The use of site factors and site classification methods for the assessment of site quality and forest productivity in Ireland

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Abstract
Site classification methods have been traditionally used in forestry to determine the most appropriate tree species to plant and to assess their potential yields on various sites. Recently the role of site classification systems has been expanded to fulfil a wider range of multifunctional forestry objectives: silvicultural practice, sustainable forest management, climate change, carbon sequestration and environmental issues. Site classification systems used in forestry, with examples of single and multifactor systems are reviewed. Forest site quality is a composite of climatic, topography and soil factors at any one location. The determination of site quality using an approach similar to that used in Canada, the United States and Britain is advocated. This approach, based on scientific principles, can be calibrated for Irish conditions, offering potential to develop a model to aid decision making on tree species selection and the assessment of forest productivity on various sites in Ireland.

Introduction

Site classification has long been used in forestry as a means of determining species suitability (Cajander 1926, Anderson 1961, Krajina 1969, Ellenburg 1998, Pyatt et al. 2001). Anderson (1950) commented that the role of a site classification was to … *strive to provide what still seems to be lacking – some relatively objective practical means of distinguishing and classifying plantable site-types, which will serve, not only to aid in the choice of tree-species to be grown, but as a basis upon which a sound silvicultural practice can be built*.

This concept, that site classification can be the basis upon which sound silvicultural practice can be built, has received renewed interest in recent years. This includes the use of site classification methods to cover silvicultural practice and aspects of forest management and planning in British Columbia (Pojar et al. 1987, Meidinger and Pojar 1991, Green and Klinka, 1994) and in Britain (Pyatt et al. 2001, Ray 2001). The idea that silvicultural decision-making requires knowledge of the growth of tree species on specific sites provides an ecological foundation for silvicultural practices. A good understanding of specific-species variability and the interactions between species and site conditions is one of the prerequisites for the development of sustainable management practices, which include timber production (Klinka and Chen 2003). Furthermore, the forest ecosystem and its protection and enhancement is vital if forestry is to be practised in a sustainable way, which will allow for long term monitoring of changes in ecological site factors caused by forest management

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and external environmental drivers (Moffat 2003). Anderson (1950) stated that the only safe basis for the choice of species is the purely ecological one, and that for a given planting area the process consists broadly of two stages. First, an analytical or inductive process or an assessment of the locality factors, and second a synthetic or deductive process or a selection of those species whose requirements through life are likely to be satisfied by the site in question. When a site was capable of supporting two or more species, he indicated that the final choice may then be based on the expected value, not volume production of the various species. The characteristics of forest sites, readily identifiable as soil, vegetation or topographic factors, can be used as the basis of prescribing silvicultural operations, such as thinning or for the prescription of ground preparation for the establishment of new forests (Zehetmayer 1954 & 1960, OCarroll 1962, Wills et al. 2001). Site classification methods have widely been used in the USA and Canada to estimate site productivity and for quantifying forest yield potential (Carmean 1975, Wang et al. 1994, Kayahara et al. 1996, Chen et al. 2002, Klinka and Chen 2003, Chen and Klinka 2003).

The classification of forest sites, in the context of site quality assessment, has also been used as a basis for fertilisation prescriptions for forest crops (OCarroll 1975, Farrell 1985, Schaible 1992, Taylor and Tabbush 1990). The challenge of climate change and greenhouse gas mitigation has increased the need for information about the forest ecosystem, and in particular increased knowledge of the relationship between forest soils, climate and productivity. Furthermore, it should be possible to estimate the amount of dry matter that is allocated to above- and below-ground components of the forest, which can in turn be used to calculate the amount of carbon sequestered in the forest. New standards of environmental protection have also increased the need for information about forest sites.

Overall, site classifications, particularly soil classifications, have received renewed interest in recent years. A major driver for this interest is the need to develop methods for monitoring soils, especially with a view to the development of sound soil conservation strategies and in assessing the effects of silvicultural practices on soil quality (Moffat 2003, Powers et al. 2005, Hopmans et al. 2005, Fisher at al. 2005).

The need for information concerning species site interactions, species performance and the correct matching of species to site (which is likely to minimise forest establishment problems) has been the catalyst for this review. In addition, the use of classification systems which evaluate forest site quality could also be used as an aid to determine the growth and yield potential of species on different site types

Site classification methods

Site classification for forestry falls broadly into two groups: single factor or multifactor methods (Savill 1983). Single factor classification systems rely on one factor to describe a forest site, such as soil or climate, whereas multifactor classifications are based on interrelationships between climate, physiography, soil (and related edaphic factors) and vegetation. Classifications based on soil characteristics are the most common single factor systems used in forestry, mainly due to the abundance of soil survey information. Soil classification methods have been used extensively for quantifying potential timber yields in the United States (Carmean 1961, Ralston 1964, Carmean,

1975) and for determining the suitability of sites for afforestation in Ireland (Dittrich 1955, Ryan 1960, Bulfin 1987 & 1990, Carey et al. 1985). Soil classification (or soil type) is often seen as a proxy for soil quality, and good relationships have been found between soil type and yield in specific geographic areas in the Republic of Ireland (National Soil Survey of Ireland, 1963-2003, O'Flanagan and Bulfin 1970, Bulfin et al. 1973, OCarroll and Farrell 1993, Bulfin 1988, Conry and Clinch 1989).

Indicator plants or plant communities have also been used for the basis of site classification (Cajander 1929, Anderson 1961, Krajina 1969, Ellenburg 1988, Klinka et al. 1989, Pyatt et al. 2001, Wilson et al. 1998, 2001 & 2005). The characteristics of the vegetation can be used as an indicator of the fertility and moisture status of a forest site. The classification of site fertility based on indicator plants and plant associations is highly developed in British Columbia, Canada, where it is used to quantify the soil moisture and soil nutrient regime of forest sites (Green and Klinka 1994). A strong relationship between the inherent soil nutrient status and vegetation type and abundance has been found in recent research carried out in Scotland (Wilson et al. 2001 & 2005) and this has formed the basis for the indirect assessment of soil nutrient and moisture regimes soil in the Ecological Site Classification (ESC) system developed for Britain. Vegetation characteristics have also been used to assess the inherent fertility of blanket peat soils in Ireland (Dickson and Savill 1974, Savill and Dickson 1975). In this system, four nutrient classes are recognised: (1) dystrophic, (2) oligotrophic, (3) mesotrophic and (4) eutrophic. Potential yields in Sitka spruce increase from the dystrophic to the eutrophic class. OCarroll (1975) used information from Ordnance Survey 6 inch: 1mile (1:10560) maps to classify potential forest sites into four fertility classes: (A) Fields and ornamental ground, (B) Furze or Whins, (C) Rough Pasture with or without outcropping rock, and (X) Woodland. He used this classification as the basis for fertiliser prescriptions for forestry land. The system is still in widespread use in Ireland by the Forest Service and Coillte. It has been used as a basis for the unenclosed/enclosed assessment of land quality for the determination of grant payment rates for afforestation by the Forest Service in the Republic of Ireland (OCarroll 1975 & 2008, Joyce and OCarroll 2002).

Multifactor site classifications are based on interrelationships between climate, physiography, soils and vegetation. An example of a multifactor classification is provided by Anderson (1961), who developed a classification based on the abundance of certain plant communities on a site. Fertility classes A to F reflect decreasing fertility levels and increasing degrees of wetness, from Dry to Wet with Peat. For each combination of fertility and moisture class, Anderson recommended selection of tree species based on their nutritional and moisture requirements. This was based on his extensive experience as a forestry practitioner in Britain and Ireland. Condon (1961) devised a multifactor classification for blanket peats, based on vegetation, topography, and peat characteristics. The five classifications, in decreasing order of site quality were: (1) Molinia Basins and Flushes, (2) Eriophorum flats and slopes, (3) Calluna slopes, (4) Calluna Knolls and (5) Tricophorum knolls.

In recent years multifactor classifications have achieved prominence in forestry as they focus on ecological site quality and its relation to the ecosystem. These systems are considered more robust, so are expected to provide a sound basis for the sustainable production of wood and the provision of other forest benefits (Pojar et al. 1987, Green and Klinka 1994, Pyatt 1995). The biogeoclimatic ecosystem classification (BEC) developed in British Columbia is a good example. It uses regional and local information about climate, vegetation communities, soil moisture and soil nutrients and has been widely used to estimate site productivity (Wang et al. 1994, Kayahara et al. 1998, Chen and Klinka 2002, Chen et al. 2002) and to cover aspects of forest management and planning in an ecological sustainable manner (Klinka et al. 1984, Pojar et al. 1987, Meidinger and Pojar 1991, Pyatt et al. 2001). The ecological site classification (ESC) currently in use in Britain is a modification of the BEC. Both systems use indicators of soil quality, notably soil moisture and soil nutrient regime, based on local site-level assessment. This system, similar to Anderson's site classification, uses a matrix of eight categories of soil moisture regime, ranging from *very wet* to *very dry*; and five categories of soil nutrient availability, ranging from *very poor* to *carbonate*. Indices of soil moisture and nutrient regime can be estimated directly from soil analysis or they can be inferred indirectly from vegetation, or site characteristics. An example of the soil quality grid of the BEC is provided in Table 1, which includes the vegetation characteristics as used in ESC (Pyatt et al. 2001).

Table 1: *An example of the soil quality grid used in the BEC with some examples of indicator plants used for indirect methods of soil quality assessment in ESC (after Wilson 1998, Pyatt et al. 2001).*

Soil moisture regime	*Soil nutrient regime*					
	Very poor	*Poor*	*Medium*	*Rich*	*Very rich*	*Carbonate*
Very dry						
Moderately dry						
Slightly dry			Wood sage			
Fresh	Cowberry	Bracken		Bluebell	Elder	
Moist	Heather	Wood sorrel			Stinging nettle	
Very moist			Lady fern			
Wet				Meadow-sweet		
Very wet	Bog myrtle					

The components of the forest site

The term site describes an abstract concept which combines a multitude of environmental factors affecting tree growth into a unified classification. Although there are biological and management factors that influence species suitability and productivity, those most likely to influence growth are climate, topography and soil (Anderson 1961, Ralston 1964, Carmean 1975, Pyatt 1995, Pyatt et al. 2001, Horgan et al. 2003, Klinka and Chen 2003) (Figure 1). All three factors are interdependent at varying degrees and scales and combine in one climatic region to create the *forest site*. Site factors have the greatest and often longest-lasting effect on the productivity of indigenous and plantation forests.

The composition of the vegetation growing on a site may provide valuable information about the site factors that are likely to have the greatest impact on tree growth (Anderson 1961). The role of climatic, topographic and edaphic site factors in explaining differences in forest growth and productivity on various sites are examined in the following sections.

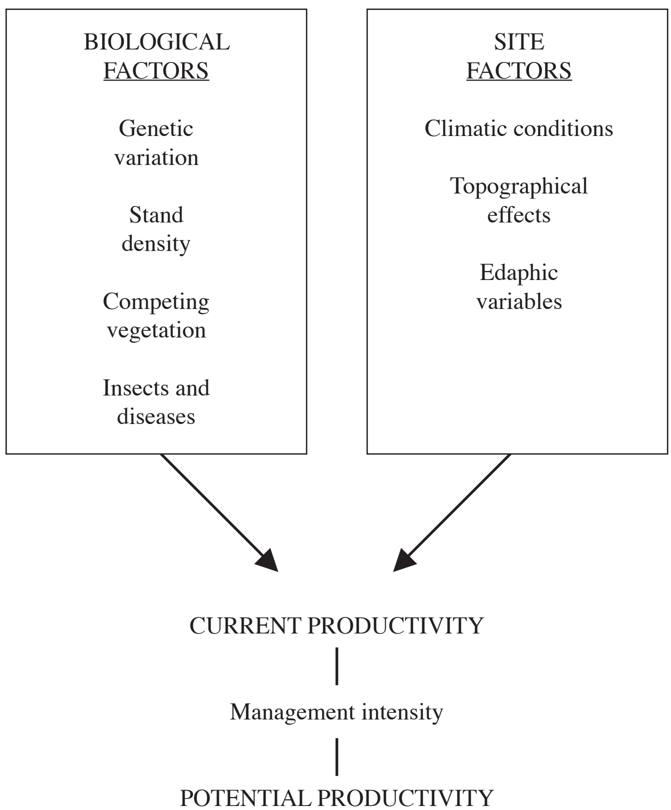

Figure 1: *The major factors regulating forest growth and productivity (after Ralston 1964).*

Climate factors and their influence on forest growth

A review of literature on forest growth and yield studies indicates that a number of key climatic factors play a role in tree growth and in forest productivity (Table 2). It is widely known that temperature or growing season warmth affects the growth rate of trees (Pyatt et al. 2001). Annual heat sums or day degrees may be particularly useful, often providing a measure of the heat available for tree growth in any year or growing season. Degree days have been shown to be highly correlated with productivity (Farr and Harris 1979, Worrell 1987, Worrell and Malcolm, Waring 2000).

Table 2: *Climate variables used to assess tree growth and productivity, with associated authors.*

Climate variable	*Author(s)*
Degree days	Farr and Harris 1979, Christie and Lines 1979, Worrell, 1987, Tyler et al. 1996
Winter rainfall	Blyth and MacLeod 1981,Tyler et al. 1996
Spring rainfall	Tyler et al. 1996
Summer rainfall	Tyler et al. 1996
Total rainfall	Tyler et al. 1996
Air temperature growing season	Blyth and MacLeod 1981
Mean spring temperature	Tyler et al. 1996
Mean summer temperature	Tyler et al. 1996
Mean winter temperature	Tyler et al. 1996
Climate zone	Wang et al. 1994, Kayahara and Pearson 1995, Klinka and Chen 2003
Global solar radiation	Waring 2000

In general, photosynthetic activity rates are low or negligible at temperatures below the most commonly used critical base temperatures (usually 5-6ºC) (Christie and Lines 1979), although positive net photosynthetic rates have been recorded at temperatures as low as -5ºC in Sitka spruce (Ludlow and Jarvis 1971, Neilson et al. 1972). The onset of flushing in trees is largely governed by the accumulation of degree days above a critical threshold (Cannell and Smith 1983). Degree days can be calculated by subtracting a base temperature from the mean daily temperature and summing these values over time, usually over a particular developmental period of interest or over a full year. Temperature variations are influenced by topography with a standard lapse rate of 1ºC for every 150 m increase in elevation (0.6ºC per 100m) (MacEntee 1976, Worrell 1987). Degree days can be reduced by as much as 10% per 100 m elevation (Keane and Sheridan 2004).

Low rainfall may limit the growth of tree species (Zehetmayer 1960, Malcolm 1970). Precipitation is highly variable, both spatially and over time. Precipitation in Ireland is characterised by plentiful rainfall, fairly well distributed throughout the year. Annual rainfall in lowland areas varies from 750 mm in parts of the east and northeast to greater than 1200 in the west, northwest and south west. Rainfall is modified by topography. Mountainous areas of Ireland receive more than 1600 mm of rain annually, with a maximum of 3200 mm recorded for Corran Tuthail in

Kerry (Keane and Sheridan 2004). Blyth and Macleod (1981) found that the growth of Sitka spruce was positively correlated with winter temperature sums and annual rainfall in a study in north east Scotland. The effect of water drought or water stress, where evapotranspiration exceeds rainfall, may be a problem on shallow or freely draining soils, which may have insufficient water storage capacity during low rainfall periods, thus limiting tree growth. This has been shown to cause problems for growth of certain tree species (Anderson 1961, MacDonald 1967, Fourt 1968, Toleman and Pyatt 1974, Jarvis and Mullins 1987). Water balance models have shown the negative effect of drought on the growth of tree species in Canada (Klinka and Carter 1990, Wang and Klinka 1996, Kayahara et al. 1997).

Exposure to the wind, results in the lowering of plant temperatures, localised water stress and mechanical damage, resulting in reductions in the leaf water balance and restriction of the rate of photosynthesis (Grace 1977, Tranquillini 1979). The result is windswept trees with branches permanently swept to the leeward side, mainly because buds on the windward side of the trees are killed. Windspeeds greater than 15 ms^{-1} may reduce the growth of conifers, which can lead to the development of trees with poor form and increased taper. Ireland has a windy climate, due to the Atlantic Ocean. Annual windspeeds in Ireland are lowest in the central plain, ranging from just over 3.5 ms^{-1} in the south midland area of Kilkenny, to 8.1 ms^{-1} at Malin Head, Co Donegal in the extreme north west (Met Eireann 2008). At higher elevations mean annual windspeeds can reach up to 12.1 ms^{-1} in Donegal (Haslett and Kelledy 1979). In Britain, tatter flags have been used to estimate windiness levels; the rate at which the flags tatter correlates with wind speed (Rutter 1968, Jack and Savill 1973, Quine and Sharp 1997, Quine 2000). Significant correlations have been found between tatter rate and the productivity of Sitka spruce (Worrell 1987, Worrell and Malcolm 1990). The development of a new wind atlas for the assessment of wind energy, offers significant potential for the assessment of windiness of forest sites in Ireland (SEI 2003).

The occurrence of sporadic severe frosts, usually of short duration, can have a devastating effect on the survival and growth of young trees. Late spring frosts often coincide with the time of flushing, and these can kill new shoots. The extent and intensity of spring frost has a major effect on species selection, especially in midland areas. Frost damage represented over 60% of all accidental damages recorded by the Forest Service in Ireland in the mid 1990s (Horgan et al. 2003, Renou-Wilson 2008). The prediction of the regional occurrence of spring frost may be possible by examining minimum monthly temperatures from long-term averages from climate data. However, local effects due to topography (e.g. frost hollows), can lead to a reduction in temperatures over relatively small distances.

Solar radiation also influences tree growth (Waring 2000). Solar radiation levels associated with changes in topography accounted for nearly half the variation observed in the growth of Sitka spruce on poorer sites in Britain in Waring's study. He states that if solar radiation was converted at maximum efficiency, then 8000 g C m^{-2} a^{-1} could be fixed during photosynthesis. When converted to wood production this is equivalent to a theoretical mean annual increment (MAI) of 70 m^3 ha^{-1} a^{-1}. This is, however, limited as only half of the photosynthate is utilized for growth, the rest is respired as CO_2 and because an increased proportion of growth is directed to root production as the environment becomes more stressful. Most of the variation in solar radiation is associated with topography, particularly slope and aspect (MacEntee 1976, Waring 2000).

Climate data and scales

When considering the impact of climate on the growth and development of trees it is important to consider what climate data are available and how appropriate they are for different spatial scales. In Ireland climate data are available from a range of synoptic meteorological stations chosen to represent mesoscale to macroscale conditions and provide the basis for a general climatology of the surrounding area. Keane (2004) provides a summary of different spatial scales where climate information may be required and their appropriate characteristic distances (Table 3). The general climatic conditions reported at regional level can differ significantly from the local climate, due to effects of elevation and topography, resulting in local climatic variations in rainfall, temperature and wind. For the individual forester or landowner, it is important to consider these *topoclimatic* (or terrain-climate) factors, as these may be as important as the general or regional pattern. Microclimate refers to the scale at which plants and animals live. It differs from mesoclimate, which prevails above the first few metres over ground level, primarily in the intensity of the changes that occur over time and with elevation (Rosenberg et al. 1983).

Data for some climate variables, such as windspeed, potential evapotranspiration and solar radiation, are available from 15 Met Eireann synoptic stations, which indicate regional trends in lowland areas. Rainfall and temperature data are more commonly available for a wider range of recording stations and may represent regional trends in upland areas or topo-scale trends in lowland areas. Climatic data at finer scales, the topo-scale and micro-scales are generally not available, except in situation where data are being collected for research or other monitoring purposes.

Table 3: *Climatic scales and characteristic distances (after Keane 2004).*

Scale	*Lowlands/plains*	*Uplands/mountains*
Regional (county/district)	100 km	10 km
Topo- (farm/field)	10 km	100 m
Micro- (field/crop)	100 m	10 m

Topography

The effect of elevation on the growth of tree species has been examined in many studies. Sitka spruce height growth decreased as elevation increased in studies carried out in Britain (Day 1946, Page 1970, Malcolm and Studholme 1972, Mayhead 1973, Worrell 1987, Worrell and Malcolm 1990). The effect of elevation can be more significant at coastal and northerly locations (Malcolm and Studholme 1972, Worrell 1987, Worrell and Malcolm 1990). It appears that the effects of elevation and associated climatic factors have a small impact on tree growth at lower elevation ranges (0-300 m) (MacMillian 1991, Hassall et al. 1994, Tyler et al. 1994, Dunbar et al. 2002). Elevation is not a causal factor itself but rather may be regarded as a composite indicator of climatic conditions (Blyth and Macleod 1981).

Elevation data are readily attainable from many sources, such as digital elevation models (DEMs), global positioning systems (GPS), altimeters and contour maps, and has widespread potential use in forestry due to ease of data collection.

The degree of shelter provided from the surrounding landscape, providing protection from prevailing winds, is also an important factor when assessing forest site factors. A method to measure the amount of geomorphic shelter provided by the surrounding landscape (Malcolm and Studholm 1972) has been developed. The level of shelter, or exposure, can be estimated from the TOPEX index for a site, which involves summing the angles of inclination to the horizon at the eight cardinal points of the compass. Lower TOPEX scores indicate that the surrounding landscape has relatively little influence on shelter in the proximity of the site. In contrast, higher TOPEX scores suggest that the surrounding landscape, such as mountains and hills, obstruct winds and thus provide greater shelter levels. Higher TOPEX scores have been associated with increased yields (Hassall et al. 1994, Worrell and Malcolm 1990b, Macmillian 1991). The collection of TOPEX measurements in the field is conceptually easily achieved, but views to the horizon may be constrained in forest situations, such as when a mature overstorey crop is present. However recent developments in geographical information systems (GIS) have led to the development of distance limited TOPEX models using digital elevation models, such as those developed for use in Britain (Quine and White 1993) and Ireland (Green 2006).

Some have found that the shape of the slope and contours affects tree growth. Sitka spruce growth was found to respond more favourably to receiving sites, than to shedding sites and this may indicate water stress problems associated with steeper slopes and nutrient accumulation in certain receiving sites (Page 1970, Malcolm 1970, Blyth and Macleod 1981, Jarvis and Mullins 1987). This could be related to the fact that slope shape affects the amount of water that is received or runs off a site. Site aspect has been shown to be significantly linked to growth rates in northern Britain (Worrell 1987, Worrell and Malcolm 1990). The height growth of Sitka spruce on sites with north-easterly aspects was greater on sites sheltered from the prevailing winds in the uplands. Hassall et al. (1994), in a study of Douglas fir, found that forests having similar site characteristics had higher yields when located on steep slopes than on gentler slopes. South-facing aspects in Scotland were more favourable for growth than north facing slopes (Cook et al. 1977, MacMillian 1991). This may be due to the greater levels of solar radiation received on south facing slopes, providing more energy for growth (Jack 1968, Waring 2000). On south facing slopes, the steeper the slopes the greater the amount of radiation that is received (MacEntee 1976). On eastern and western slopes, gentler slopes receive higher radiation levels. On northern slopes, radiation decreases with increasing slope.

Edaphic factors

Edaphic factors refer to the physical and chemical composition of the soil. Soil properties can be used to assess soil quality and may help explain site differences in tree growth. Some of the soil variables that have been found to be most important in previous site/yield studies are presented in Table 4. These include chemical indicators such as pH, total carbon, sulphur, available SO_4 form of S, extractable P, K, Mg and Ca, cation exchange capacity (CEC), exchangeable Ca, Mg and K. Total nitrogen (N), mineralisable N, the two inorganic N components NO_3 and NH_4. Soil pH, NO_3 form of N and calcium are good indicators of potential soil N availability and relate closely to the species composition of the ground vegetation in British forests, according to Wilson et al. (2001). In some infertile soils, the NH_4 form of N or total N may be of greater importance since NO_3 availability is usually low in these soils. The chemical composition of the soil is usually estimated from samples taken from the forest floor or from the soil fraction at a predefined depth, usually 30 cm.

The chemical composition of the parent material may have a marked effect on fertility. Sedimentary rocks, with the exception of some sandstones, as a general rule give rise to more fertile soils than primary or metamorphic rocks. Basic parent materials give more fertile soils than acid parent material and metamorphic rocks. Rocks with high silica or quartz content tend to lead to the most infertile conditions. Various physical characteristics, such as drainage, porosity, gleying and watertable depth, are important soil factors and can be determined from soil profile analysis in the field or from descriptions provided in soil survey bulletins published by the National Soil Survey (An Foras Talúntais, now Teagasc).

Inadequate soil drainage may lead to anaerobic conditions, which reduce root growth and site productivity potential (Blyth and Macleod 1981, Macmillian 1991). Studies undertaken to examine the effect of edaphic factors on growth and yield are not universally applicable as these studies differ in the range of climatic, site and soil variables chosen. The variable(s) that emerge as the most important in explaining tree growth may reflect specific species interactions with soil factors (Moffat 2003).

Soils can be categorised into similar classes on the basis of the availability of both nutrients and soil moisture. Determination of actual soil nutrient regimes involves removing soil samples from a predefined depth (rooting depth), and then determining the nutrient elements in the soil using laboratory chemical analysis procedures.

Characterisation of soil moisture regime involves determining water table or gleying depth in poorly drained soils, or the calculation of potential water balance using available water capacity of the soil and the balance between potential and actual evapotranspiration for freely drained soils. Under field conditions, it may be more practical to determine soil moisture and soil nutrient regime using field keys based on soil morphological properties and site characteristics (Green and Klinka 1994, Pyatt et al. 2001).

Table 4: *Soil characteristics examined in a selection of site/yield studies.*

Soil property	*Author(s)*
Parent material	*Cook et al. 1977, Blyth and MacLeod 1981, Dunbar et al. 2002*
Soil group/type	Malcolm and Studholme 1972, Cook et al. 1977, Blyth and MacLeod 1981, Worrell 1987, Macmillian 1991, Hassall et al. 1994, Tyler et al. 1996
Soil series	Page 1970, Bulfin 1973, Conry and Clinch 1989
Soil texture	Malcolm and Studholme 1972
Soil drainage	Malcolm and Studholme 1972, Blyth and MacLeod 1981, Macmillian 1991, Hassall et al. 1994, Tyler et al. 1996
Total soil depth	Page 1970, Hassall et al. 1994
Peat depth	Hassall et al. 1994
Depth of raw humus	Day 1946
Hue of soil, chroma value of soil, Munsell colour value of soil	Page 1970
Moisture content % at 15 cm, Moisture content % of the B horizon	Page 1970
Bulk density at 6 inches, bulk density at 30 cm	Page 1970, Blyth and MacLeod 1981
Soil temperature	Blyth and MacLeod 1981
Soil pH	Blyth and MacLeod 1981, OCarroll and Farrell 1993
Total N of organic layer	Blyth and MacLeod 1981
Total P	Blyth and MacLeod 1981
Soil C	OCarroll and Farrell 1993
Soil N	OCarroll and Farrell 1993
Mineralisable N of forest floor and of soil at 30 cm	Klinka and Carter 1990
NO3-N, NH4-N	Wilson et al. 2005
Air porosity	OCarroll and Farrell 1993
Thickness of profile	Blyth and MacLeod 1981
Depth of mottling	Blyth and MacLeod 1981
Stone content	Blyth and MacLeod 1981
Depth of rooting	Malcolm and Studholme 1972, Blyth and MacLeod 1981
Effective rooting depth	Blyth and MacLeod 1981
Free rooting depth	Day 1946
Soil nutrient regime	Wang et al. 1994, Kayahara and Pearson 1995, Klinka and Chen 2003
Soil moisture regime	Wang et al. 1994, Kayahara and Pearson 1995, Klinka and Chen 2003

Vegetation classifications

Various indicator plants or plant communities have been used as a guide to the productive potential of sites. The classifications devised by Cajander (1926), Anderson (1961), Krajina, (1969), Ellenburg, (1988) and Klinka et al. (1989) have all been used as a basis for classifying the fertility and soil moisture status of sites. Plant community assemblages may provide a sound ecological basis for forest species selection and productivity assessment. Anderson (1961) suggested that vegetation is a better and more practicable indication of soil fertility. He says that chemical analysis of the soil may only show the relative proportions of certain nutrients present in the soil, whereas the vegetation cover gives an indication of the extent to which these are available for plant growth. Wilson et al. (1998) used the ground vegetation in British woodlands to examine the relationship between species composition and soil nutrient regime determined from soil chemical analysis. He further indicated that crop yields of Scots pine and Japanese larch appeared to be broadly correlated with soil nutrient regime. In recent years, the use of vegetation to assess soil moisture regime and soil nutrient regime has received widespread acceptance as a means of evaluating soil quality (Klinka et al. 1999, Wilson et al. 2001& 2005). This can form the basis for species selection, and the assessment of site productivity potential. The use of ground vegetation has the potential to assist with soil assessments, producing reliable indications of soil moisture and soil nutrient conditions without the need for laboratory soil analyses (Wilson 2009).

Discussion

Good silvicultural decision-making and planning require knowledge of the growth of tree species across the full range forest site types in Ireland. The term site describes a complex phenomenon, a composite for the expression or combination of climatic, topographic and edaphic factors. For example, peaty podzol soils form mainly where the underlying parent material is inherently acid. These soils tend to be found most commonly on high elevation sites (especially where the slopes are steep). The higher amounts of rainfall received and the type of vegetation found at high elevations promote podzolisation. The nutrient and moisture status of such soils are generally less favourable for tree growth. Since these sites are most commonly found at higher elevations, the prevailing climatic conditions tend to limit tree growth there.

The main climatic factors deemed important for forestry have been well documented and include temperature (e.g. degree days). Climatic variables, such as annual or seasonal rainfall, provide information about moisture availability; low availability limits tree growth. The moisture balance method (difference between potential evapotranspiration and precipitation) may be used to indicate areas where drought is likely to reduce growth, which might be expected on soils with limited water storage capacity. Windspeed information is a very useful indicator of the inherent exposure of forest sites. These could be very useful in the west and north-west of Ireland and at coastal locations where windspeed and frequency of wind storms are likely to be particularly limiting factors for growth. For other sites, especially those in the midlands of Ireland, climate variables such as minimum temperatures, which could indicate frost risk, might be considered. Some of these data are available from Met Eireann synoptic stations, and are suitable for use at a regional scale.

For specific sites, location, elevation, proximity to the coast and slope will affect the micro- or topo-climate. Appropriate lapse factors need to be used in any site assessment model. To obtain specific climate data for particular studies, on-site data collection may be necessary. The role of topography is also important. The use of scoring systems, such as TOPEX, will give an indication of the amount of shelter provided by the surrounding landscape. The slope and aspect of sites may be important, especially as it affects solar radiation levels. The topographical position and slope shape influence both water and nutrient availability. Lower or concave slopes are likely to retain more water (in some cases nutrient-carrying water flushes) than areas on higher, steeper slopes. The development of soils is closely associated with topography, which makes it difficult to separate the effects of topography from changes in associated soil factors. For example, it is well known that yields decrease as elevation increases. However, this effect is more dramatically expressed at higher elevations than at lower elevations. It is likely that elevation is really a proxy for climate; the more severe climates tend to be associated with higher elevation sites. Degree days and site information on windiness and/or exposure might better explain declines in productivity with elevation. The use of soil chemical analysis and soil physical attributes may also be useful in site assessment, but these can be time consuming and expensive to carry out. The use of soil classification systems to assess soil quality has potential, especially where the soils are grouped into homogenous units based on moisture or nutrient status.

The advantages of single factor analyses of data derived from soil, vegetation or fertility classifications are their ease of use and simplicity. The fertility and moisture status of soils can be readily determined from many soil attributes. The classification systems developed in other countries to assess forest site productivity potential, such as the biogeoclimatic ecosystem classification (Canada) and the ecological site classification (Britain) could perhaps be modified for use in Ireland.

The provision of data on actual soil moisture and soil nutrient regimes from soil profile data and soil chemical analysis data may provide additional important information. Plant communities have been successfully used as indicators of soil nutrient status in the ESC system used in Scotland, so it is likely that a similar relationship will be found for sites in Ireland. Once established, soil quality indicators can then form the basis for the development of a method for assessing species suitability and the assessment of potential productivity of sites.

Conclusion

A range of variables is suitable for use in determining species suitability and productivity and for site classification in Ireland. Single factor classifications, such as one based on soil or vegetation, can provide good guidance on species suitability for a given site and on potential yields. Soil, vegetation and climate data, may however be combined to provide a more robust assessment of site productivity potential, especially in the context of sustainability issues. Site classification methods, such as the multifactor systems currently operated in Canada and Britain might be modified for use in Irish forestry.

While the factors which best describe site quality and its implications for tree growth are well known, there is less information available about how tree species grow on different site types in Ireland. Many questions remain to be answered, such as the reason why some broadleaved species such as oak and ash species frequently perform poorly on land which had been devoted to agriculture for several generations. Scientifically based understanding of species-specific site-soil relationships is needed to complement ongoing research work in other areas and to keep pace with advances being made in tree improvement. It is clear that the knowledge-based approach to species selection, based largely on experience of forestry practitioners, can help formulate hypotheses about species/site relations, but lacks the basis for understanding the causal mechanisms that affect the growth and performance of tree species. The expert research approach (based on scientific evaluation of tree species in relation to their environment or the sum of all the components of site), such as that undertaken in Canada by Klinka (2008) and the United States is an excellent model to providing a solid scientific basis for the selection of tree species and assessing site productivity in Ireland. A new model of this type would provide foresters with the opportunity to confidently recommend tree species to landowners for different conditions. It will also give state organisations and landowners confidence that their investment is underpinned by solid research and will yield the best returns for all involved. To this end, the establishment of temporary research plots (0.04 ha size) in forest stands, to determine species specific site interactions for the major tree species in Ireland is proposed. When this is complete, the ecological amplitude, nutritional requirements and productivity of tree species in Ireland on various sites types can be compared.

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