# Developing a site classification system to assess the impact of climate change on species selection in Ireland

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## Abstract

Correct matching of tree species to site is the first and most fundamental step in sustainable forest management. This key art, practised by foresters over centuries, was neglected in Britain and Ireland during a period of rapid forest expansion in the mid to late 20th century. The period of expansion was dominated by intensive site amelioration to plant a small number of chosen species. Forestry has matured to recognise sustainable management as key to the delivery of multiple values to society. Site classification can be used to re-establish the link between site type and species choice, and multifactor classification systems are currently used by forest practitioners in different countries. Since 2001, Ecological Site Classification (ESC) has provided support on ecological suitability analysis and site yield estimation for forest managers in Britain. Recently it has been extended to consider changes in suitability and yield resulting from different climate change scenario projections.

We are now developing a similar system for site/species suitability analysis in Ireland in the CLIMADAPT project, which is part of the CLIM-IT programme funded by COFORD. CLIMADAPT will develop a decision support methodology, similar to ESC, using soil and climatic information for Ireland. The paper discusses the stand-based and spatial analysis modules within CLIMADAPT. Spatial information is useful for strategic decision making, and stand-based analysis is appropriate for operational decisions. CLIMADAPT will be delivered as a web-application, to allow wide access to practitioners in Ireland.

Future climate projections suggest warmer, drier summers in the south and east of Ireland. This may affect growth and yield for drought sensitive species such as spruce, beech and ash. The project is also investigating the degree to which climate variables affect drought sensitive and drought tolerant species along a climatic gradient through Ireland and Britain. Knowledge and information about changes in species suitability, species tolerance and forest management adaptation will be incorporated within the decision support tool.

## Keywords

Ecological classification, forest classification, adaptation, climate change, web applications, knowledge-based models, species choice

## Background

A key decision in forestry, which has a bearing on subsequent sustainable forest management opportunities, is choosing the right tree species for a site. For example, poor species choice reduces establishment success (Perks et al. 2007), and leads to poor growth (Pyatt et al. 2001), poor form and low timber quality (MacDonald and

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Hubert 2002), and stressed trees frequently suffer from increased incidence of damage from pests and diseases (Evans et al. 2002).

The ability of the forester to recognise site conditions and select well suited tree species is of fundamental importance. Throughout the middle to later part of the 20th century commercial forestry objectives tended to be ranked most highly, prompted by government forest policy that favoured single species, even-aged conifer forest. Forest expansion was, mainly driven by the state sector and focussed largely on fast growing conifer species from the Pacific North West – in particular Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and lodgepole pine (*Pinus contorta* Douglas ex Loudon). The acquisition of land for forestry in Ireland was hampered by a policy which set strict upper limits to the value of land which could qualify (Joyce et al. 1998). The poor quality of land available at such a low price resulted in afforestation being predominantly comprised of coniferous species capable of growing on poor and wet sites. It was necessary to adjust site conditions through ground preparation and fertilization to ensure growth on the marginal land that was less valuable for agriculture (Ray and Broome 2003). The sequence of events paved the way for a generation of forest managers practised in this form of commercial forestry, and the skill of selecting species according to site type declined.

Policy targets for forest cover in Ireland date back to 1948 when a forest cover of 1 million acres, to be achieved by an annual planting programme of 25,000 acres (10,000 ha) was agreed in a bid to start a reforestation policy in Ireland, and reduce the reliance on wood imports (OCarroll 2004).

Since the introduction of the afforestation grants and premium scheme in the mid 1980s, more than 250,000 ha has been established over the period 1990 to 2006 (Black et al. in press). Rapid expansion in the private sector, and changes in the conditions of the forestry grant and the premium schemes have resulted in an increase in broadleaf cover since the 1990s. Recent National Forest Inventory data suggest that 24% of the forest estate is comprised of broadleaves (NFI 2007).

Forests have a role to play in sequestering carbon dioxide from the atmosphere, and so recent incentives have been offered to encourage forest expansion. The Irish Government has committed to expanding ‘Kyoto forests’ that will contribute towards the emissions reduction targets as outlined in the National Climate Change Strategy (NCCS) 2007-2012. It has also been recognised (Black 2008, Malone 2008) that to ensure forests continue to play a role in greenhouse gas emissions reductions, a programme of forest expansion of 7,500 to 10,000 ha $yr^{-1}$ will be required over the next 20-30 years. To achieve this target a range of stakeholders, including environmental and conservation agencies, public, business and of course landowners must be persuaded that forest expansion is attractive. Guidance on species choice in Ireland has been published (Horgan et al. 2004), and recommendations for the selection and silviculture of broadleaved trees is also available (Joyce et al. 1998). Site classification has an important role in this regard as it will encourage improved species choice, and more importantly it should demonstrate the evolving recommendations on climate change adaptation (Ray 2008b, 2008a, Ray et al. 2008). Forests planted now will grow and mature through a period of unprecedented climate change. Therefore the new challenge of site classification systems is to assist and support robust species choice and silvicultural systems to minimise the negative effects of climate change on forests and forest ecosystems, as well as other goods and services that forests provide to society.

Site classification systems have been used in Scandinavia (Cajander 1926) and central Europe (Ellenberg 1988) to describe the natural forest cover of regions using biophysical variables describing site and climatic characteristics (see examples in Ellenberg 1988). However, in Ireland (as in Britain) very little of the natural forest cover remains due to clearance, which started about 5500 BP (Cross 2006), and resulted in a woodland cover of only 1% of the land area at the beginning of the 20th century (Rackham 1986). A recent estimate of native woodland by the Forest Service (Higgins et al. 2004) indicated less than 0.8% of the land area had native woodland cover, and all was highly modified.

In Britain, work on Ecological Site Classification (ESC) began in 1992. The project was conceived following a study tour of British Columbia where the Biogeoclimatic Ecosystem Classification (BEC) system is used to classify natural forests (Krajina 1969, Pojar et al. 1987, Klinka et al. 1989). The ESC method (Pyatt et al. 2001, Ray 2001) was adapted to suit the site classification of species of tree in plantation forests, and to classify the semi-natural woodland types described in the National Vegetation Classification (Rodwell 1991).

The approach in Germany, of adapting forestry to site conditions, was described as Forstgesellschaft (planted forest communities) by Ellenberg (1988). Similar approaches have been suggested for use in Britain (Anderson 1950, Anderson and Fairbairn 1955), and indeed multi-factor site classifications have been developed in Germany (Wagenknecht et al. 1956), Finland (Kuusipalo 1985) and later in France (Rameau et al. 1993), and the US (Barnes et al. 1982, Cleland et al. 1993) which also classifies managed and highly modified forest types.

ESC methodology took shape over four years and the project was expanded in 1996, in order to develop ESC as a computer-based decision support system (DSS) tool. A focus was the developing policy for sustainable forestry following the 1992 Earth Summit (Anon 1992), and the vision was a user-friendly computer DSS system that could deliver the complex methodology of ESC, allowing users to assess the ecological suitability of alternative forest planning options. It was envisaged that the development of ESC-DSS would provide a core planning tool for species choice, and would provide a stimulus for linked modules to help guide forest managers and planners by indicating the likely effects of management on forest ecology. ESC was also deployed on a GIS system (Clare and Ray 2001, Ray and Broome 2003, Ray et al. 2003) and has since been used to assess the impacts of projected climate change scenarios on species suitability (Ray et al. 2002, Broadmeadow and Ray 2005, Broadmeadow et al. 2005, Ray 2008b, 2008a). The introduction of climate change projections to study impacts on species suitability is facilitated by the multi-factor design of the system. Each of the climatic variables can be substituted for future projections, and, with dynamic coupling between climate and soil factors, to accommodate adjustments in soil moisture and nutrient supply in projected future climates.

This paper describes the spatial and site-based components of the CLIMADAPT decision support tool. The spatial system uses digital soil data and is useful for strategic planning, whereas the stand-based system can be used to help select species for a site, based on information surveyed at that site. Both are based on the ESC methodology, and provide an assessment of species choice in the projected changing climate of Ireland.

## Methods

*CLIMADAPT concept*

Plans for a computer-based site classification system for Ireland were included in a research programme to investigate and develop climate change mitigation and adaptation options. It is important to consider the interaction between the impacts of climate change, adaptation for sustainable forestry and mitigation options. Future climate change policies and actions should consider all of these factors.

Multi-factor forest site classification systems, by definition, separate the effects of climatic and edaphic factors on tree species, woodland community, or forest type suitability. However, most site classification systems do not differentiate the effect of the climatic variables. For example, Flore Forestièr Française (FFF) (Rameau et al. 1993) defines major climatic zones in France to differentiate climatic effects on species suitability; the Ecosite classification system of Alberta (Beckingham and Archibald 1996) defines typical seasonal and annual climate variables for natural sub-regions. The ESC development had followed a different approach, in which the variability of climate was defined in four climatic factors: warmth (accumulated temperature - AT), droughtiness (moisture deficit - MD), wind exposure (DAMS), and continentality (see Pyatt et al. 2001 for definitions). The suitability class (Very Suitable, Suitable, or Unsuitable) of different tree species and semi-natural woodland communities was linked to each of the climatic factors, and to two soil quality factors representing soil wetness (soil moisture regime - SMR) and soil fertility (soil nutrient regime - SNR) following a similar method to those described for BEC (Pojar et al. 1987), Ecosites (Beckingham and Archibald 1996) and FFF (Rameau et al. 1993).

It is the differentiation of climatic variables that has allowed future climate projections from the scenarios described by the Intergovernmental Panel on Climate Change (IPCC) to be included in ESC. The mean monthly temperature, total rainfall and evapotranspiration projections from the Hadley Centre Regional Climate Model, published by the United Kingdom Climate Impacts Programme (UKCIP) (Hulme et al. 2002) were used to estimate future values of AT and MD, and the effect on SMR and SNR through dynamically coupled models. A similar approach was used to develop the six classification factors for CLIMADAPT based on Regional Climate Model simulations for Ireland.

The CLIMADAPT site classification system (Figure 1) offers both spatial (national and regional) assessments of species suitability based on low resolution digital data and site-based assessments of tree species suitability. Site analyses also use digital climatic data for baseline and future climate projections, supplemented by more precise site quality assessment gathered by the user, based on soil and vegetation surveys of the site type. The complete system is developed as a web-application, offering wide accessibility.

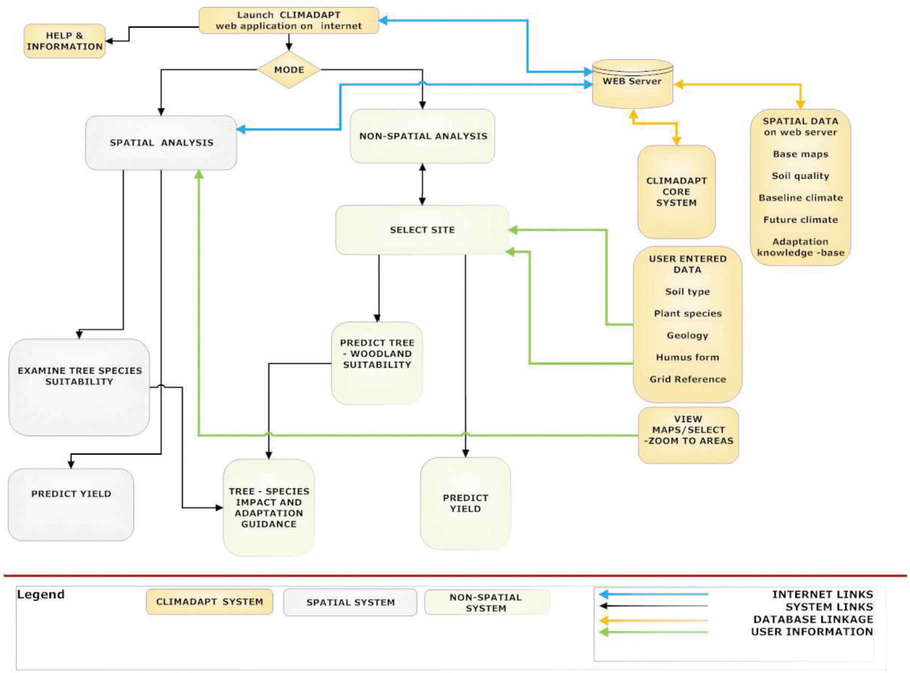



**Figure 1:** *Schematic overview of the CLIMADAPT site classification system showing site-based, spatial, and web-service components.*

## Results

*30-year period mean climate data*

The CLIMADAPT baseline and future climate data for Ireland have been calculated from simulations of future climate scenarios (IPCC - A2 and B1 scenarios). The simulations are from a regional climate model (RCM) developed by the Rossby Centre in Sweden (McGrath et al. 2005). The data have been calculated using a dynamic downscaling method, published by the Community Climate Change Consortium for Ireland (C4I), and validated using back-casting techniques (McGrath et al. 2005). The simulated daily mean temperatures, daily total rainfall, and daily total evaporation were compiled into mean monthly values for simulated future 30-year averages. Accumulated temperature and climatic moisture deficit were calculated for the growing season (March to October inclusive). A relationship (Ray et al. 2002) was used to estimate actual evapotranspiration (AET) from potential evapotranspiration (PET), from which the maximum seasonal moisture deficit was calculated from mean AET and rainfall. Example spatial data representations of moisture deficit (Figure 2a-

c) show the changes associated with drier and warmer summers in the south and east of Ireland for climate simulations associated with the B1 and A2 emissions scenarios.

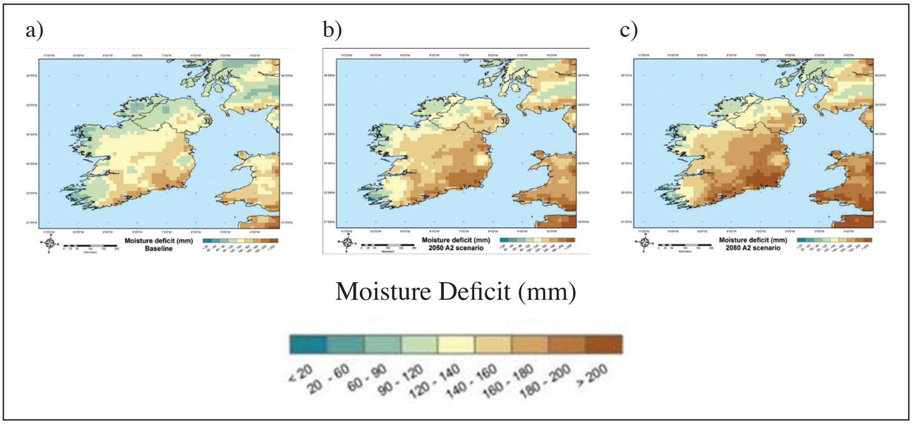



**Figure 2:** *Average moisture deficit (mm) for a) the Baseline Period 1961-1990, and from simulations for the 30-year climate period 2020-2050 for b) the B1 Medium-Low emissions scenario and c) the A2 Medium-High emissions scenario*.

The wind climate of Ireland was modelled using the DAMS approach (Quine and White 1993). This used a method proposed by Quine (2000) who correlated windiness scores and mean windspeed with the probability of extreme wind events and the parameters of the Weibull distribution. In developing the method for Ireland, the assumption was that the relationship between mean wind speed and the c parameter of the Weibull distribution was the same in Ireland and Britain.

**Extreme climate data**

The representation of climate data in all site classification systems has focussed on 'typical' or on 'average' climatic conditions, and this includes the climate data used in ESC. However, changes in climate over the last 40 years in Britain (Barnett et al. 2006, Jenkins et al. 2007) and over the last century in Ireland (McElwain and Sweeney 2003), and projections of future climate change (FAR 2007), indicate that the seasonal distribution of rainfall has changed, and is likely to continue to change, to slightly drier summers and wetter winters. In addition, projections suggest that the climate will become more variable. Therefore, it is very likely that there will be an increase in the incidence of extreme events such as dry and hot summers, intense rainfall events, leading to flooding events in summer and winter. Although the CLIMADAPT site classification is based on average climate data over a 30-year period, it will include information on the projected likelihood of extreme events on tree species. This will be in the form of a database that links extreme events with sensitive species on particular site types. One example links the projected frequency of dry summers to areas of Ireland (Figure 3), thereby providing a mechanism to assess the risk of drought damage to sensitive species caused by frequent dry summers.

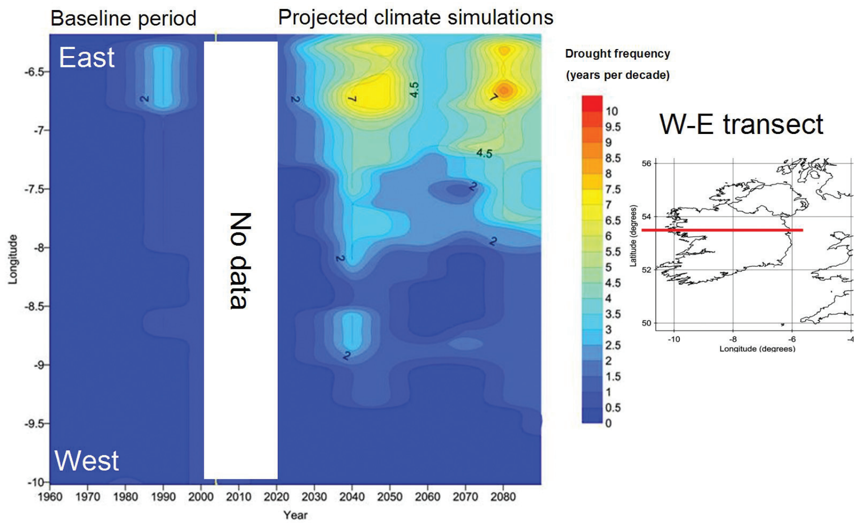



**Figure 3:** *The frequency of dry or droughty summers along a transect through the centre of Ireland, defined as the number of years per decade the moisture deficit is projected to equal or exceed 180 mm.*

## Frost sensitivity

Many species, including Sitka spruce, are sensitive to frost. Damage can occur during the period of flushing, when young tender shoots can be damaged, but more critically in the autumn, prior to hardening following warm weather. Central Ireland is particularly prone to late spring frosts (Renou-Wilson et al. 2008), and Sitka spruce is not recommended on frost sensitive sites (Renou and Farrell 2005). Given the predominance of a mild oceanic climate over much of Ireland, the risk of frost is low for many site types, but is particularly severe on flat land in the Midlands central areas. A site classification should therefore assess the risk of frost to sensitive species, particularly since a predicted change to a warmer climate might tempt foresters to plant less hardy species.

For CLIMADAPT a method has been developed based on five topographic variables including elevation, slope, aspect, slope plan and profile curvature, as well as distance from the sea. Each variable was classified in three risk categories; low, medium and high, based on expert knowledge and literature. Slope exposure was set to high risk for East and South-East slopes, medium for North-East and South and low for North, South-West and North-West facing slopes (Day and Peace 1949). Concave and flat areas were set to high frost risk whereas convex areas were set to low risk. Also inland regions of Ireland were set to high risk with the risk decreasing when getting closer to the sea. All variables were combined to produce a tentative frost risk map (Figure 4) that compares well with the published map (Keane and Sheridan 2004) of the date of the last spring air frost, with a 2-year return period. Frost risk is not included as a constraint within CLIMADAPT, but the frost risk score for a site will be held in the database and provided to the user for information and assessment.

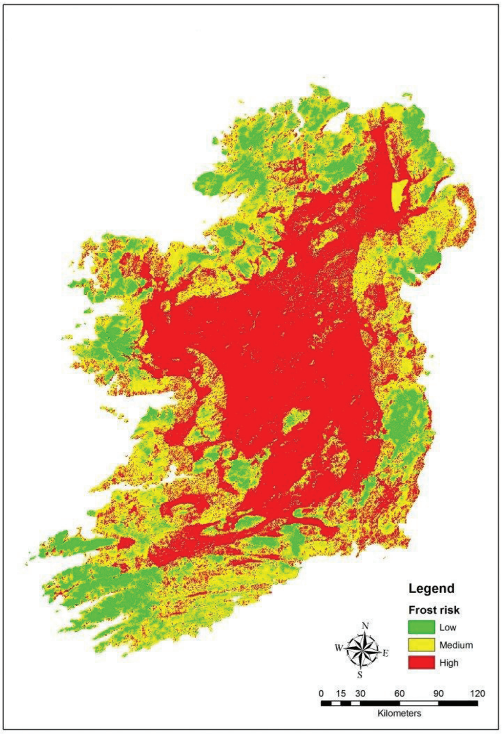
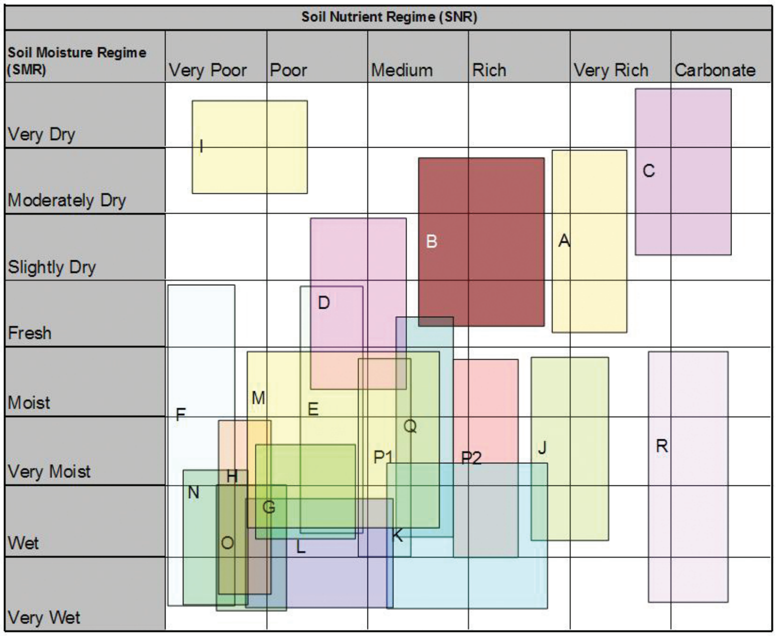



**Figure 4:** *Tentative map showing the distribution of damaging frosts in Ireland calculated from topographic variables.*

**Soil quality**

Soil fertility and water availability axes are used in CLIMADAPT to describe soil quality, in a similar way to BEC and ESC, in which axes define classes in an edatopic grid. For CLIMADAPT the soil classification follows the Irish Forest Soil Classification description in Horgan et al. (2004). This is a modified version of the site classification used by the Forestry Commission (GB) as described in ESC (Pyatt et al. 2001). At a Delphi meeting of forest soil experts in Ireland the soil types were arranged within an edatopic grid (Figure 5). The position on Soil Moisture Regime (SMR) axis of the grid follows the method described by Pyatt et al. (2001) in Tables 3 and 4. Soil Nutrient Regime (SNR) was estimated by the expert group, since the main method of positioning fertility in CLIMADAPT is through vascular indicator plants using the modified (Hill et al. 1999) R and N values originally described by Ellenberg (1988). Observations have shown that soil type assessments alone can give unreliable estimates of soil quality and that a survey of vascular plants that occur in a stand (or adjacent – in dense stands of conifers) will provide a more precise estimate.




| Soil Type Description - For full descriptions see Horgan *et al.* (2004) | | | |
|---|---|---|---|
| A Alkaline brown earths/ grey brown podzolics | F Indurated iron-pan podzols (scrawed with heather) | K Gleys/ peaty gleys (blue grey profile fertility class B) | P1 Cutaway raised bogs (milled peat post 1980) |
| B Acid brown earths & brown podzolics | G Peaty podzolised gleys (organic layer present) | L Gleys - peaty gleys (fertility class C) | P2 Fen peat |
| C Rendzina/shallow brown earths/ shallow grey-brown podzolics | H Peaty podzolised gleys (scrawed) | M Flushed blanket peat | Q Cutaway raised bogs (hand-machine sod pre-1980) |
| D Podzols/peaty podzols and weak iron pans | I Lithosols | N Unflushed blanket peat and intact raised bog | R Marl |
| E Indurated iron-pan podzols (with furze) | J Gleys and peaty gleys (mottled) fertility class A or B | O Cutaway blanket bogs (millet peat) | |

**Figure 5:** *The proposed edatopic grid of CLIMADAPT based on axes of soil moisture regime (SMR) and soil nutrient regime (SNR). Soil quality default values are defined by the central position of the soil type on the edatopic grid. Descriptions of each soil type are shown (Horgan et al. 2004).*

## CLIMADAPT modules

The CLIMADAPT decision support tool provides two methods of access. The first is a spatial module which uses coarse resolution soil data to show the regional spatial distribution of suitable tree species, and how suitability and yield may change with climate change. The second mode of access is through a stand based module in which the user inputs information from soil and plant survey to specify more accurately site conditions. CLIMADAPT uses the survey information to show tree species suitability and yield. Here we discuss results from the development of each module.

**I Spatial Module**

This is accessible through a web browser and uses Google™ Map backdrops to locate points or areas of interest. The interface provides access to all of the spatial datasets used in CLIMADAPT. Spatial analyses will be useful for assessing the changes in suitability or yield of species, and in future climates, across the country or at a regional level.

*Spatial soil data*

The spatial component of CLIMADAPT uses digital soils and sub-soils (lithology) data generated by Teagasc with co-operation of the Forest Service, Environmental Protection Agency, and Geological Survey Ireland, from a project completed in May 2006 (see Fealy et al. 2006 and Black et al. in press). Although the spatial data has low resolution (captured from imagery at a spatial scale of 1:40,000) it does provide a useful method of assessing national and regional trends and priorities for adaptation.

*Spatial suitability analysis*

The suitability of different species of tree to site types was explored and developed by five experts using a modified Delphi approach (MacMillan and Marshall 2005) in Dublin during the summer of 2007. The meeting sought agreement on the threshold values of tree species suitability on each of the four climatic variables used in CLIMADAPT. Using the results of the Dublin Delphi meeting, continuous functions were developed to describe a suitability response against each climatic variable. This information was compared with existing response curves used in ESC for Britain. The correspondence between the two methods was good for most species, but poor for some. Overall suitability of a species for a site is determined by the most limiting factor; two or more favourable factors cannot compensate for one which is unfavourable.

A comparison of the ESC model output and the model developed from the Dublin Delphi process is shown for Sitka spruce in Figure 6. The AT models (Figure 6a) are very similar at the AT suitability threshold 0.5 but diverge at the Suitable/Very Suitable threshold. As a result the Dublin model sets a lower climatic warmth threshold (1050 day.degrees above 5ºC) for Very Suitable compared with ESC (1250 day.degrees above 5ºC). The models for moisture deficit (Figure 6b) are quite different, ESC shows a higher moisture deficit threshold between U-S and S-VS compared with the Dublin model, and this causes areas with a MD above 130 mm to be shown as unsuitable in Ireland. This difference is the main cause of the inconsistency between the models shown in Figure 7, in which large areas of eastern, central, and southern Ireland are described as either Unsuitable or Suitable compared to an ESC classification of Very Suitable or Suitable (green areas).

In view of the discrepancy between the Dublin Delphi process and the results of the Delphi experts in Britain, CLIMADAPT will incorporate the latter models as these have been tried and tested for a longer period in Britain. For Sitka spruce and lodgepole pine this is likely to be a temporary measure, as a suitability and yield validation project using point samples from the National Forest Inventory will produce empirically derived models in the near future.

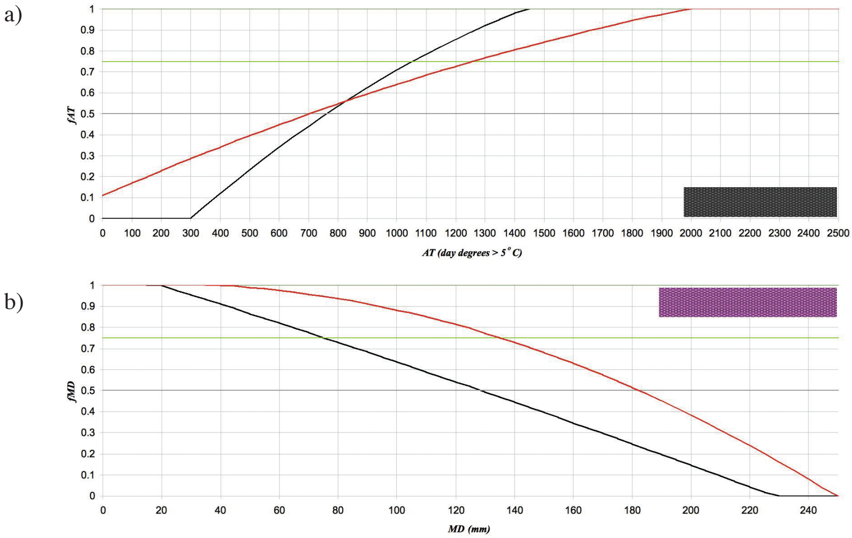



**Figure 6:** *A comparison of the Delphi group work in Dublin (2007) and the Ecological Site Classification expert group work in Edinburgh, Scotland (2000) to develop response curves showing the suitability of Sitka spruce according to a) Accumulated Temperature (AT - day. degrees above 5°C) and b) Moisture Deficit (MD - mm). Suitability is classified on a scale from 0 to 1, where values >= 0.75 are Very Suitable, >= 0.5 are Suitable and <0.5 are Unsuitable.*

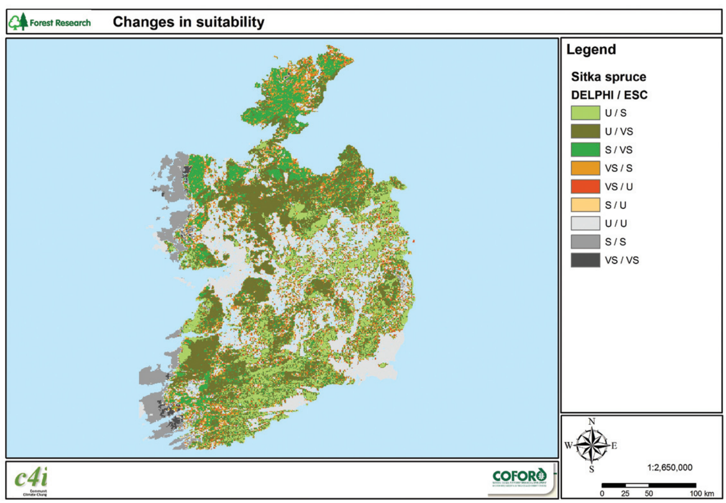



**Figure 7:** *A spatial comparison of the results from using different suitability models described by the Dublin Delphi group (2007) and the Edinburgh expert group for ESC (2000). The groups specified the range of AT and MD for assessing the suitability of Sitka spruce in Ireland. The map classifies areas in colour where the models show a different suitability defined by the map legend: U - Unsuitable, S - Suitable, VS - Very Suitable. Areas in which the models show the same suitability result are shown by a grey-scale.*

**II Site-based module**

To demonstrate the site-based version of CLIMADAPT, the suitability of Sitka spruce was assessed for the permanent sample plot at Avoca Forest, Ballinvalley, Co Wicklow. In Table 1, following a method described by Pyatt et al. (2001), data from a vascular plant survey were used to calculate the cover weighted mean Ellenberg R + N values (Hill et al. 1999), based on British conditions from associations described by Ellenberg (1988). This provides a mechanism to adjust the default SNR for a site, in which observed plant species provide information of the soil fertility (Wilson et al. 2001 and 2005). The SMR at Avoca was estimated from soil texture, rooting depth, and stoniness from soil pit observations. The method of calculating SMR in CLIMADAPT, for dry soils and wet soils, is the same as described by Pyatt et al. (2001). Table 2 includes the estimates of SMR and SNR from default digital data (as used in the spatial analysis) and from site survey. It shows how the accuracy of the CLIMADAPT site classification is improved by site investigation.

For all soil types it is important to assess rooting depth. For wet soils the anaerobic conditions of winter waterlogging may restrict rooting depth causing problems of droughtiness in the summer in soils where the water table fluctuates seasonally. For this reason, in CLIMADAPT the summer and winter seasonal SMR is calculated and used for separate suitability analyses for future climate change projections (Table 2). This is an important feature that can assess the degree to which projected changes in seasonal rainfall might affect rooting depth with consequences on summer droughtiness.

At Avoca the SMR was classed as fresh/slightly dry, from combining MD (128 mm) and available water capacity (AWC = 154 mm.m-1), using the method suggested by Pyatt et al. (2001). Slight signs of gleying resulting in orange mottles at a depth of 0.75 m also suggest a SMR class of Fresh (Pyatt et al. 2001).

Table 2 also provides a summary of climatic information for the baseline period and for the 2050 A2 emissions scenario. The Avoca site is favourably warm (AT = 1865 day. degrees >5°C) for tree growth and has a moderate mean summer moisture deficit (MD = 128mm). Wind exposure, measured by DAMS (see Quine and White 1994) and continentality measured by a modified Conrad Index (Conrad 1946) are also shown.

The projected climate change in 2050 using the A2 emissions scenario suggests the default SMR values at Avoca will become half a class drier in the summer, whereas JFK is likely to become moderately dry during summer conditions. The change will occur as a result of a seasonal shift in the rainfall distribution coupled with warmer summers. Default winter SMR has been adjusted in CLIMADAPT from slightly dry to fresh/moist suggesting the wetter winter conditions.

*Site-based suitability analysis*

Table 3 shows the general yield class estimated from top height measurements at different ages using relationships published by Edwards and Christie (1974), and the site index predicted from the dynamic growth model GROWFOR (Broad and Lynch 2006). Table 4 compares predicted suitability and yield estimates using CLIMADAPT.

**Table 1:** *Vascular plant indicator species of the woodland floor at the Sitka spruce permanent sample plot at Avoca, Co Wicklow.*

| Plant species | Cover proportion % | Ellenberg - R+N value | SNR class |
|---|---|---|---|
| Broad buckler-fern | 2 | 9 | Medium |
| Foxglove | 2 | 9 | Medium |
| Bracken | 5 | 6 | Poor |
| Bramble | 20 | 12 | Very Rich |
| Holly | 2 | 10 | Rich |
| Creeping soft-grass | 60 | 6 | Poor |
| Common bent | 40 | 8 | Medium |
| Chickweed | 2 | 13 | Very Rich |
| Wood sorrel | 5 | 8 | Medium |
| Hard fern | 1 | 6 | Poor |
| Cover weighted mean | | 7.8 | Medium |

**Table 2:** *Sitka spruce plot at Avoca, Co Wicklow, showing baseline climate, projected future climatic variables, and estimates of soil quality.*

| Site attribute | Avoca |
|---|---|
| Species | Sitka spruce P.1943 |
| Location | Avoca PSP, Wicklow |
| Latitude (deg. N) | 52.864803o |
| Longitude (deg. W) | 6.170690o |
| Elevation (m) | 167 |
| Slope (deg.) | 9.9 |
| Aspect (deg.) | 242 |
| Topography | Water shedding site |
| Soil quality | |
| Soil type | Brown earth |
| Soil texture | Silt-clay Loam |
| AWC constant (mm.m-1) | 180 |
| Rooting depth - RD (m) | 0.75 |
| Effective RD = RD + capillary zone (capillary zone = 0.15 m) | 0.90 |
| Stoniness (%) | 5 |
| AWC (mm.m-1) | (180 x 0.90) x 0.95 = 154 |
| Mean winter waterlogging (m) | Below 0.80 |

| *Site attribute* | *Avoca* |
|---|---|
| *SMR (default)* | Slightly dry |
| *SNR (default)* | Medium - rich |
| *SMR (measured)* | Fresh/slightly dry |
| *SNR (measured from Table 1 for Avoca)* | Medium |
| *Baseline climate* | |
| *Accumulated Temperature (day. degrees>5oC)* | 1865 |
| *Moisture Deficit (mm)* | 128 |
| *Wind Exposure (DAMS)* | 16 |
| *Continentality (Conrad)* | 5 |
| *Projected climate 2050 A2 scenario and soil quality adjustment* | |
| *Accumulated temperature (day.degrees>5)* | 1880 |
| *Moisture deficit (mm)* | 153 |
| *Wind exposure (DAMS)* | 16 |
| *Continentality (Conrad)* | 5 |
| *SMR (default summer)* | Slightly dry |
| *SMR (default winter)* | Fresh/moist |
| *SNR (default)* | Medium |

**Table 3:** *Comparison of measured top height and general yield class and site index estimates of Sitka spruce in 2 permanent sample plots at Avoca*.

| Factors | Mean of plots 1 and 6 |
|---|---|
| Year measured | 1971 |
| Age (yr) | 28 |
| Mean top height (m) | 17.1 |
| Site Index (GROWFOR)[1] | 18.5 |
| Yield -GYC (m3ha-1yr-1)[2] | 20 |
| CLIMADAPT yield estimate 1961-2000 ($m^3ha^{-1}yr^{-1}$) | 23 |
| CLIMADAPT suitability score3 and constraint factor 1961-2000 baseline | 0.72 – marginal/very Suitable |
| CLIMADAPT yield estimate 2050 A2 scenario ($m^3ha^{-1}yr^{-1}$ ) | 18 |
| CLIMADAPT suitability score3 and constraint factor 2050 A2 scenario | 0.55 – marginal/suitable |

[1] GROWFOR - Broad and Lynch (2006)
[2] General yield class - Edwards and Christie (1974)
[3] Suitability scores: 0-0.5 = Unsuitable; 0.5-0.75 = Suitable; 0.75-1 = Very Suitable

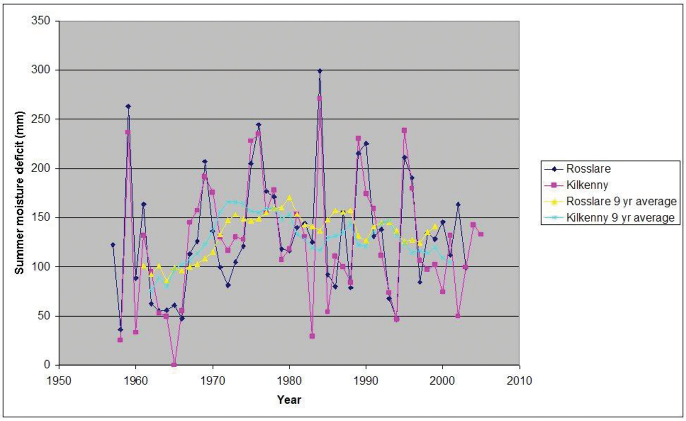



**Figure 8:** *Comparison of summer moisture deficit from rainfall and evaporation recorded at Rosslare and Kilkenny meteorological stations close to the Avoca permanent sample plot.*

Moisture deficits calculated from meteorological stations in the region of Avoca (at Kilkenny and Rosslare) show reasonably good agreement and consistency between records (Figures 8 and 9). Assuming rainfall is similar between the forest site and the meteorological stations, it shows that Avoca experienced 6 years with high moisture deficit over the last 35 years, and although the 9-year running average declined during the 1960s, it increased in the 1970s, and has since declined slowly. Climate change projections suggest the frequency of high summer moisture deficits will increase. Sitka spruce is considered suitable in climates where the mean moisture deficit is below 200 mm (Pyatt et al. 2001). More frequent exceedance of this threshold is likely to cause drought stress to trees leading to cracking, stem shake, and biotic impacts (Green and Ray 2009).

Over the same period, the warmth index, accumulated temperature (AT - day degrees above 5°C), has increased substantially since the mid 1960s. Figure 9 shows more than a 10% increase in the 9-year running mean between 1960-2000, as a result of warmer and longer growing seasons, from recent decadal changes in warmth. Climate change projections for the A2 emission scenario suggest AT will increase from 1865 to 1880 day degrees above 5°C by 2050 compared with the baseline climate period. Warmer growing seasons will stimulate increased growth, assuming moisture and nutrients remain in sufficient supply.

## Climate change adaptation

The CLIMADAPT suitability and yield model shows that Sitka spruce at Avoca (Table 4) is Suitable, indeed borderline Very Suitable. By 2050, for the Medium-a High emissions scenario, the suitability score declines to borderline Suitable, and the CLIMADAPT yield model suggests that productivity will decline at Avoca to YC 18 ($m^3$ $ha^{-1}$ $yr^{-1}$) as a result of an increased moisture deficit caused by drier and warmer summers. The average climatic factors in CLIMADAPT are not able to reflect variability or extreme events, and so climatic suitability is assessed for the 30-year

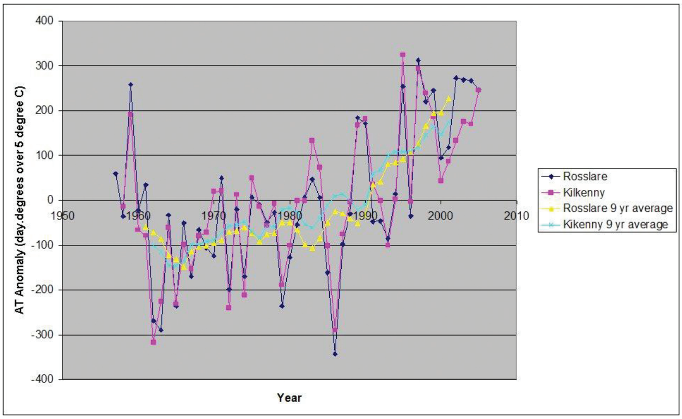



**Figure 9:** *Comparison of the warmth index (accumulated temperature) throughout the April to September growing season from records from Rosslare and Kilkenny meteorlogical stations, close to the Avoca permanent sample plot.*

period (1961-1990) as a whole. The site is fertile and warm, and so a change to a more drought tolerant species, such as Douglas fir (*Pseudotsuga menziesii* (Mirabel) Franco), Corsican pine (*Pinus nigra* Arnold ssp. Laricio Maire), or sweet chestnut (*Castanea sativa* Mill.), or a mixture of several species, would form the basis of a robust adaptation strategy. On less fertile mineral soils, species such as Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Miller), and in addition sessile oak (*Quercus petraea*) could be considered on sites further west.

Severe summer moisture stress in Sitka spruce can damage the stem causing longitudinal lesions and cracks to develop (Green and Ray 2009). Following stress conditions spruce is susceptible to biotic impacts (Csoka 1997, Broadmeadow et al. 2005, Rouault et al. 2006) and in particular aphid attack (Day et al. 1998, Evans et al. 2002).

Soils affected by fluctuating water tables are particularly sensitive to climate change due to the likelihood of even wetter winters and drier summers. Such changes will have an increasing impact on decisions as to how and when forest operations may be carried out. Wetter winter conditions will certainly affect operations that could damage soil, cause rutting and cause soil to erode and enter watercourses.

Many tree species are also sensitive to fluctuating water tables. For many species, wetter winters will increase anaerobic soil environments, thereby restricting the depth of rooting further. Consequently, drier summer conditions may have a more serious impact on trees that have restricted rooting depths. On these sites the range of suitable species is limited. It has been reported that lodgepole pine is able to tolerate seasonally fluctuating water tables on nutritionally poor soils (Coutts and Philipson 1978). Other species such as downy birch (Betula pubescens Ehrh.), Norway spruce (*Picea abies* (L.) Karsten), sycamore (*Acer pseudoplatanus* L.), pedunculate oak (*Quercus robur* L.), and common alder (*Alnus glutinosa* (L). Gaertner) may also be suitable on seasonally waterlogged soils.

The link between climatic factors projected under different climate change emissions scenarios, site fertility and the seasonal change in SMR need to be considered in choosing species suited to future climate conditions at a particular site. A database within CLIMADAPT will provide this context sensitive information in relation to a suitability analysis of conditions at the site.

For foresters, climate change adaptation is about adjusting silvicultural systems in response to actual or potential climatic threats and opportunities. Seeking to benefit from improvements in climate as well as being aware of, and minimising, the impacts of negative climatic change. General recommendations have been made on changes to silvicultural systems in Britain (Broadmeadow and Ray 2005, Ray 2008b, 2008a) which favour mixed species woodlands for a 'no-regrets' management policy. However, there may also be a case for adaptation to take advantage of warmer sites, and faster growth on sites with adequate water supply. On such sites the selection of material of superior provenance would provide wood for fuel, or other products, to offset the emissions of carbon from fossil fuel use (Broadmeadow and Matthews 2003).

It is clear that climate modellers are uncertain about the rate and the degree to which the climate will change in the future, and it is inevitable that there will never be certainty in this regard. However, this is no excuse for inaction, as evidence shows that the climate has changed in recent decades and that it is very likely to continue to change as a result of recent increases in the emissions of greenhouse gases into the atmosphere. There appears to be a great risk in not adapting tree species and forest management systems for resilient woodlands in the future.

**Conclusions and recommendations**

Modern computer-based spatial and operational site classification systems provide an efficient mechanism for strategic scenario planning, targeting incentives, and providing key decision support on tree species choice at an operational level. Site classification systems are fundamental decision support tools for forest managers, and are central to the concept of initiating sustainable forest management.

Multi-factoral site classification systems can be particularly useful at separating the component effects of site, and therefore have an important role to play in assessing changes in site conditions likely as a result of climate change. These tools must be developed to help foresters judge how, when, and where to adapt to the impacts of climate change.

Forest expansion is now recognised as an integral concept for countries striving to meet greenhouse gas emissions reduction targets under the Kyoto Protocol. Indeed industrialised countries are keen to identify where and how forests might be expanded as part of an integrated land-use policy initiative. In Ireland, as in many other European countries, incentives will almost certainly be required to encourage woodland expansion.

Climate change adaptation requires incentives to help woodland owners and manages reduce and spread the risk of uncertain future impacts on forests. Management must move away from always accepting single species - same age plantations, to more mixed species - mixed age forests. However, there is likely to be a continued role for fast grown single species stands of improved or specific trait selected material for climate change mitigation. Spatially explicit site classification systems have an important strategic role in helping forest policy teams assess expansion opportunities, and they provide a high level overview of regional priorities for species selection and suitable management systems.

Site classification systems must be developed using methods to allow information and new data to be easily incorporated. This requires a framework approach to design, and a modular schema to the data and information systems used. Climate change modellers will continue to update us with their most recent findings. This will require the development of new functionality in site classification systems, such as probabilistic forecasting, as well as risk classification and analysis.

The Delphi approach is a powerful mechanism for gleaning information from both experience- and evidence-based knowledge. The approach is best performed by domain experts familiar with the issues of the problem to be evaluated.

At the Dublin Delphi group meeting, the group of forest scientists were the best domain experts available for the task. However, the Delphi process failed to reach a robust agreement on species suitability thresholds for moisture deficit for several species. Furthermore, the compromise threshold values obtained were not consistent with the Delphi procedure performed for ESC in 2000. The problem was almost certainly an artefact of the Delphi process in Dublin. The expert group may have misidentified or confounded the effects of climatic moisture deficit and soil moisture regime. In retrospect, although the Delphi experts had information to support the analysis, more time should have been allocated to ensuring that experts were comfortable with the climatic factors, their individual effects, and the nature of their interdependence.

Delphi derived models for CLIMADAPT were developed from both the Dublin meeting and from the ESC Delphi meeting performed for Britain in 2000. The models are intended only to show initial relationships and responses and will be replaced by process-based model components in due course.

The key requirement of decision support tools includes a mechanism to organise and process information in a transparent, repeatable, and systematic way. Site classification systems must be able to provide this function to allow the forestry authority to audit the rationale and science that underpins key decisions on species choice in forests.

Finally, the development of CLIMADAPT will help add to the site classification work already achieved (Horgan et al. 2004) by providing the framework for climate change impacts to be assessed, and by extending the accessibility of a forest site classification system on the internet. It is hoped that this information provision will play a part in disseminating the impacts of climate change on forests and forestry in Ireland, help forest policy makers assess the opportunities of forest expansion in mitigating climate change in Ireland, and help forest managers and owners make informed decisions based on the current thinking of climate impacts and forest adaptation.

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**References**

Anderson, M.L. 1950. *The selection of tree species*. Oliver & Boyd, Edinburgh.

Anderson, M.L. and Fairbairn, W.A. 1955. *Division of Scotland into climatic sub-regions as an aid to silviculture*. 1. Bulletin of the Forestry Department, University of Edinburgh, Edinburgh.

Anon. 1992. *Earth Summit*. In United Nations conference of environment and development. The Regency Press, London and Rio de Janeiro.

Barnes, B.V., Pregitzer, K.S., Spies, T.A. and Spooner, V.H. 1982. Ecological Forest Site Classification. *Journal of Forestry* 80: 493-498.

Barnett, C., Hossell, J., Perry, M., Procter, C. and Hughes, G. 2006. *A handbook of climate trends across Scotland*. Sniffer Project CC03, Scotland and Northern Ireland Forum for Environmental Research.

Beckingham, J.D. and Archibald J.H. 1996. *Field Guide to Ecosites of Northern Alberta*. Special Report 5, Canadian Forest Service.

Black, K.G. 2008. Ireland's forest carbon reporting system. In Hendrick, E. and Black, K.G., eds. *Forests, Carbon and Climate Change - Local and International Perspectives*. COFORD, Dublin.

Black, K.G., O'Brien, P., Redmond, J., Barrett, F. and Twomey, M. In Press: The extent of peatland afforestation in Ireland. *Irish Forestry.*

Broad, L. and Lynch, T. 2006. Growth models for Sitka spruce in Ireland. *Irish Forestry* 63 (1-2): 53-80.

Broadmeadow, M. and. Matthews, R. 2003. Forests, carbon and climate change: the UK contribution. Information Note 48. Forestry Commission, Edinburgh.

Broadmeadow, M. and Ray, D. 2005. *Climate change and British Woodland*. Research Information Note 69. Forestry Commission, Edinburgh.

Broadmeadow, M., Ray, D. and Samuel, C. 2005. Climate change and the future for broadleaved tree species in Britain. *Forestry* 78:145-167.

Cajander, A.K. 1926. The theory of forest types. *Acta Forestalia Fennica* 29:1-108.

Clare, J. and Ray, D. 2001. A Spatial Model of Ecological Site Classification for forest management in Britain. In Konecny. M., ed. *Proceedings of the 4th AGILE Conference on Geographic Information Science*. Brno, April 19-21.

Cleland, D.T., Hart, J.B., Host, G.E, Pregitzer, K.S. and Ramm, C.W. 1993. *Ecological Classification and Inventory System of the Huron-Manitee National Forests*. United States Department of Agriculture, Forest Service.

Conrad, V. 1946. Usual formulas of continentality and their limits of validity. *Transactions of the American Geophysical Union* 27: 663-4.

Coutts, M.P. and Philipson, J. 1978. Tolerance of tree roots to waterlogging 1. Survival of Sitka spruce and lodgepole pine. *New Phytologist* 80:63-69.

Cross, J.R. 2006. The Potential Natural Vegetation of Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy* 106B: 65-116.

Csoka, G. 1997. Increased insect damage in Hungarian forests under drought impact. *Biologia Bratislava* 52: 159-162.

Day, K.R., Halldorsson, G., Harding, S. and Straw, N.A. 1998. *The green spruce aphid in western Europe: ecology, status, impacts and prospects for management*. Technical Paper 24. Forestry Commission, Edinburgh.

Day, W.R. and Peace, T.R. 1949. *Spring Frosts*. Forestry Commission Bulletin No.18. HMSO, London.

Edwards, P.N. and Christie J.M. 1981. *Yield models for forest management*, Forestry Commission Booklet 48. Forestry Commission, Edinburgh.

Ellenberg, H. 1988. *Vegetation ecology of Central Europe*. 4th (English) edition, Cambridge University Press, Cambridge.

Evans, H., Straw, N. and Watt, A. 2002. Climate Change: Implications for insect pests. In Broadmeadow M., ed. *Climate Change: Impacts on UK Forests*. Bulletin 125. Forestry Commission, Edinburgh.

FAR. 2007. Contribution of working group 1 to the fourth annual assessment report of the Intergovernmental Panel on Climate Change. IPCC, Geneva.

Fealy, R., Loftus, M. and Meehan, G. 2006. *EPA Soil and Subsoil Mapping Project: Summary, Methodology, Description for Subsoils, Land Cover, Habitat and Soils Mapping/Modelling*. EPA Project Report. Environmental Protection Agency, Dublin.

Green, S. and Ray, D. 2009. *Potential impacts of drought and disease on forestry in Scotland*. Research Note FCRN04. Forestry Commission, Edinburgh.

Higgins, G.T., Martin, J.R. and Perrin, P.M. 2004. *National Survey of Native Woodland in Ireland*. Internal Report to the National Parks and Wildlife Service, Dublin.

Hill, M.O., Mountford, J.O., Roy, D.B. and Bunce, R.G.H. 1999. Ellenberg's indicator values for British plants. Institute of Terrestrial Ecology, Huntingdon.

Horgan, T., Keane, M., McCarthy, R., Lally, M. and Thompson, D. 2004. *A Guide to Forest Tree Species Selection and Silviculture in Ireland*. O'Carroll, J. ed. COFORD, Dublin.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J.,

Murphy, J.M., Hassell, D., Boorman, P., MacDonald, R. and Hill, S. 2002. *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report*. Tyndall Centre for Climate Change Research, School of Environmental Science, University of East Anglia, Norwich, UK.

Jenkins, G.J., Perry, M.C. and Prior, M.J.O. 2007. *The climate of the United Kingdom and recent trends*. Met Office Hadley Centre, Exeter, UK.

Joyce, P.M., Huss, J., McCarthy, R., Pfeifer, A. and Hendrick, E. 1998. *Growing Broadleaves*. COFORD, Dublin.

Keane, T. and Sheridan, T. 2004. *Climate of Ireland*. In Collins, J., ed., Climate, weather and Irish agriculture, p 27-62. 2nd edition, AGMET, University College Dublin, Dublin.

Klinka, K., Krajina V.J., Ceska, A. and Scagel, A.M. 1989. *Indicator plants of coastal British Columbia*. UBC Press, Vancouver, BC.

Krajina, V.J. 1969. *Ecology of forest trees in British Columbia*. In Krajina V.J, ed. Ecology of Western North America, p 1-146. University of British Columbia, Department of Botany.

Kuusipalo, J. 1985. An ecological study of upland forest site classification in Southern Finland. *Acta Forestalia Fennica* 192:1-78.

MacDonald, E., and Hubert, J. 2002. A review of the effects of silviculture on timber quality of Sitka spruce. *Forestry* 75:107-138.

MacMillan, D. C. and Marshall, K. 2005. The Delphi process - an expert-based approach to ecological modelling in data poor environments. *Animal Conservation* 9: 11-19.

Malone, J. 2008. Factors Affecting Afforestation in Ireland in Recent Years. Irish Government Paper, Dublin.

McElwain, L. and Sweeney, J. 2003. Climate change in Ireland - recent trends in temperature and precipitation. *Irish Geography* 36: 97-111.

McGrath, R., Nishimura, E., Nolan, P., Semmler, T., Sweeney, C. and Wang, S. 2005. *Climate Change: Regional Climate Model Predictions for Ireland* Environmental Protection Agency, Dublin.

NFI. 2007. National Forest Inventory - Republic of Ireland - Results. Government Publications, Dublin.

OCarroll, N. 2004. *Forestry in Ireland – A Concise History.* COFORD, Dublin.

Perks, M.P., Harrison, A.J. and Bathgate, S.J. 2007. Establishment Management Information System (EMIS): Delivering Good Practice Advice on Tree Establishment in the Uplands of Britain. In Reynolds, K.M., Thomson, A.J., Köhl, M., Shannon, M.A., Ray, D. and Rennolls, K., eds., p 412-424. *Sustainable Forestry: from monitoring and modelling to knowledge management and policy science*. CAB International, Wallingford.

Pojar, J., Klinka, K. and Meidinger, D.V. 1987. Biogeoclimatic Ecosystem Classification in British Columbia. *Forest Ecology and Management* 22: 119-154.

Pyatt, D.G., Ray, D. and Fletcher, J. 2001. *An Ecological Site Classification for Forestry in Great Britain*. Bulletin 124. Forestry Commission, Edinburgh.

Quine, C.P. and White, I.M.S. 1994. Using the relationship between rate of tatter and topographic variables to predict site windiness in upland Britain. *Forestry* 67: 245-256.

Quine, C., 2000. Estimation of mean wind climate and probability of strong winds for wind risk assessment. *Forestry:* 73(3): 247-258.

Rackham, O. 1986. History of the [British and Irish] countryside. Dent, London.

Rameau, J.C., Mansion, D. and Dume, G. 1993. *Flore Forestière Française*. Ministère de l'Agriculture et de la Forêt, Paris

Ray, D. 2001. Ecological Site Classification Decision Support System V1.7. Forestry Commission, Edinburgh.

Ray, D. 2008a. Impacts of climate change on forestry in Wales. Research Note 301. Forestry Commission, Edinburgh.

Ray, D. 2008b. *Impacts of climate change on forests in Scotland – a preliminary synopsis of spatial modelling research*. Research Note 301. Forestry Commission, Edinburgh.

Ray, D. and Broome, A. 2003. Ecological Site Classification: supporting decisions from the stand to the landscape scale. In *Forest Research Annual Report 2001-2002*. The Stationery Office, Edinburgh.

Ray, D., Clare, J. and Purdy, K. 2003. Applying an Ecological Site Classification to woodland design at the landscape scale. In Humphrey A.N.J., Latham, J., Gray, H., Kirby, K., Poulsom, E. and Quine, C., eds. *The Restoration of Wooded Landscapes*. Forestry Commission, Edinburgh.

Ray, D., Pyatt, G. and Broadmeadow, M. 2002. Modelling the future climatic suitability of plantation forest tree species. In Broadmeadow, M., ed. *Climate Change: Impacts on UK Forests*. Forestry Commission Bulletin 125. Forestry Commission, Edinburgh.

Ray, D., Xenakis, G., Semmler, T. and Black, K. 2008. The impact of climate change on forests in Ireland and some options for adaptation. In Hendrick, E. and Black, K.G., eds. *Forests, Carbon and Climate Change - Local and International Perspectives*. COFORD, Dublin.

Renou-Wilson, F., Keane, M. and Farrell, E.P. 2008. Effect of planting stocktype and cultivation treatment on the establishment of Norway spruce on cutaway peatlands. *New Forests* 36: 307-330.

Renou, F., and Farrell, E.P. 2005. Reclaiming peatlands for forestry: the Irish experience. In Stanturf, J.A. and Madsen, P., eds. *Restoration of Boreal and Temperate Forests*. CRC Press, Boca Raton, US.

Rodwell, J.S. 1991. *British Plant Communities, 1: Woodlands and scrub*. Cambridge University Press, Cambridge.

Rouault, G., Candau, J.-N., Lieutier, F., Nageleisen, L.-M., Martin J.-C. and Warzee, N. 2006. Effects of drought and heat on forest insect populations in relation to the 2003 drought in Western Europe. *Annals of Forest Science* 63: 613-624.

Wagenknecht, E., Scammoni, A., Richter, A. and Lehmann, J. 1956. Eberswalde 1953: Wege zu Standortgerechter Forstwirtschaft. Newmann Verlag, Berlin.

Wilson, S.M., Pyatt, D.G., Malcolm, D.C. and Connolly, T. 2001. The use of ground vegetation and humus type as indicators of soil nutrient regime for an ecological site classification of British forests. *Forest Ecology and Management* 140: 101-16.

Wilson, S.M., Pyatt, D.G., Ray, D., Malcolm, D.C. and Connolly, T. 2005. Indices of soil nitrogen availability for an ecological site classification of British forests. *Forest Ecology and Management* 220: 51-65.