norway spruce (*Picea abies* L.), Douglas fir (*Pseudotsuga menziesii* Mirb. Franco), grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.), western hemlock (*Tsuga heterophylla* Raf. Sarg.), subalpine fir (*Abies lasciocarpa* [Hook.] Nutt.) and western red cedar (*Thuja plicata* D. Don.), all planted in 3 row by 3 row "nursing" mixtures with Japanese larch and Scots pine. There were two replicates of each treatment with a plot size of 0.2 ha. The mixture plots were thinned in 1970–1972 to remove larch or pine trees in the outer rows that were interfering with the nursed species. The whole experiment was thinned to favour the best trees in 1988 and 1999/2000.

Assessments of height and survival took place at 2–5 year intervals up to 25 years after planting. Thereafter there was a gap of 20 years until height, diameter and basal area were assessed in 1999 and again in 2010. The subalpine fir, red oak and sycamore plots had failed by 15 years after planting while the Corsican pine suffered serious mortality from shoot dieback caused by *Brunchorstia pinea*. The Douglas fir and grand fir plots were partially affected by windblow in the 1990's. All these treatments were excluded from the most recent assessments. Data analysis followed standard analysis of variance procedures for a randomised block design.

RESULTS

Climate change

The estimated values for AT and MD for the three periods (baseline, 2050's, 2080's) derived using the Weather Generator in UKCP09 show progressive increases in warmth and particularly moisture deficit over the course of the present century (Table 3). Thus the median value for AT increases by about 75% over the time periods, but the median moisture deficit is estimated to be about seven times higher by the 2080's. For both parameters, the rise from the baseline to the 2050's is greater than that from the 2050's to the 2080's. The magnitude of the changes in median AT is equivalent to moving to a climate characteristic of the lowlands of southern Britain whereas the equivalent change in MD would represent the foothills of south-western Britain (Pyatt et al. 2001; their Figs. 2 and 3).

Table 3. Estimated median and 90th percentile values of Accumulated Temperature (AT) and Moisture Deficit (MD) at Craik forest for three time periods

Period	AT		MD	
	median	90th percentile	median	90th percentile
Baseline 1961–1990	1,110	1,585	12.6	187
2050's	1,690	2,482	63.1	290
2080's	1,956	2,948	91.4	359

Species suitability

Analysis of species suitability based on median values for the baseline period (1961–1990) showed that two conifers, Sitka spruce and noble fir (*Abies procera* Rehd.) and three broadleaves [downy birch, sycamore, and aspen (*Populus tremula* L.] were well suited (i.e. average scores < 2) to the climate that prevailed at Craik (Table 4). By contrast the species such as Corsican pine, pedunculate oak and black poplar hybrids (e.g. *Populus* × *generosa*) were poorly suited to the cool upland climate. Other species that had been planted in Craik such as Norway spruce, Scots and lodgepole pines, and larches were generally found to be "suitable" for the climate in Craik but their sensitivity to the oceanic climate and to exposure at higher elevations limited the amount of sites where their performance would meet the "very suitable" category and resulted in higher scores. Most of the other species examined were capable of growing only in lower, more sheltered and warmer areas of the forest.

When species suitability was examined for the median climate of the 2050's and the 2080's, there were no substantial changes in suitability although minor shifts were observed. Sitka spruce, downy birch and aspen were still projected to be very suitable species in both periods. Noble fir and sycamore showed opposing trends, with the former becoming less suitable over time and the latter becoming better suited to the projected climate. Lodgepole pine and Japanese larch were both pro-

Table 4. Predicted climatic suitability of 24 tree species at Craik forest for the baseline period (1961–1990), 2050's, and 2080's based on the Ecological Site Classification (ESC). This uses the median values projected for AT and MD for each period. Suitability is scored from 1–3: very suitable to unsuitable. The ten species with the best (i.e. lowest) ESC score are highlighted in bold type

Species	Baseline	2050's	2080's
Picea sitchensis	1.67	1.67	1.71
Picea abies	2.16	2.16	2.16
Pinus sylvestris	2.38	2.34	2.17
Pinus contorta	2.01	1.65	1.56
Pinus nigra ssp. *laricio*	3.00	2.95	2.56
Pseudotsuga menziesii	2.73	2.70	2.68
Abies procera	1.54	1.67	2.00
Abies grandis	2.75	2.69	2.69
Tsuga heterophylla	2.72	2.72	2.72
Larix kaempferi	2.01	1.95	1.95
Larix decidua	2.67	2.64	2.58
Thuja plicata	2.72	2.72	2.72
Betula pendula	2.72	2.65	2.65
Betula pubescens	1.96	1.96	1.96
Quercus robur	2.92	2.86	2.86
Quercus petraea	2.67	2.60	2.60
Fagus sylvatica	2.38	2.28	2.28
Fraxinus excelsior	2.30	2.22	2.22
Populus tremula	1.96	1.96	1.96
Acer pseudoplatanus	1.89	1.66	1.66
Alnus glutinosa	2.74	2.72	2.72
Nothofagus nervosa	2.76	2.70	2.70
Populus × canadensis, P. × generosa	3.00	2.86	2.86
Prunus avium	2.58	2.49	2.48

Table 5. Change in ESC suitability (scored 1–3: very suitable to unsuitable) of the ten 'most suitable' species in the baseline period, 2050's and 2080's after projections using median and 90th percentile values of AT and MD. Also the main ESC limiting factor affecting each species: SNR-soil nutrient regime, MD-moisture deficit, DAMS-detailed aspect measure of scoring (a measure of exposure)

Species	Baseline median	Baseline 90th percentile	2050's median	2050's 90th percentile	2080's median	2080's 90th percentile	Limiting ESC factor median	Limiting ESC factor-90th percentile
Picea sitchensis	1.67	2.65	1.67	3.00	1,71	3.00	SNR	MD
Picea abies	2.16	2.16	2.16	2.16	2.16	2.16	SNR	SNR
Pinus sylvestris	2.38	2.16	2.34	2.16	2.17	2.16	DAMS	DAMS
Pinus contorta	2.01	1.56	1.65	1.56	1.56	1.56	DAMS	DAMS
Abies procera	1.54	3.00	1.67	3.00	2.00	3.00	SNR	MD
Larix kaempferi	2.01	2.35	1.95	3.00	1.95	3.00	DAMS	MD
Betula pubescens	1.96	2.18	1.96	2.18	1.96	2.18	DAMS	DAMS
Fraxinus excelsior	2.30	2.34	2.22	2.40	2.22	2.40	SNR	SNR
Populus tremula	1.96	2.11	1.96	2.18	1.96	2.18	SNR	SNR
Acer pseudoplatanus	1.89	2.00	1.66	2.02	1.66	2.02	SNR	SNR

jected to become more widely suitable as a result of a warmer and drier climate, a trend also evident in the slightly higher scores for species such as Corsican pine and black poplar.

We therefore took the ten species that appeared to be the most suitable for the median climate in all three periods and examined how their suitability might change under the 90th percentile scenarios, i.e. if the change in climate to warmer and drier conditions was more extreme (Table 5). These results suggested that noble fir would be unsuitable at all periods and that Sitka spruce and Japanese larch would be unsuitable in both the 2050's and the 2080's. Norway spruce, Scots and lodgepole pines

Table 6. Basal area ($m^2 \cdot ha^{-1}$) and height growth (m) of eight pure and mixed species stands in the Rosedale experiment after 55 years. Standard error of the difference (SED) is shown for comparison of basal area between treatments

Treatment	Basal area	First species proportion of basal area (%)	Top heights (in order of species)	Yield class of first species ($m^3 \cdot ha^{-1} \cdot year^{-1}$)
Picea abies, Larix kaempferi and *Pinus sylvestris*	30.4^{bc}	82.4	20.9, *22.5*	12
Larix kaempferi	37.1^{ab}		22.6	10
Pinus sylvestris	37.3^{ab}		18.5	8
Tsuga heterophylla, Larix kaempferi and *Pinus sylvestris*	54.7^{a}	71.0	22.5, 22.5, 18.2	12
Picea sitchiensis, Larix kaempferi and *Pinus sylvestris*	53.5^{a}	83.3	24.5, 22.6, 15.5	14
Larix decidua	27.3^{bc}		20.8	8
Betula spp.	17.0^{c}		16.8	4
Thuja plicata, Larix kaempferi and *Pinus sylvestris*	54.2^{a}	76.8	18.8, 22.3, 17.8	12
SED	8.1			

Different letter suffuxes within a column indicate where treatments are significantly different at $P < 0.05$, yield class is an estimate of productivity in even-aged stands in Britain according to Edwards and Christie (1981), in italic – no Scots pine remained in the treatment were not 'sensitive' to these more extreme scenarios, while the broadleaves showed minor declines in suitability between the median and the 90th percentile scenarios. The greater sensitivity of noble fir, Sitka spruce and Japanese larch to the 90th percentile projection was because the ESC projections indicated that moisture deficit would become the main factor limiting their performance. The other species were primarily affected either by exposure or by soil nutrient regime.

Experimental evidence

After 55 years, there were significant differences in basal area between the eight treatments at Rosedale where survival had allowed the formation of a closed stand (Table 6). The highest basal area values were found in the mixed plots containing either western hemlock, Sitka spruce or western cedar: the mixed plot with Norway spruce was significantly less productive. The lowest values were found in the birch and European larch plots while the Scots pine and Japanese larch treatments were intermediate between these and the most productive plots. In all the mixtures the nursed species (i.e. Norway spruce, western hemlock, Sitka spruce and western cedar) was becoming the dominant component of the treatment, amounting to about 70 to 80% of basal area although their stocking at planting had been only 33% of these treatments. Sitka spruce and Japanese larch were the tallest species growing in the experiment while birch was the smallest. Estimated productivity (Yield Class) was highest in Sitka spruce and lowest in birch. The productivities found in this experiment when compared with those at Craik (cf. Tables 1 and 6) were slightly lower for Sitka spruce, Norway spruce and Japanese larch, and slightly higher for Scots pine. In all species other than Norway spruce, where a German provenance was used, the seed sources used would have been considered acceptable under current recommendations (Lines 1987).

DISCUSSION

The analysis of species suitability at Craik under the median projections for the baseline climate (Table 4) confirmed that the dominant tree species present in the forest, Sitka spruce, was well suited to the prevailing climate conditions. Noble fir was the only one of the other four well suited species that might have equalled the timber productivity obtained from Sitka spruce, but previous reviews suggested that, under British conditions, the quality of the timber of noble fir was of poorer quality (Aldhous, Low 1974). Limitations to the growth of Sitka spruce under the baseline scenario were mainly due to the species' sensitivity to poorer soil nutrient conditions and these can be largely overcome by appropriate establishment practices including the use of fertilisers and/or nursing mixtures (Taylor 1991).

Examination of species suitability for the 2050's and 2080's under the median climate revealed relatively few changes in species performance although noble fir became less suitable towards the end of the century whereas both Scots and lodgepole pine became more suitable. The favourable response of Sitka spruce to a warming climate is in line with previous studies which showed a positive relationship between Sitka spruce productivity and AT in northern Britain (Worrell, Malcolm 1990; MacMillan 1991) including Craik and surrounding forests (Sing et al. 2006). Such positive growth responses are expected to be widespread in the northern and western parts of Atlantic Europe wherever the soil moisture is not limiting to growth (Lindner et al. 2010). The potential benefits of higher spring (April to June) temperatures for Scots pine and Japanese larch in Scotland were highlighted in a previous study (Tyler et al. 1996) while Xenakis et al. (2011) showed timber yields of Scots pine to be higher on warmer, drier and more sheltered sites. Noble fir is a high elevation species in its native range where it grows in a moist, maritime region (Franklin 1990), but its growth is less vigorous under warmer, drier conditions and there is a greater incidence of "drought crack" in the stems (Aldhous, Low 1974). Downy birch is the native birch species found on wetter soils in the uplands and it will tolerate exposure although the stem form is often poor and productivity tends to be low (Cameron 1996). Aspen is a widespread but uncommon species in native woodlands in Scotland which tolerates a wide range of sites and exposures (Worrell 1995). Sycamore tolerates exposure well and can produce high quality timber on moister and more fertile soils, although it can be seriously damaged by bark stripping by grey squirrels (*Sciurus canadensis*) (Savill 1991).

However, when species suitability was examined under the more "extreme" conditions of the 90th percentile projections, there were important changes in projected performance. The main current conifer, Sitka spruce, and two other potentially important ones, Japanese larch and noble fir, experienced serious declines in suitability by the 2050's while most of the other species were either unaffected or showed minor changes in suitability. The decline in suitability of the three conifer species was due to MD being projected to increase to values > 200 mm under these projections. These findings were based on extreme projections of likely outcomes under the medium emissions scenario and are therefore subject to all the uncertainties that attend attempts to model future climates (Murphy et al. 2009). However, before discounting these findings, one should note that the medium emissions scenario may itself be conservative under revised estimates for the global climate, and moisture deficits of this order were recorded in Scotland in the last decade. Thus severe dieback and subsequent drought crack were reported in Sitka spruce and Norway spruce plantations in eastern Scotland after the dry summer of 2003 when soil moisture deficits exceeded 200 mm for several months (Green et al. 2008). This information has been used to classify soils in eastern Scotland where the risk of future drought damage might be greater (Green, Ray 2009) so that brown earth soils were classed as having a "medium" drought potential, while gleys and peat soils were classed as having a "low" drought potential. Applying this classification to Craik would suggest that more freely draining soils on south facing aspects might be areas potentially sensitive to future dry spells. About ten per cent of the forest falls into this "riskier" category and Sitka spruce is present on 60% of sites in this category.

The estimates of changes in suitability of different species make no allowance for possible effects of other abiotic factors such as increased incidence of wind damage or for the impact of a range of biotic pests. While the UKCP09 projections do not provide evidence for an increase in the frequency or intensity of damaging winter storms (Murphy et al. 2009), the increased winter rainfall is likely to result in wetter soils and possibly shallower rooting. These factors are likely to increase the risk of windthrow (Quine et al. 1995) and may constrain the use of alternative silvicultural systems to clear felling, given that implementation of such systems depends on the feasibility of regular thinning interventions (Mason 2003). The warming climate is likely to increase the incidence of insect pests such as the green spruce aphid (*Elatobium abietinum*) which is known to reduce the volume increment in mid-rotation Sitka spruce (Straw et al. 2011). The potential use of Scots and lodgepole pines at Craik is currently limited because of the impacts of *Dothistroma* needle blight elsewhere in Britain (Brown, Webber 2008) while Japanese larch has proved very vulnerable to attack by *Phytophthora ramorum* (Forestry Commission 2011). Thus the suitability ratings provided by the ESC system need to be seen as a first filter, allowing the identification of species that may be suited to a future climate, but that such ratings need to be tested against other information, including results from long-term trials.

The value of the Rosedale experiment lies in the provision of information on the performance of a range of species of potential interest at Craik when grown on similar soils under somewhat warmer and appreciably drier conditions. An interesting feature of the results is that all the species grown in mixture performed slightly better at this site than projected using ESC (data not shown) indicating that the nutritional benefits from nursing mixtures may extend well into the rotation, although they were previously described only for the establishment phase (Taylor 1991). This highlights the need for knowledge-based systems that provide guidance on species performance on specific sites under defined climatic conditions to be regularly updated with better information derived both from empirical trials and from ecophysiological studies (Xenakis et al. 2011). One point of note is the extent to what all the mixtures are progressively being dominated by the nursed species (Table 6) with the likelihood that these plots will end up as pure stands of the nursed species. The tendency for intimate conifer and broadleaved mixtures in upland Britain to end up as pure stands of the most vigorous species was noted previously (e.g. Mason 2006). This may reflect the fact that many species used in British forestry are light demanding or intermediate in shade tolerance (Malcolm et al. 2001) whereas mixtures often discussed in the European literature such as Norway spruce and beech (*Fagus sylvatica* L.) (Knoke et al. 2008) are generally composed of at least one shade tolerant species so that competition for light is less intense.

In the light of these results, we need to consider the relative feasibility of applying the three strategies proposed by Bolte et al. (2009) for adaptation to climate change in central Europe to an Atlantic Sitka spruce forest such as Craik. The economic value of most of the forests for timber production would rule out a "passive adaptation" strategy while the risks of windthrow make any medium-term attempt of "conservation of structures" unrealistic. Therefore only an 'active adaptation' approach appears to be appropriate at Craik although not all the components of this approach seem practicable throughout the forest. The exposed climate and the lack of deep rooting soils mean that the possibility of transforming the regular stands by thinning to develop a more irregular and resilient stand structure managed under continuous cover forestry is likely to be restricted to about 25–30% of the forests (Nicoll personal communication). The current 35–50 year rotation is already comparatively short by European standards and a further reduction would run the risk of decreasing the overall quality of timber produced because of an increasing proportion of juvenile core in the sawlog outturn (Moore 2011). The possibility of creating stands with intimate mixtures of a range of species seems unlikely to be practical in the long run, although ephemeral mixed stands may increasingly occur in the establishment phase as a result of natural colonisation and give short-term benefits to biodiversity and to landscape (Mason 2006). Thus, it appears that increasing species diversification will be the most practical method to help foresters adapt Craik forest to projected climate change.

This in turn raises the question of how quickly action needs to be taken and whether such actions should be taken over the whole forest or concentrated in specific areas. The answer to this question is, at least in part, dependent on the attitude to risk of the particular forest enterprise and its managers (Hannewinkel et al. 2011). This attitude may vary according to the type of owner, since the perspective of a single individual with one forest holding is likely to be different from that of a national or international forest company with holdings spread across several regions or countries. An extreme event within the life span of stands currently being planted could have a serious impact on the growth of the main species (Table 5), the future production of timber from the forest and the provision of other ecosystem services. However, the examination of suitability of the ESC results for Craik suggests that by the 2050's there is a low probability of a serious warming and drying of the climate which would have a catastrophic impact on the performance of Sitka spruce. These indications suggest that a wholesale change in species choice need not be undertaken immediately. Given that most organisations involved in natural resource management are risk-averse (Lawrence, Gillett 2011), a desirable outcome could be to start to create large areas of potential alternative species on more vulnerable sites within the forest (e.g. the south facing slopes) so that future generations of managers have access to useful information on the performance of these species if and when serious climate change impacts occur. The scale of such plantings should probably be in the range of 10–50 ha in any decade to ensure that they are not overlooked in future management. Candidates for this role at Craik revealed by the ESC analysis include Norway spruce, aspen and sycamore, assuming that the poor form and timber quality rule out the use of downy birch (Cameron 1996). The wider use of sycamore or aspen could allow the creation of markets for quality timber from the former species or for fibre grown on short rotations if aspen was used. Other possibilities could include the use of hybrids between Sitka spruce and interior spruces which are reported to have greater drought tolerance (Grossnickle 1996) or the use of oriental spruce (*Picea orientalis* [L.] Link.) which is reported to cope reasonably well with dry conditions in Britain (Johnson, More 2004).

One conclusion from this paper is that silvicultural options for adaptation to climate change should be tested and implemented at the operational level of a forest or equivalent management unit to check their applicability in particular circumstances. It is clear from the preceding sections that a single "top-down" approach to adaptation is unlikely to succeed and may founder because of the failure to take into account local site and climatic factors. Thus the potential roles of species diversification, the fostering of mixed stands or the promotion of alternative silvicultural systems may vary according to the rates of growth characteristic of a particular location and the predicted timescale of risks from projected climate change. This emphasises the importance of having access to a network of well-maintained field trials with a range of species and silvicultural systems to act as bio-indicators of potential performance in a changing climate. One role for these trials should be to provide supporting data to allow the validation and improvement of existing systems of climate matching (Broadmeadow et al. 2005; Xenakis et al. 2011). Finally, we would highlight the need for forest researchers to consider the uncertainty involved in climate change projections and the consequent range of possible outcomes for forests. This variation should be incorporated into an exploration of the risks that may result from these outcomes. This information then needs to be translated at relevant spatial and temporal scales into suitable formats that can be used by forest managers at a tactical level as they seek to plan the future development of their forests over future decades in an uncertain world.

Acknowledgements

The work involved in preparing this paper was carried out under the auspices of the EU Interreg IVC project ForestClim. We are grateful for support from Stefania Pizzirani in preparing some of the datasets used in this paper. Christina Tracey and colleagues at Dumfries and Borders Forest District of Forestry Commission Scotland provided access to key datasets and feedback on the initial findings in the research. Duncan Ray and Bruce Nicoll provided valuable comments on early drafts of this paper.

References

Aldhous J.R., Low A.J. (1974): The Potential of Western Hemlock, Western Red Cedar, Grand Fir and Noble Fir in Britain. Forestry Commission Bulletin 49**,** London, HMSO: 105.

Allen C.D., Macalady A.K., Chenchouini, H., Bachelet A.D., McDowell N., Vennetier M., Kitzbergerg T., Riglingh A., Breshearsi D. D., Hoggj E.H., Gonzalezk P., Fenshaml R., Zhangm Z., Castron J., Demidovao N., Limp J.-H., Allardq G., Runningr S.W., Semercis A., Cobbt N. (2010): A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management, ***259***: 660–684.

Anonymous (2010): A Guide for Increasing Tree Species Diversity in Wales. Aberystwyth, Forestry Commission Wales: 41.

Anonymous (2011): Ecological Site Classification Decision Support System (ESC-DSS). Available at http://www.forestry.gov.uk/esc (accessed November 3, 2011).

Battistiti A., Stasny M., Netherer S., Robinet C., Shopf A., Roques A., Larsson S. (2005): Expansion of geographic range in the pine processionary moth caused by increased winter temperatures. Ecological Applications, ***15***: 2084–2096.

Bodin P., Wiman B.L.B. (2007): The usefulness of stability concepts in forest management when coping with increasing climate uncertainties. Forest Ecology and Management, ***242***: 541–552.

Bolte A., Ammer C., Lof M., Madsen P., Nabuurs G-J., Schall P., Spathelf P., Rock J. (2009): Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. Scandinavian journal of Forest Research, ***24***: 473–482.

Bréda N., Huc R., Granier A., Dreyer E. (2006): Temperate forest trees and stands under severe driught: a review of ecophysiological respondese, adaptation processes and long-term concequences. Annals of Forest Science, ***6***: 625–644.

Broadmeadow M., Ray D., Samuel C.J.A. (2005): Climate change and the future for broadleaved species in Britain. Forestry, ***78***: 145–161.

Broadmeadow M.S.J., Webber J.F., Ray D., Berry P. (2009): An assessment of likely future impacts of climate change on UK forests. In: Read D.J., Freer-Smith P.H., Morison J.I.L., Hanley N., West C.C., Snowdon P. (eds): Combating Climate Change – A Role for UK Forests. An Assessment of the Potential of the UK's Trees and Woodlands to Mitigate and Adapt to Climate Change. Edinburgh, The Stationery Office: 67–98.

Brown A., Webber J. (2008): Red Band Needle Blight of Conifers in Britain. Forestry Commission Research Note 2. Edinburgh, Forestry Commission: 8.

Cameron A.D. (1996): Managing birch woodlands for the production of quality timber. Forestry, ***69***: 357–371.

Dewar J. (1986): The Forestry Commission subcompartment database. In: Mason W.L., Muetzelfeldt R. (eds): Computers in Forestry. Edinburgh, Institute of Chartered Foresters: 91–95.

Edwards P.N., Christie J.M. (1981): Yield Models for Forest Management. Forestry Commission Booklet 48. London, HMSO: 32 (plus Appendices).

Forestry Commission (2011): *Phytopthora ramorum*. Available at http://www.forestry.gov.uk/pramorum (accessed November 10, 2011).

Franklin J.F. (1990): *Abies procera*. In: Burns M.R., Honkala B.A., Silvics of North America. Volume 1, Conifers. Agriculture Handbook 654. USDA, Washington: 139–154..

Gardiner B.A., Blennow K., Carnus J.M., Fleischer P., Ingermarson F., Landmann G., Lindner M., Marzano M., Nicoll B., Orazio C., Peyron J.L., Reviron M. P., Schelhaas M. J., Schuck A., Spielmann M., Usbeck T. (2010): Destructive Storms in European Forests: Past and Forthcoming Impacts. Final report to European Commission – DG Environment. Bordeaux, EFI Atlantic: 138.

Gonthier P., Giordano L., Nicolotti G. (2010): Further observations on sudden diebaks of Scots pine in the European Alps. Forestry Chronicle, ***86***: 110–117.

Green S., Ray D. (2009): Potential Impacts of Drought and Disease on Forestry in Scotland. Forestry Commission Research Note 4. Edinburgh, Forestry Commission: 8.

Green S., Hendry S.J., Redfern D.B. (2008): Drought damage to pole-stage Sitka spruce and other conifers in north-east Scotland. Scottish Forestry, ***62***: 10–18.

Grossnickle S., Sutton B.C.S., Folk R.S., Gawley R.J. (1996): Relationship between nuclear DNA markers and physiological parameters in Sitka × interior spruce populations. Tree Physiology, ***16***: 547–555.

Hannewinkel M., Hummel S., Albrecht A. (2011): Assessing natural hazards in forestry for risk management: a review. European Journal of Forest Research, ***130***: 329–351.

Intergovernmental Panel on Climate Change (IPCC) (2007): Summary of Policymakers. In: Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (eds): Climate Change 2007: The Physical Science Basis. Contribution of Workong Group I to the Fourth Assessment Report of the Intergovernmental Panel of Climate Change. New York, Cambridge University Press: 996.

Janowiak M.K., Swanston C.W., Nagle L.M., Webster C.R., Palik B.J., Twery M.J., Bradford J.B., Parker, L.R., Hille A.T., Johnson S.M. (2011): Silvicultural Decision-making in an Uncertain Climate Future: A Workshop-based Exploration of Considerations, Strategies, and Approaches. General Technical Report NRS–81. Newtown Square, USDA Forest Service: 14.

Johnson O., More D. (2004): Tree Guide. London, Harper Collins: 464.

Jones P.D., Kilsby C.G., Harpham C., Glenis V., Burton A. (2009): UK climate projections science report: projections of future daily climate for the UK from the weather generator. University of Newcastle. Available at http://ukclimateprojections.defra.gov.uk/content/view/945/500 (accessed November 10, 2011)

Kolstrom M., Lindner M., Vilen T., Maroschek M., Seidl R., Lexer M.J., Netherer S., Kremer A., Delzon S., Barbati A., Marchetti M., Corona P. (2011): Reviewing the science and implementation of climate change adaptation measures in European forestry. Forests (2011), ***2***: 961–982.

Knoke T., Ammer C., Stimm B., Mosandl R. (2008): Admixing broadleaved to coniferous species: a review on yield, ecological stability, and economics. European Journal of Forest Research, ***127***: 89–101.

Lawrence A., Gillett S. (2011): Human Dimensions of Adaptive Forest Management and Climate Change: A Review of International Experience. Edinburgh, Forestry Commission: 44.

Lee S.J., Matthews R.W. (2004): An Indication of the Likely Volume Gains from Improved Sitka Spruce Planting Stock. Forestry Commission Information Note 55. Edinburgh, Forestry Commission: 4.

Lindner M., Maroschek M., Netherer S., Kremer A., Barbati A., Garcia-Gonzalo J., Seidl R., Delzon S., Corona P., Kolstrom M., Lexer M.J., Marchetti M. (2010): Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management, ***259:*** 698–709.

Lindroth A., Lagergren F., Grelle A., Klemedtsson L., Langvall O., Weslien P., Tuulik J. (2009): Storms can cause Europe-wide reduction in forest carbon sink. Global Change Biology ***15:*** 346–355.

Lines R. (1987): Choice of Seed Origins for the Main Forest Species in Britain. Forestry Commission Bulletin 66. London, HMSO: 61.

MacMillan D.C. (1991): Predicting the general yield class of Sitka spruce on better quality land in Scotland. Forestry, ***64:*** 359–372.

Magnani F., Mencuccini M., Borghetti M., Berbigier P., Berninger F., Delzon S., Grelle A., Hari P., Jarvis P.G., Kolari P., Kowalski A.S., Lankreijer H., Law B.E., Lindroth A., Loustau D., Manca G., Moncrieff J.B., Rayment M., Tedeschi V., Valentini R., Grace J. (2007): The human footprint in the carbon cycle of temperate and boreal forests. Nature, ***447***: 848–852.

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

Mason W.L. (2003): Continuous Cover Forestry: developing close-to-nature forest management in conifer plantations in upland Britain. Scottish Forestry, ***57***: 141–149.

Mason W.L. (2006): Managing Mixed Stands of Conifers and Broadleaves in Upland Forests in Britain. Forestry Commission Information Note 83. Edinburgh, Forestry Commission: 6.

Mason W.L. (2007): Changes in the management of British forests between 1945 and 2000 and possible future trends. Ibis, ***149***: 41–52.

Mason W.L., Jinks R., Harrison A.J. (2008): An overview of long-term experiments in Great Britain managed by Forest Research. In: Karlsson K. (ed.): Long Term Field Experiments in Forest Research. Working Papers of the Finnish Forest Research Institute, ***105***: 13–20.

Mason W.L., Meredieu C. (2011): Silvicultural strategies, sustainability, and adaptation to climate change in forests of the Atlantic region of Europe. Journal of Forest Planning, ***16***: 1–11.

Mason W.L., Perks M.P. (2011): Sitka spruce (*Picea sitchensis*) forests in Atlantic Europe: changes in forest management and possible consequences for carbon sequestration. Scandinavian Journal of Forest Research, (Supplement) ***11***: 72–81.

Matthews J.D. (1989): Silvicultural Systems. Oxford, Oxford University Press: 284.

Millar C.I., Stephenson N.L., Stephens S.L. (2007): Climate change and forests of the future: Managing in the face of uncertainty. Ecological Applications, ***17***: 2145–2151.

Moore J. (2011): Wood properties and uses of Sitka spruce in Britain. Forestry Commission Research Report. Edinburgh, Forestry Commission: 48.

Murphy J., Sexton D., Jenkins G., Boorman P., Booth B., et al. (2009): UK Climate Projections science report: Climate change projections. Available at http://ukclimateprojections.defra.gov.uk/content/view/944/500/ (accessed November 10, 2011).

Nakicenovic N., Swart R. (eds) (2000): IPCC Special Report on Emissions Scenarios. Cambridge, Cambridge University Press: 570.

Ogden A.E., Innes J. (2007): Incorporation climate change adaptation considerations into forest management planning in the boreal forest. International Forestry Review, ***9***: 713–733.

Paquette A., Messier C. (2010): The role of plantations in managing the world's forests in the Anthropocene. Frontiers Ecology and Environment, ***8***: 27–34.

Pommerening A., Murphy S.T. (2004): A review of the history, definitions and methods of continuous cover forestry with special attention to afforestation and restocking. Forestry, ***7***: 7–46.

Pussinen A., Nabuurs G.J., Wieggers H.J.J., Reinds G.J., Wamelink G.W.W., Kros J., Mol-Dijkstra J.P., De Vries W. (2009): Modelling long term impacts of environmental change on mid- and high latitude European forests and options for adaptive forest management. Forest Ecology and Management, ***258***: 1806–1813.

Pyatt D.G., Ray D., Fletcher J. (2001): An Ecological Site Classification for Forestry in Great Britain. Forestry Commission Bulletin 124. Edinburgh, Forestry Commission: 74.

Quine C.P., Coutts M.P., Gardiner B.A., Pyatt D.G. (1995): Forests and Wind: Management to Minimise Damage. Forestry Commission Bulletin 114. London, HMSO: 24.

Ray D. (2008): Impacts of Climate Change on Forests in Scotland. A preliminary synopsis of spatial modelling research. Forestry Commission Research Note 101. Edinburgh, Forestry Commission: 8.

Savill P.S. (1991): The Silviculture of Trees Used in British forestry. Wallingford, CAB International: 143.

Schelhass M.J., Nabuurs G.J., Schuck A. (2003): Natural disturbances in the European forests in the 19th and 20th centuries. Global Change Biology, ***9***: 1620–1633.

Sing L., Peace A., Ray D., Brown T. (2006): Modelling Sitka spruce yield in southern Scotland. In: Reynolds K. (eds): Sustainable Forestry in Theory and Practice. Portland, USDA Forest Service. Available at http://www.fs.fed.us/pnw/pubs/pnw_gtr688/TOC/IMandITsession5.htm. (Accessed November 10, 2011).

Spittlehouse D.L., Stewart R.B. (2003): Adaptation to climate change in forest management. BC Journal of Ecosystems and Management, ***4***: 1–11.

Straw N., Fielding N., Green G., Price J., Williams D. (2011): Defoliation and growth relationships for mid-rotation Sitka spruce attacked by the green spruce aphid, *Elatobium abietinum* (Walker). Forest Ecology and Management, ***262***: 1223–1235.

Taylor C.M.A. (1991): Forest Fertilisation in Great Britain. Forestry Commission Bulletin 95, London, HMSO: 24.

Tyler A.L., MacMillan D.C., Dutch J.C. (1996): Models to predict the general yield class of Douglas fir, Japanese larch and Scots pine on better quality land in Scotland. Forestry, ***69***: 13–24.

Watt M.S., Kriticos D.J., Alcaraz S., Brown A.V., Leriche A. (2009): The hosts and potential geographic range of Dothistroma needle blight. Forest Ecology and Management, ***257***: 1505–1519.

Woods A., Coates K.D., Hamann A. (2005): Is an unprecedented dothistroma needle blight epidemic related to climate change? BioScience, ***55***: 761–769.

Worrell R. (1995): European aspen (*Populus tremual* L.): a review with particular reference to Scotland. 1. Distribution, ecology, and genetic variation. Forestry, ***68***: 93–105.

Worrell R., Malcolm D.C. (1990): Productivity of Sitka Spruce in Northern Britain: 2. Prediction from site factors. Forestry, ***63***: 119–128.

Xenakis G., Ray D., Mencuccini M. (2011): Effects of climate and site characteristics on Scots pine growth. European Journal of Forest Research, ***131***: 427–439.

Received for publication December 6, 2011
Accepted after corrections March 15, 2012

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