Silvicultural strategies, sustainability, and adaptation to climate change in forest of the Atlantic region of Europe.

William L. Mason, Céline Meredieu

Review

Silvicultural Strategies, Sustainability, and Adaptation to Climate Change in Forests of the Atlantic Region of Europe

William L. Mason[*1] and Céline Meredieu[*2]

ABSTRACT

Many forests of the Atlantic region of western Europe are plantations created in the last century after a long history of deforestation. These forests have high growth rates by European standards and support competitive wood using industries. However, in some countries of the region (Scotland, Wales) there is increasing pressure to diversify the forests to meet the requirements of multifunctional forestry, while in other areas (the Landes region of south-west France) recent severe storm damage raises the need to increase the resilience of plantations to future climate change. A range of silvicultural systems can be used to diversify plantation forests, but these will have different impacts on indicators of sustainability. The framework of Forest Management Alternatives (FMAs) developed in the EU Eforwood project spans the range of possible stand manipulation from no intervention in a long-term reserve to complete above-ground biomass removal in short rotation forestry. Using the example of a Sitka spruce stand in Scotland, we present the values of a range of economic, environmental, and social indicators associated with each FMA. Traditional plantation management practices based on planting a single species and patch clear felling are more attractive in economic terms than for ecosystem services. A favoured alternative of combined objective forestry using a range of species and smaller clearfelled areas is not as attractive in economic terms and produces only small gains in ecosystem services. A close-to-nature option produces greater recreational and biodiversity benefits, while being only marginally less economically viable than clearfelling, because the use of natural regeneration saves on restocking costs. Current policies and guidelines for adapting forests to climate change propose greater use of less intensive FMAs at the expense of traditional plantation management and we illustrate possible impacts of such scenarios on selected sustainability indicators. Future development of this framework will need to link growth models with predictions of stand vulnerability to abiotic and biotic risks to allow more rigorous examination of the effects of changes in the balance of FMAs upon sustainability indicators. We outline research challenges which need to be tackled to allow managers to devise and implement appropriate silvicultural strategies to adapt Atlantic forests to climate change.

Keywords: plantation forests, silvicultural systems, sustainability, climate change

INTRODUCTION

The Atlantic region of western Europe covers more than 20 degrees of latitude, stretching from Cape Wrath at the northern end of Scotland (58° 36′ N) to Tarifa (36° N) at the southern tip of Spain. This region contains all of Ireland, the western parts of Great Britain and France, the north-western and south-western provinces of Spain, and all of Portugal. These areas are characterised by an oceanic climate with relatively mild winters, regular rainfall spread by westerly winds, and comparatively long growing seasons. Furthermore, the northern part of the region receives the warming effect of the Gulf Stream which allows genera like *Eucalyptus* spp. to be grown at high lati-

Corresponding author: William L. Mason
E-mail: bill.mason@forestry.gsi.gov.uk
[*1] Forest Research, Northern Research Station, Roslin, Scotland, EH25 9SY, UK
[*2] INRA, UMR1202 BIOGECO, 69 Route d'Arcachon, F-33612 Cestas Cedex, France

tudes (57° N) in western Scotland. The benign climate coupled with varied food supplies available from land and sea resulted in early colonisation by hunter-gatherer bands following the start of the current interglacial some 11,500 years ago (CUNLIFFE, 2001). This was followed by the development of settled human societies by some 5,000 years ago and in the subsequent millennia the ready access to marine transport routes led to considerable trading between the coastal areas of the region which became characterised by common 'Celtic' languages some 3,000 years ago (CUNLIFFE, 2001). Despite many political and social differences over subsequent millennia (e.g. the differential impact of the Roman empire (Perlin, 1989)), the various countries and provinces of the Atlantic seaboard retain a long history of shared experience which was recognised by the European Union in the establishment of the 'Atlantic Arc' region in 1989 (CUNLIFFE, 2001).

The forests of this region have been exploited by humans for thousands of years with evidence of systematic coppice management of broadleaved woodland some 5,000 years ago (RACKHAM, 2006). A consequence of this history was the gradual reduction in forest cover over the centuries leading to the formation of heathland vegetation and scrub woodlands in many parts of the region (e.g. SMOUT, 2003). Thus, in Scotland forest cover in 1900 was about 4% of the land area (MASON, 2007), while the equivalent figure for Ireland was 1% (COILLTE, 2007). In south-west France, by the late 1700s, the reduction of forest cover had been enhanced by burning to facilitate grazing leading to the formation of extensive areas of heath and swamp, while the coastal sand dunes became a threat to inland villages in the absence of protective forests (REED, 1954). From about 1700 onwards, there was increasing recognition of the need to restore forest cover to the degraded landscapes of the region as a means of revitalising impoverished rural economies and to provide greater visual diversity (HOUSE and DINGWALL, 2003). The last two centuries have seen a progressive restoration of forest cover of the region, mainly through the establishment of productive plantation forests. In Portugal, there are about 650,000 ha of eucalyptus plantations, mainly *Eucalyptus globulus* LABILL. (ANON., 2009b), grown on a 12 year pulpwood rotation. In north Spain, plantations of maritime pine (*Pinus pinaster* AIT.) cover about 600,000 ha while those of radiata pine (*Pinus radiata* D. DON.) make up a further 90,000 ha (BALBOA-MURIAS *et al.*, 2006). Further north, the Landes area of France now contains 826,000 ha of even-aged maritime pine forests (IFN, 2009a), while there are extensive plantations of Sitka spruce (*Picea sitchensis* BONG. CARR.) in the British Isles with 528,000 ha in Scotland (FORESTRY COMMISSION, 2008) and 328,000 in Ireland (FOREST SERVICE, 2007). All these plantation forests are highly productive by European standards with increments of 10–24 m^3 ha^{-1} yr^{-1} or more (DUNCKER *et al.*, 2008) and support important wood using industries.

Since the beginning of the 1990s there has been an increasing emphasis throughout the world on the principle of sustainable forest management (SFM) for multiple benefits. European guidelines on SFM were developed at the 1993 Helsinki Ministerial Conference on the Protection of Forests in Europe (MCPFE, 1993) and have been refined through further MCPFE declarations. These guidelines oblige member states of the EU to consider the environmental and social functions of forests as well as the economic returns generated through timber production. Meeting these obligations is arguably more problematic for countries in the Atlantic region because plantation forests managed primarily for timber production are such a major component of the forest resource. For instance, in Ireland and the United Kingdom, plantations make up 90 and 69 per cent respectively of the forest area (FAO, 2001) while in Les Landes almost 50% of all forests are of plantation origin (more than 80% of annual reforestation since 1999; CRPF AQUITAINE, 2009).

For this reason, intensive research has been undertaken to try and understand the ecosystem services provided by plantation forests in the region (e.g. biodiversity – see HUMPHREY *et al.*, 2003; BRIN *et al.*, 2008). In Great Britain, there has been increasing recognition of the benefits provided by appropriate management of native woodland types, such as Caledonian pinewoods of northern Scotland (Mason *et al.*, 2004), and of the desirability of restoring native woodland communities where conifer plantations were established on sites that were previously broadleaved woodland (THOMPSON *et al.*, 2003). This has reflected changes in the forestry policies of the various countries of the United Kingdom where both the Welsh (ANON., 2009a) and the Scottish (ANON., 2006) forestry strategies propose the use of a wider range of silvicultural systems. This will mean fewer single species stands managed on patch clear felling regimes and more irregular stand structures containing a mixture of species and managed under Continuous Cover Forestry (CCF) regimes. However, the impacts of such changes on the forestry-wood chain are not clear, since MACDONALD *et al.* (2010) show that certain forms of CCF can result in a reduction in the timber quality of Sitka spruce. MASON (2007) estimated that changes in Scottish forests to accommodate multipurpose management might result in a 20 per cent or greater decline in conifer plantation area by 2030 with consequent declines in long-term timber supplies.

A further complication is that the future management of these plantation forests needs not only to respect the demands imposed by meeting the objectives of multi-purpose forest management, but must also consider how best to increase their resilience to projected climate change. Modelling of changes in the French climate suggest that a Mediterranean climate, defined by a water balance of less than 350 mm $year^{-1}$, would cover between 60 and 80 per cent of mainland France by the end of the century with consequent changes in the distribution of the main timber producing species (CACOT and PEYRON, 2009). Similarly, RAY (2008) has used projections of climate change to predict that parts of eastern Scotland will become unsuitable for growing Sitka spruce by 2080, because of decreased soil moisture availability during the growing season. There is also the concern that climate change may increase the likelihood of damage by pests and pathogens or by extreme events, such as the wind damage caused by storm Klaus in south-western France in January 2009 when 37.1 Mm^3 of maritime pine were blown down or broken, equivalent to five years annual harvest in the region (IFN, 2009b).

In the plantation forests of the Atlantic region, a range of silvicultural systems can be used ranging from intensive clear felling with artificial regeneration to the fostering of irregular stand structures based on natural regeneration (Malcolm *et al.*, 2001). This variety of silvicultural systems coupled with the different tree species, site and climatic conditions can make it difficult to compare forest management approaches and their potential impacts on indicators of sustainability at either a country or a regional scale. In this paper we use a framework for classifying forest management options at a European level (Duncker *et al.*, 2008) to show how these options provide varying combinations of timber and non-timber outputs, and consider the interaction with silvicultural strategies proposed to adapt forests to climate change. This analysis is mainly based upon our experience with the Sitka spruce forests of Scotland and the maritime pine forests of south-western France.

A FRAMEWORK FOR CLASSIFYING FOREST MANAGEMENT OPTIONS

Duncker *et al.* (2008) have outlined the concept of Forest Management Alternatives (FMAs) whereby each FMA consists of a particular pattern of stand development supported by characteristic forest operational processes. These are operations such as soil cultivation, weed control, thinning and timing and extent of felling. FMAs can be defined by the general management objectives and a corresponding intensity of forest resource manipulation. They identified five FMAs in Europe which, arranged in order of increasing intensity of wood biomass removal, are:

- Unmanaged forest nature reserve (FMA 1);
- Close-to-nature forestry (FMA 2);
- Combined objective forestry (FMA 3);
- Intensive even-aged forestry (FMA 4);
- Wood biomass production (FMA 5).

Features used to distinguish between these FMAs include: species composition, management of stand density and/or pattern, age pattern/ phases of development, stand edges/ boundaries, amount and intensity of timber and biomass removal, and site conditions. The amount of external energy used in operational processes also differs between management alternatives.

The salient characteristics of each FMA are outlined below.

Unmanaged forest nature reserve (FMA 1)

The main objective of an unmanaged forest nature reserve is to allow natural processes and disturbances (e.g. windthrow) to create natural, ecologically valuable habitats. It will tend to be dominated by stands in the old growth and understorey reinitiation phases (*sensu* Oliver and Larson, 1996). No operations are allowed in a forest reserve that might change the nature of the area. Examples of this FMA in the plantation forests of the Atlantic region are rare, although some stands in Britain managed as biological retentions are developing this type of structure (Peterken *et al.*, 1992; Humphrey, 2005).

Close-to-nature forestry (FMA 2)

The aim here is to manage a stand with the emulation of natural processes as a guiding principle. Financial return is important, but management interventions must enhance or conserve the ecological functions of the forest. Timber can be harvested and extracted, but some standing and fallen dead wood is left, which may reduce productivity. Only native or site adapted tree species are chosen. Natural regeneration is the preferred method of establishing new seedlings. The rotation length is generally much longer than the age of maximum mean annual volume increment (MMAI) and harvesting uses small scale removals resulting in the development of an irregular and intimately mixed stand structure. The silvicultural systems characteristic of this FMA would be single tree and group selection, plus irregular shelterwood (terminology follows Matthews, 1989). This type of management is being introduced into Sitka spruce forests in Scotland (Mason, 2003) and Ireland (Ni Dhubhain, 2003), and similar structures can be found in old maritime pine stands in Les Landes managed to stabilize coastal dunes (Sardin, 2009).

Combined objective forestry (FMA 3)

In this FMA, management pursues a combination of economic (timber production) and non-market objectives. Mixtures of tree species are often promoted, comprising both native and introduced species suitable for the site. Natural regeneration is the preferred method of restocking, but planting is also widely used. Site cultivation and/or fertilisation may be carried out to speed up the development of a young stand. The rotation length is similar to the age of MMAI and the harvesting system is generally designed around small scale clear felling with groups of trees retained for longer periods to meet landscape and biodiversity objectives. A number of shelterwood silvicultural systems (uniform, group, strip) are practiced in this FMA, as well as small patch clear felling. Forest management aims to produce sawlogs as a primary timber product. This type of management is found throughout the region wherever landscape or other non-market aspects are important objectives of management.

Intensive even-aged forestry (FMA 4)

The main objective in intensive even-aged forestry is to produce timber, although landscape and biodiversity may feature as secondary objectives. Typical stands tend to be even-aged, and are composed of one or very few species. Any species can be suitable provided it is site adapted and non-invasive, and planting is the preferred method of regeneration. Intensive site management including cultivation and weed control is used to ensure rapid establishment. Genetically improved material is often planted when available. The rotation length is often less than or similar to the age of MMAI and clear felling is normal practice, although seed tree systems may be used on less fertile sites where wind hazard is low. Stands in areas of high wind risk may not be thinned. In some cases, whole tree harvesting may occur but logging residues (including branches and root systems) are normally left on site. This is the typical management approach in much of the region (e.g. Rodriguez-Soaillero *et al*., 2000; ONF, 2003; Mason, 2007; CRPF Aquitaine, 2009) and Table 1 shows the main features of this FMA in Sitka spruce and maritime pine forests.

Wood biomass production (aka short rotation forestry) (FMA 5)

The main objective is to produce the highest amount of small dimension wood biomass or fibre. Tree species selection depends mainly on the economic return, as long as the species is not invasive. Pure stands of single species are generally favoured and intensive site management may occur to ensure rapid canopy closure. Stands cycle between stand initiation and stem exclusion with a short, rotation period i.e. from 5-25 years depending on species characteristics and the economic return. The intensity of harvesting is at its maximum compared to the other alternatives. The final felling is a clear-cut with removal of all woody residues, if there is a suitable market. Currently the eucalyptus plantations in Portugal and north-west Spain (Duncker *et al*., 2008) would be the main example of this approach within the Atlantic region.

LINKING FMAS TO SUSTAINABILITY INDICATORS

Consideration of the various FMAs listed above and the different operations associated with each, indicates that they will have varying impacts on different aspects of sustainability. For instance, regimes favouring FMA 5 will tend to result in much lower levels of standing and fallen deadwood than is found under FMA 1, with a consequent reduction in biodiversity associated with the deadwood habitat (Brin *et al*., 2008). Similarly, public preference for larger trees and more diverse structures is likely to result in higher valuation being given to forests managed under FMAs 1 or 2 than under FMAs 4 and 5 (Edwards *et al*., 2011). By contrast, supplies of timber of regular dimensions and quality are likely to be greater under FMA 4 than under FMA 2, particularly when the benefits of

Table 1 A list of the main features characteristic of current plantation management (equivalent to FMA 4) for Sitka spruce forests in Scotland and maritime pine forests in Les Landes, France (see note for data sources)

Feature	Sitka spruce	Maritime pine
Genetic improvement	First generation seed orchard to cuttings of full sib families (10-30% genetic gain)	First and second generation seed orchards (15%-30% genetic gain respectively)
Ground preparation	Mounding (scarification on some drier soils)	Ploughing (complete or partial)
Drainage	Yes	Yes
Planting density (trees ha^{-1})	2,700	1,000-1,400
Weeding	1-3 times: chemical or hand	2-3 times: mechanical
Chemical protection	Against large pine weevil (*Hylobius abietis*)	In nursery, against large pine weevil (*Hylobius abietis*)
Fertilizer inputs	Rare	Recommended P_2O_5 60-80 kg ha^{-1}
Pruning	No	Rare 600 trees to 3 m at 6 m height; 400 trees to 6 m at 10 m height
Thinning	Only on 50 % of sites of lower wind risk; 2-3 times from years 20-25. Higher wind risk sites are unthinned.	3 to 5 times from years 15-30
Final stand density (trees ha^{-1})	300-1,000 (thinned - unthinned)	200-300
Rotation age (years)	35-50	35-60
Average productivity (m^3 ha^{-1} $year^{-1}$)	14	10.5

Note: the main data source used to compile this table was Duncker *et al*., 2008, with additional information from Mason (2007) and ONF (2003).

genetic improvement are considered (MACDONALD *et al.*, 2010).

By formulating the relationship between a given FMA and indicators of sustainability, such as those proposed by the MCPFE (MCPFE, 2002), one can explore the impacts of changes in the balance of FMAs in a given country or region upon the future sustainability of the forestry wood chain (PAIVINEN and LINDNER, 2008). Such changes could arise as a result of new forestry policies, as described above for Scotland and Wales, or from the abandonment of agricultural lands as found in many mountain areas of Europe, or as a consequence of climate change. Ideally, the relationship between a FMA and a particular indicator should be quantified, as can be achieved for wood production using country specific or European growth models (NABUURS *et al.*, 2007a), but where quantitative data are lacking, qualitative measures involving expert judgment can be a helpful surrogate (EDWARDS *et al.*, 2011).

Within the EU 'Eforwood' project, a primary goal is to develop a computer-based tool for sustainability impact assessment ('ToSIA') for the European forestry wood chain (PAIVINEN and LINDNER, 2008; LINDNER *et al.*, 2010). A set of 27 indicators has been proposed to encompass the three pillars of sustainability: nine indicators under the 'economic' pillar, seven under 'social', and ten under 'environmental' (RAMESTEINER *et al.*, 2006). In the following section, we show how values of a subset of the Eforwood indicators can vary with FMA, using Sitka spruce forests in Scotland as an example.

FMAS AND SELECTED SUSTAINABILITY INDICATORS IN SITKA SPRUCE FORESTS

The estimates in Table 2 are based around a hypothetical stand of average productivity growing at 14 m^3 ha^{-1} yr^{-1}. It is assumed both that the risk of windthrow imposes no major constraint to management i.e. all FMAs are equally plausible on the site, and that there is no difference in productivity between FMAs in line with similar simulations of management options in British forests (MACDONALD *et al.*, 2010). The Net Present Value (NPV) calculations use 1 and 3 per cent interest rates and are based on the yields predicted by existing British yield tables (EDWARDS and CHRISTIE, 1981) for a stand of average productivity given normal thinning regimes. Management and other costs and revenues are derived from figures provided by MASON (2007). The yield models assume FMA 4 management and were extrapolated to other FMAs using expert judgement e.g. assuming proportionately lower yields for stands of Sitka spruce growing in mixture with other species. Timber quality and properties were predicted using models of wood density and tree taper developed by GARDINER *et al.* (2005). Recreational values were based on a 1-10 scoring system (a low score indicates a low recreational value and vice versa) (EDWARDS *et al.*, 2011). Biodiversity value was based on the same approach (M. Smith., Forest Research, pers.comm.) and inte-

Table 2 Estimates of values of a range of sustainability indicators by Forest Management Alternative (FMA) for an average productivity (14 m^3 ha^{-1} $year^{-1}$) stand of Sitka spruce in Scotland

Sustainability indicator	FMA				
	1: Unmanaged forest nature reserve	2: Close to nature forestry	3: Combined objective forestry	4: Intensive even-aged forestry	5: Wood biomass production
Assumed rotation length (years)	200	100	60	50	25
NPV @ 1% (euros/ha)	−5,200	4,620	3,260	4,850	2,370
NPV @ 3% (euros/ha)	−2,690	−750	−2,200	−1,400	−1,280
Recreational value (score 1-10)	5.9	6.7	4.4	3.6	2.8
Biodiversity value (score 1-10)	6.6	5.0	3.7	2.1	1.2
Carbon stocks (t C ha^{-1})	215	135	120	110	60
Machinery emissions (t CO_2 eq ha^{-1} yr^{-1})	0.01	0.06	0.09	0.10	0.16
Employment (FTE $100ha^{-1}$)	0.21	0.48	0.51	0.56	0.59

All values are for a base year of 2005.

grates a number of factors known to influence biodiversity and to be influenced by forest management (HUMPHREY *et al.*, 2003; RAULUND-RASMUSSEN *et al.*, 2008). These are: *structural features* such as vertical and horizontal structure within a stand, associated habitats such as open ground, and the presence and amount of dead wood; *compositional aspects* include ground flora, faunal diversity, tree and shrub diversity, and the abundance of epiphytes and fungi; lastly *functional attributes* comprise the naturalness of the stand and the continuity of woodland cover on the site. Calculations of carbon stocks, machinery emissions, and current and projected per cent forest area are based on MASON *et al.* (2009a). Lastly, the employment statistics are based on data from the late 1990s (FORESTRY COMMISSION, 2001) and include haulage of timber from forest to the mill as well as within forest operations. The statistics distinguish between establishment and harvesting operations and the figures were allocated by FMA assuming proportionately greater activity in both areas in FMA 4 and 5. The framework can be expanded to provide for other indicators of sustainability (e.g. soil nutrient status, water quality - RAULUND-RASMUSSEN *et al.*, 2008) as existing knowledge on the impacts of management on a particular indicator is collated.

FMA 4 is the traditional form of management for Sitka spruce forests in Scotland and produces a positive return at a 1 per cent interest rate and a negative one at 3 per cent. It provides a comparatively high rate of employment and maintains reasonable carbon stocks, but has comparatively low recreational and biodiversity value compared to some of the less intensive management alternatives. By contrast, close-to-nature forest management provides higher recreational and biodiversity values, maintains slightly higher carbon stocks, is slightly less profitable at a 1 per cent interest rate but produces a less negative result at a 3 per cent rate than FMA 4. This latter result is critically dependent upon the assumption that restocking in FMA 2 is achieved entirely by natural regeneration, thus reducing the establishment costs incurred in FMA 4 by operations such as site preparation and planting (see Table 1). However, if a 20 per cent genetic gain is built into the NPV calculations for FMA 4, the net effect is to almost eliminate the deficit for this option because of assumed improvements in sawlog yields (data not shown).

An interesting feature of these results is that combined objective forestry seems less attractive in either economic or socio-environmental terms than close-to-nature or intensive even-aged management. This is largely because the introduction of other species into a Sitka spruce matrix results in lower yields than in the pure Sitka spruce stands characteristic of FMA 4, while still incurring many of the establishment and management costs associated with the latter. Furthermore, the shorter rotation length compared to FMA 2 means that fewer biodiversity and recreational benefits are achieved, since these tend to be associated with older ages of stands (EDWARDS *et al.*, 2011). As would be expected, FMA 1 has the highest biodiversity value and a high recreational score, but the need to provide a basic level of management input (e.g. path and track maintenance, control of browsing animals) results in a negative financial outturn. The estimates for FMA 5 are affected by the lack of an established woodfuel market within the UK keeping prices for woodfuel products relatively low, while the intensity of harvesting and the rotation length result in lower recreational and biodiversity values.

An attraction of this framework is that one can link the indicator values with the proportions of different FMAs to explore the impact of different policy scenarios. In Table 3 we established the current and likely distribution of FMAs in Sitka spruce forests under a 'business as usual' scenario (year 2005 as a reference; EDWARDS *et al.*, 2011) and two other potential distributions of FMAs to compare their relative effects. In Table 4 we illustrate the consequences for some of the sustainability indicators discussed above. The two projected scenarios considered were: Natura 2000 and projected UK policy. The estimates of per cent forest area by FMA for 'Natura 2000' are based on those for all conifer forests in the UK (EDWARDS *et al.*, 2011) while that for 'projected UK policy' is taken from MASON *et al.* (2009a). The 'Natura 2000' scenario assumes greater emphasis is given to nature conservation in forests (EUROPEAN COMMISSION, 2003) and assumes that at least 15 per cent of the forest area is transferred to either FMA 1 or

Table 3 Percentage distribution of Forest Management Alternatives (FMA) for Sitka spruce forests in Scotland under 3 different scenarios (see text for details)

Scenario	FMA				
	1: Unmanaged forest nature reserve	2: Close to nature forestry	3: Combined objective forestry	4: Intensive even-aged forestry	5: Wood biomass production
Business as usual (reference)	0.5	7.0	22.0	70.0	0.5
Natura 2000	1.7	23.3	18.1	56.6	0.3
Projected UK policy	5.0	15.0	50.0	25.0	5.0

Table 4 Impact of 2 different scenarios upon relative values of selected sustainability indicators

Indicator	Scenario	
	Natura 2000	Projected UK policy
NPV @ 1%	0.98	0.77
Recreational value	1.13	1.13
Biodiversity value	1.17	1.32
Carbon stocks	1.04	1.06
Machinery emissions	0.92	0.92
Employment	0.97	0.94

Relative values are expressed as a ratio of those for the business as usual scenario (see text for details).

FMA 2 with restrictions on harvesting in these alternatives.

Both alternative scenarios show a switch away from FMA 4 towards less intensive management regimes in FMAs 1-3, but the change is less in the Natura 2000 scenario than under projected UK policy. The latter results in a greater proportion of combined objective forestry (FMA 3) and of unmanaged forest nature reserves (FMA 1) than the other scenarios. As a consequence, there are greater impacts on some important indicators such as a 23 per cent fall in NPV and 32 per cent increase for biodiversity compared with business as usual. By contrast the Natura 2000 scenario has minor effects on NPV (2 per cent reduction) while providing reasonable increases in recreation and biodiversity value (13 and 17 per cent respectively).

These findings are illustrative and make no allowance for possible changes within a FMA such as improved management leading to a higher sawlog outturn or the impact of changing market conditions like a strengthening in the demand for wood fuel. They also do not allow for any impact of the transition process necessary to move from one scenario to another. However, this framework provides a useful means of demonstrating the potential impacts of changes in forest management, such as the increasing concern to implement effective strategies to adapt Atlantic forests to projected climate change.

SILVICULTURAL STRATEGIES FOR ADAPTING FORESTS TO CLIMATE CHANGE

Examination of recent British and French guidance on adaptation of forests shows broad agreement on the general measures to be implemented over the next decade (e.g. Cacot and Peyron, 2009; Mason *et al.*, 2009b). These measures can be interpreted as a recommendation for greater diversification of forests as part of risk planning, including use of provenance mixtures, fostering mixed species stands, lengthening rotations, more thinning especially in areas at risk from drought, development of more stable stand structures, and the use of a wider range of silvicultural systems. An additional point identified by Cacot and Peyron (2009) is the desirability of testing new genetically improved varieties of maritime pine for their potential sensitivity to drought. Taken as a whole, these recommendations could be seen as an endorsement of policies that seek to increase the representation of FMAs 1-3 in Atlantic forests at the expense of FMA 4.

However, these adaptation principles are, as yet, too general to be of practical use in forest management. The advice to diversify forests, for instance by transforming more forests to FMA 2 from FMA 4, overlooks the fact that the thinning operations necessary to implement this transformation can increase the vulnerability of the thinned stands to windthrow, especially in the oceanic climate of Atlantic Europe (Mason, 2003). The converse is that intensive thinning of young stands managed under FMA 4, as practiced with maritime pine, can increase the risks of windthrow since there is insufficient crown contact to provide within stand stability and individual trees become vulnerable to strong winds (Cucchi and Bert, 2003). These increases in risk as a consequence of thinning are without considering any possible effect of climate change on the occurrence of extreme events, such as storms or summer droughts. Furthermore, the prescription to lengthen rotations overlooks the fact that younger stands which are actively managed have greater flexibility to withstand climate change, whereas older stands show less resilience and can be vulnerable to extreme events (Nabuurs *et al.*, 2007b).

In addition, one impact of the warming climate, when coupled with higher CO_2 concentrations and greater nitrogen deposition, could be to increase forest growth rates in the Atlantic region (Pussinen *et al.*, 2009). These authors project that, for this zone[1], net primary production will increase by 115-153 per cent by the end of the century from the current level of 7 t C ha^{-1} yr^{-1} while similar increases are projected for tree and carbon stocks. They identify higher felling levels as one option open to foresters to allow increase the forests' resilience to climate change. Thus, adaptation of Atlantic forests to climate change may also need to consider more sophisticated management of FMA 4 stands including deployment of improved genetic material which may also provide higher quality timber to substitute for more carbon intensive materials (e.g. steel, concrete) used in construction.

DISCUSSION

In other parts of the world, it is possible to consider meeting the demands of multi-purpose forest management by

[1]Note that for Pussinen *et al.* (2009), the Atlantic region excludes Portugal and parts of Spain and includes more eastern parts of the UK and France, and all of Denmark, Belgium, Netherlands, Luxemburg.

focussing wood production in relatively small areas of intensively managed plantations while the range of ecosystem services are provided by extensively managed natural forests. However, in the Atlantic region, the history of deforestation followed by reforestation with plantations means that it is the plantation resource which has to be managed in a variety of ways to ensure the supply of a full range of ecosystem services. In the British Isles this can be seen in recent forestry policy statements, where, for example, the recent Welsh forestry strategy seeks to progressively reduce reliance upon clearfelling (i.e. FMA 4) in favour of a range of alternative silvicultural systems (i.e. FMAs 2 and 3) (ANON., 2009a, p 19). Such changes can have substantial impacts upon other aspects of the forestry wood chain, such as the available supply of timber over time and the employment provided, or the rates of carbon sequestration achieved within forest stands. However, it can be difficult for policy makers and forest managers to explore the potential impacts of such policy changes without access to a framework that links possible management alternatives to a range of important sustainability indicators. The attraction of the FMA structure presented in this paper is that it provides a simple framework which is capable of being applied across a range of forest types (DUNCKER *et al.*, 2008) and provides a transparent means of exploring trade-offs between different silvicultural approaches (e.g. PIZZIRANI *et al.*, 2010). The importance attributed to different indicators can be adjusted through relative weightings derived in discussion with stakeholders, for instance through techniques of multi-criteria analysis (WOLFSLEHNER *et al.*, 2005). When coupled with growth models, the approach can be used to examine changes in sustainability over time, as has been shown through the use of the growth simulator EFISCEN (SCHELHAAS *et al.*, 2007) to help estimate recreational benefits (EDWARDS *et al.*, 2011), and it could also be combined with GIS to provide geospatial information (ALVAREZ and FIELD, 2009).

The results presented in Tables 2 and 4 are based on the assumption that all FMAs are equally plausible, but in reality there are different abiotic and biotic risks associated with these options. In the Atlantic region there is a history of severe damage from wind (e.g. in Scotland in 1953, 1968, 1976 and 1998; in Les Landes in 1976, 1996, 1999 and 2009; BESSEMOULIN, 2009) and the non-thin and shorter rotation policy adopted in Sitka spruce stands on more exposed sites in Scotland (MASON, 2007) can be seen as a means of adapting management to climatic risk. On such sites it is unrealistic to assume that transformation to FMA 2 is a possibility and therefore the choices are restricted to FMA 3-5. The hazards associated with climate change are not merely dependant upon a FMA but are also influenced by species and site characteristics. For instance, in northern Britain the vulnerability of lodgepole pine (*Pinus contorta* DOUGL.) stands managed under a non-thin variant of FMA 4 is often much greater than for Sitka spruce on the same site type, because of the greater susceptibility of the former to the needle cast fungus *Dothistroma septosporum* (BROWN and WEBBER, 2008).

Successful delivery of policies to increase resilience of Atlantic plantation forests will ultimately depend upon identifying those sites and stands at greatest risk from climatic impacts and using site based silviculture to undertake appropriate remedial actions. This will require an integration of probabilistic modelling of the occurrence of an extreme event, such as provided by the ForestGALES wind risk model (GARDINER *et al.*, 2006), with predictions of species response to soil moisture availability, as through the Ecological Site Classification (RAY *et al.*, 2002). These predictions can be linked to site and stand characteristics and projections of anticipated climate change to identify those areas of forests most at risk. A possible structure of a vulnerability classification would be to identify those stands that would be vulnerable within the next 10 years, those that could be vulnerable within 20-25 years, and those that might be vulnerable in a longer timeframe. The first category could become a priority for actions such as a change of species or provenance; the second might be where remedial silvicultural measures such as more intensive thinning were undertaken, whilst the third would remain under the current silvicultural regime, but with regular monitoring to check that no unforeseen hazards were developing. Such a framework could also be used to incorporate improved knowledge of the potential impact of a range of pests and pathogens, especially how these might be affected by silvicultural regimes (JACTEL *et al.*, 2009).

CONCLUSIONS

Adapting Atlantic forests to climate change presents a number of research challenges. The eight priorities listed below were developed for forests in the UK (MASON *et al.*, 2009a), but we believe that these may be generally applicable throughout the Atlantic region:

1. Develop methodologies to help forest managers identify sites and stands most vulnerable to climate change;
2. Development of data-bases/knowledge on how different species/provenances are expected to respond to climate change (e.g. climate envelope modelling) matched by studies on how their populations and distributions are actually changing;
3. Improved understanding of the factors that will become limiting for species at a regional level;
4. Trialling of species/provenances/genetically improved varieties that may be suitable for the current and projected Atlantic climate;
5. Improved understanding of how climate change will alter disturbance regimes of wind, fire, pests and diseases;
6. Improve predictions of changes in wind climate and adapt existing wind risk models to predict vulnerability of more varied stand structures;
7. Adaptation of growth models developed for even-aged forests of single species to more diverse forest types and/or provision of more flexible models;

8. Improved understanding of appropriate decision-making methods-including methods of dealing with uncertainty and the integration of multiple societal values as illustrated here using the FMA approach.

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