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Sitka spruce site index in response to varying soil moisture and nutrients in three different climate regions in Ireland

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ABSTRACT

We examined the relationships between Sitka spruce (*Picea sitchensis* (Bong.) Carr.) site index, windspeed, former land use, soil moisture and soil nutrients with a view to identifying factors limiting the growth potential of the species in three climate regions in Ireland. We selected plantations covering three climate regions (delineated on the basis of 'growing season' balance of precipitation and potential evapotranspiration; representing dry, moist and wet climate regions) located on sites representing the range of soil moisture regimes (SMR), soil nutrient regimes (SNR), and land use types found throughout Ireland. Site index of Sitka spruce varied among climate region, with significantly lower site index associated with the wet climate region mainly due to the deterioration in edaphic conditions and adverse climatic conditions. The effect of edaphic variables (SMR, SNR) on site index was consistent across climate regions, site index increasing with increasing SNR, and decreasing with excess moisture or moisture deficit. Site index reached a maximum on fresh/very rich sites in the dry and moist climate regions and on moist/rich sites in the wet climate region. In the dry climate region, water supply (SMR) was the most important variable regulating growth, in wetter windier climates nutrient supply (SNR) was the most important factor, accounting for 69% of the variation in site index. The study has allowed region-specific recommendations to be made for successful plantation establishment in Ireland and for countries with similar climatic regions.

1. Introduction

Sitka spruce (*Picea sitchensis* (Bong.) Carr.) is the most important commercial tree species in Ireland, where it has wide ecological amplitude, growing successfully across a range of climatic conditions and site types, associated with mountain and hill landscapes and to a lesser extent, lowland landscapes (Farrelly et al., 2009). The widespread use of the species for the establishment of plantation forests in Ireland on submarginal and marginal agricultural land in the 20th century, earned the species a reputation of not too exacting in terms of site quality requirements. Recent afforestation programmes where the species has been planted on a wider range of site types, have indicated that the species shows an increased response in growth on lands with some form of previous agricultural land usage (Farrelly et al., 2009).

For forest managers, the identification of site quality measures related to forest productivity offers the opportunity to assess the potential productivity of land for afforestation where forest stands or trees are absent (Monserud et al., 1990; Chen et al., 1998). The use of site quality variables to assess the potential forest productivity of land is commonly used in forestry as the realizable part of the site potential for volume/height growth is related to site quality (Skovsgaard and Vanclay, 2007). Site index, the top height of dominant and co-dominant trees at a reference age, is widely used to measure forest productivity in even aged stands provided that height growth is not affected by suppression, or damage due to insects or disease (Spurr and Barnes, 1980; Monserud, 1984; Nigh, 1997; Chen et al., 1998). Recently new site index curves for Sitka spruce developed for use in Ireland (Broad and Lynch, 2006) offers the potential to use site index as a method for the assessment of potential forest productivity in Ireland.

Previous studies that have attempted to establish which site quality variables are useful indicators of productivity have focussed on using relationships between site quality variables and the productivity of Sitka spruce have had varying degrees of success (e.g. Blyth and MacLeod, 1981; Worrell and Malcolm, 1990; MacMillan, 1991; Hassall et al., 1994). The identification of which site quality variables are useful indicators of Sitka spruce productivity differs between studies, because the range of site quality variables examined varies widely between studies, studies are restricted to a narrow range of environmental factors where growth is strongly correlated with one or two variables, whose variability over the study area is low. For example, in southeast Alaska, soil

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physical properties such as soil depth, soil drainage, coarse fragment and organic carbon content were important factors related to Sitka spruce site index (Stephens et al., 1968; Ford et al., 1998). On the other hand, in Great Britain, soil moisture content, soil colour, depth of raw humus, drainage status, and total N and P contents of the organic layer were important variables related to the yield class of Sitka spruce (Page, 1970; Blyth and MacLeod, 1981). Climatic variables also show significant relationships with the productivity of the species. Along the pacific coast of North America, Farr and Harris (1979) showed that site index of the species was strongly related to latitude and accumulated temperature. Climate related variables have been shown to play a much more significant role in the growth of the species at higher elevations where lower temperatures and increased wind exposure restrict the growth of the species in northern Britain (Blyth and MacLeod, 1981; Worrell and Malcolm, 1990).

Where the ecology of the species has been examined from a more basic consideration of environmental variables, it has been shown that edaphic variables (soil moisture and nutrient regime) such as those used in the Biogeoclimatic Ecosystem Classification in British Columbia, show strong relationships with the growth of the species (e.g. Pearson, 1992; Farrelly et al., 2011). The species shows a positive response to increasing nutrients and best growth has been observed in Canada and Ireland on sites having no moisture deficit or excess moisture and high nitrogen availability, (i.e. fresh to very moist sites, with rich to very rich soil nutrient regimes) (Pearson, 1992; Farrelly et al., 2011). Thus the identification of which site quality measures are useful indicators of the productivity of Sitka spruce is dependent on variables showing strong relationships with growth in specific study areas, making it difficult to extrapolate results outside of specific areas.

To provide a better understanding of the growth of Sitka spruce in relation to different study areas using similar measures of ecological site quality, we examined the response in site index to varying climate, soil moisture and nutrients to determine if the nature and strength of relationships between site quality measures and site index varied according to climate region.

2. Materials and methods

2.1. Study area and sampling methods

The climate of Ireland, which is situated at middle latitudes (51° 25′ N to 55° 23′ N), is influenced by the prevailing westerly winds and the proximity of the Atlantic Ocean. The climate is characterised as mesothermal maritime (Cfb) under the Koppen climate classification. Precipitation is fairly well distributed throughout the year with no distinct dry season; annual precipitation in the lowlands ranges from about 750 mm in the east to 1200 mm in the west and from 1600 mm to 3200 mm in the upland areas (Keane and Sheridan, 2004). The mean daily temperature in Ireland is 9.5 °C with the warmest summer temperatures occurring in July, averaging 14.7 °C, and coldest temperatures occurring in January, averaging 4.6 °C.

Stands selected for this study covered the entire range of pure Sitka spruce stands (of mixed Queen Charlotte Islands, Washington and home collected seed origin) that were even-aged, uniformly stocked, and at post establishment stage (the range of ages was 15–83 years) in the Republic of Ireland covering a total of 30,275 stands (greater than 1 ha in size) occupying an area of 158,241 ha. In order to represent a range of regional climatic conditions, we characterised and delineated three regional climates based on the balance between precipitation (P) and potential evapotranspiration (PE) over the growing season, representing dry (where $PE > P$), moist (where $P - PE$, $\leqslant$150 mm) and wet (where $P - PE$ >150 mm) climatic regions (Fig. 1; Table 1). Within each regional climate stands were stratified according to soil type (a proxy for soil moisture and soil nutrient regime) using the General Soil Map of Ireland (Gardiner and Radford, 1980), and randomly selected to cover as many soil types in each climate region as time and resources allowed. Sampled soils (according to the Irish Soil classification, with the FAO system of soil classification in parenthesis) included Brown Earths (Cambisols), Organic soils (Histosols), Podzols (Humic and Orthic podzols), Grey Brown Podzolics (Luvisols), Gleys (Gleysols) and Rendzinas (Chernozems).

In total, 201 stands were visited between October 2006 and April 2009. The stands selected for field visit were even-aged, uniform in canopy cover, understory vegetation, humus form and soil characteristics, and were aged between 16 and 83 years (mean 31.4 years). Within each stand, a sample plot was randomly located no nearer than 10 m from the stand edge to reduce edge effects. Sample plots were 0.04 ha (20 × 20 m) in size; smaller plots, i.e. 0.02 ha (20 × 10 m) and 0.01 ha (10 × 10 m) were used in younger unthinned crops or where time constraints prevailed.

2.2. Determination of site quality factors

Climate maps for Ireland (Sweeney and Fealy, 2003) were used to derive mean annual precipitation, temperature and annual sum degree – days >5 °C to characterise the climate in each study area (Table 1). Mean annual windspeed for each plot was derived from a national wind atlas of Ireland (Anon, 2003).

We derived information regarding former land use for each plot using direct evidence from field visits and from Ordnance Survey of Ireland (OSI) 6 inch to the 1 mile (1:10,560) maps. The presence of enclosures on the site, together with historical information from maps regarding vegetation and field boundaries, were used to classify plots into four former land uses according to OCarroll's (1975) classification as follows: (i) former cultivated fields; (ii) abandoned fields with Ulex or Pteridium spp.; (iii) unenclosed ground with rough pasture and/or outcropping rock; and (iv) Old Woodland sites.

Soil moisture regimes (SMR) (moderately dry, slightly dry, fresh, moist, very moist, wet and very wet) were identified using the occurrence and duration of phases of water use, the ratio between actual and potential evapotranspiration, the occurrence and depth of watertable and depth of prominent mottling according to the methods of Wang and Klinka (1996). For organic soils rooting depth was used (Pyatt et al., 2001), as rooting depth shows a close relationship with depth of watertable (Ray and Nicoll, 1998). A generalised simple forest soil water balance model was used in the study to calculate actual evapotranspiration (AET) based on an approach developed by Thornwaite (Mills, 2000). The model was driven by precipitation, potential evapotranspiration, and used soil depth (corrected by coarse fragment content) and texture data to calculate available water storage capacity. The soil storage available to plants was calculated by subtracting water content at wilting point (WP) from that at field capacity (FC) using soil texture (Saxton et al., 1986). Mean monthly potential evapotranspiration (PET) and mean monthly precipitation (P) (mm) of 30 year normals were available from climate maps (Sweeney and Fealy, 2003). Thereafter, each of the water budget components were calculated by comparing values for precipitation and potential evapotranspiration and monitoring water stored in the soil. If P exceeds PET, there is sufficient water and AET will be equal to PET. If there is not sufficient water in the soil to meet PET, then there is a deficit, the deficit is defined as the difference between PET and AET. The duration of deficit (in months) and the ratio between AET and PET were used to calculate SMR (Wang and Klinka, 1996). Moderately dry and slightly dry soils were only encountered in the dry climate region. Soil nutrient regimes (SNR) were identified using a combination of soil morphological