The distribution and productivity of Sitka spruce (Picea sitchensis) in Ireland in relation to site, soil and climatic factors

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Abstract

An analysis of the geographic distribution and productivity of Sitka spruce with reference to site, soil and climate characteristics, planted between the years 1924–1991 was conducted. Sitka spruce plantations have been established throughout Ireland from latitude 51° N on Cape Clear Island off the south-west coast of Co Cork, to 55° N on the Inishowen Peninsula in Co Donegal. Climate models were used to characterise the range in rainfall and temperature of sites afforested with Sitka spruce. Annual accumulated temperature above 5°C and growing season potential water balance (deficit or surplus) were used to derive five climate zones. Seventy percent of Sitka spruce stands had annual accumulated temperatures >1200 degree days per year. Only 7% of the area was classified as having a potential growing season water deficit. Sitka spruce has been most commonly planted on Mountain & Hill sites below the 450 m contour, typically on peat, gley and podzol soils. A stratified random sampling scheme was used to assess productivity on different soils, climate zones and elevation classes. Results indicate that the most productive stands occurred on deep, moist, well-aerated soils, of moderate to rich nutrient status. Yields on low and high level blanket peats were significantly lower than on grey-brown podzolics, acid brown earths, brown earths and gley soils. Productivity varied between elevation classes, but was only significantly lower at elevations over 500 m. Significantly lower yields were found in high rainfall areas where rainfall exceeded potential evapotranspiration by more than 150 mm during the growing season, these areas are associated with blanket peat, peaty podzol and lithosol soils. The national average weighted yield class was found to be 17.0 $m^3ha^{-1}a^{-1}$.

Keywords

Sitka spruce, site factors, climate zonation, degree days, moisture availability, productivity, general yield class

Introduction

Sitka spruce (*Picea sitchensis* (Bong.) Carr.) was introduced to Ireland in 1835 as a specimen tree at Curraghmore, Co Waterford. The tree had reached a height of 32 m by the late 19th century, and 55 m by the late 1990s (Twomey et al. 2002).

The earliest plantations were mixtures with larch (*Larix* spp.); the first (with European larch (*Larix decidua* Mill.)) was established at Glenart, Co Wicklow in the mid 1870s, at an elevation of 90 m (Joyce and OCarroll 2002). In 1905, two plots of were established as part of the Avondale (Co Wicklow) forest demonstration plots, in

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50:50 mixture with Japanese larch (*Larix kaempferi* (Lam.) Carr.), at 1.2 m spacing (Carey 2004). A further plantation was established in 1912 at the Lough Eske estate in Co Donegal, as a mixture with western red cedar (*Thuja plicata* **Donn ex D. Don**), European larch and Scots pine (*Pinus sylvestris* L.). Productive growth in those plots established the suitability of Sitka spruce for Irish forestry (Mooney 1956).

The species does not seem to have been planted pure before 1909, but rather, as indicated, in mixture with larch and with Norway spruce (*Picea abies* **(L.) Karst)**, lodgepole pine (*Pinus contorta* **Douglas ex Louden**), and birch (*Betula spp*).

Just over 47 ha of Sitka spruce had been planted prior to the start of World War 1. During the war years, 1914–1918, a further 68 ha were planted. Forbes, writing in 1925 about forestry in Ireland, stated that Sitka spruce was extensively grown on damp soils, and appeared to be the most rapidly growing spruce species.

The influence of the Avondale plots, established by Forbes in the 1920s, led to an increase in planting of the species by the state on wet ground, on exposed grassy areas and generally at elevations in the range 300–550 m (Joyce and OCarroll 2002). By the end of the 1920s Sitka spruce was well established as a plantation species, and over the subsequent two decades or so, from 1929-1948 it accounted for 24% of the afforestation programme. A census of woodlands conducted in 1958 estimated the area of Sitka spruce planted up to 1948 as 8,891 ha.

By the early 1950s the productive potential of Sitka spruce in Irish forestry was being more fully realized. Joyce (1953) reported that the cumulative production (490 m^3ha^{-1}) of a 30-year-old crop of Sitka spruce exceeded that of crop of Norway spruce (290 m^3ha^{-1}) of the same age growing on similar soil in Co Westmeath.

Odekoven (1957) commented that the thrifty growth characteristics of Sitka spruce, giving high yields on relatively short rotations, together with its excellent timber qualities, made it one of the most valuable species in the state.

A notable feature of government policy at the time was that afforestation should proceed only where there was no agricultural use for the land. As result, most afforestation was confined to marginal or sub-marginal agricultural lands. A further consequence was that during the period from the early 1950s until the mid to late 1980s, considerable areas of marginal land unsuitable for agriculture, such as Cloosh Valley in Galway and blanket peat areas of south-west Sligo and west and north-west Mayo, were afforested, mainly with Sitka spruce, lodgepole pine (*Pinus contorta* **Douglas ex Louden**) (O'Gruinneil 1956, Condon 1961). In fact, by 1956 Sitka spruce had become the most widely planted species in the Forestry Division's afforestation programme on blanket peat (O'Gruinneil 1956, White 1956), and on peat covered moorlands (Parkin 1957).

The area of Sitka spruce in 1958 was estimated as 22,471 ha, or 22.5% of the total forest estate (O'Flanagan 1973). By 1977, Sitka spruce had become the most common tree species in Ireland, occupying 110,753 ha, or 45% of the total area of high forest (Purcell 1977). By 1984, Sitka spruce occupied 49% of the forest area (Anon 1985).

In the 1970s and 1980s the range of site types on which the species was planted widened. Lowland agricultural sites were being planted (O'Flanagan and Bulfin 1970, Bulfin 1987 & 1988). In particular, gley soils which were inherently more fertile than peatland, but which suffered from impeded drainage and waterlogging, were beginning to be planted. This pattern continued with the large afforestation schemes of the 1980s and 1990s, with Sitka spruce being planted on a still wider range of sites. Today, Sitka spruce remains the most important tree species in Irish forestry, occupying 52.3% of the total forest estate or 327,000 ha (Forest Service 2007), and 60% (231,744 ha) of the area owned by Coillte (The Irish Forestry Board). Forest Service afforestation data show that Sitka spruce accounted for 61.6% of all private, grant-aided afforestation (114,000 ha) from 1980–2006 (Forest Service 2008).

The purpose of this paper is two-fold: first to describe the characteristics of sites on which Sitka spruce has been planted between 1924–1991; second to describe the derivation of a mean General Yield Class for Sitka spruce in Ireland, and to test what effect, if any, climate regime, elevation class, and soil type have on the productivity of the species.

Materials and methods

Stand selection

All subcompartments containing pure stands of Sitka spruce, which were over 1 ha in area, and were at least 15 years of age, were selected from a database of Coillte-owned forest. In addition, all private stands classed as 'Spruce' or 'Private Grant Aided' (PGA)[a], which were over 1 ha in area, and were at least 15 years of age were identified from the Forest Inventory and Planning System (FIPS) database of the Forest Service, Department of Agriculture, Food and Fisheries (Gallagher et al. 2001). The age constraint of 15 years or greater was based on results from a larger study examining the productivity of Sitka spruce in Ireland, which included only crops which were at least 15 years old in 2006 (planted up to and including 1991). The minimum area requirement of 1 ha was set in order to avoid edge effects. The selection provided 30,275 stands of Sitka spruce, occupying an area of 158,241 ha (Table 1).

Table 1: *Distribution of Sitka spruce stands planted up to and including 1991 by ownership type.*

Ownership	*Number of stands*	*Area ha*	*%*
State	23,590	109,959	69.5
Private	6,706	48,282	31.5
Total	30,296	158,241	100.0

The location of stands is in Table 2 and Figure 1.

a No differentiation at species level is made in the FIPS database, although it was assumed that most stands classified as Spruce and Private Grant Aided which were over 15 years of age would be predominately Sitka spruce, based on studies by Redmond et al. (2003) and Maguire (2009).

Table 2: *Summary location statistics of Sitka spruce stands planted up to and including 1991.*

Location variable	*Unit*	*Mean*	*Range*	*Std dev*
Longitude	Decimal degrees	8.2	6.0 - 10.4	0.95
Latitude	Decimal degrees	53.2	51.4 - 55.3	0.89
Dist. from sea	km	27.2	0.1 - 91.0	19.5

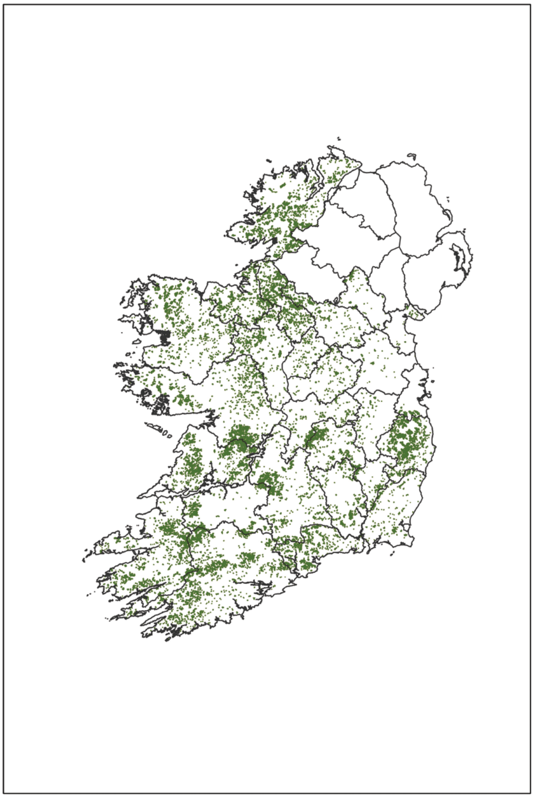

Figure 1: *Distribution of Sitka spruce stands in Ireland.*

In order to characterise sites on which Sitka spruce was planted, stands were classified by elevation class, landscape type, soil association and climate variables in a Geographic Information System (GIS). Elevations were taken from a Digital Elevation Model (DEM), which had a horizontal and vertical resolution of 25 and 1 m, respectively, and which covered the entire land area of the country. Stands were allocated to elevation bands based on 100 m increments, starting at sea level (0 m) to 600 m above sea level.

Based on the General Soil Map of Ireland (Gardiner and Radford 1980) stands were allocated to one of the following landscape types:Mountain & Hill; Hill Land; Rolling Lowland; Drumlin; and Flat to Undulating Terrain. The soil association for each stand was also taken from the General Soil Map of Ireland. A soil association is not a soil classification but is a cartographic unit. It consists of one or more Great Soil Groups, usually formed from the same type of parent material, which are associated in the landscape in a particular pattern. In each association there are principal and associated soils. The principal soil usually comprises about 75% of the association, but this may be as low as 50% or as high as 100% (Gardiner and Radford 1980). The 44 soil associations are grouped according to principal soil type (Table 1, Appendix).

Climate variables
Climate data associated with each stand were derived from 1 x 1 km climate surfaces (raster maps) provided by the Department of Geography, National University of Maynooth (Sweeney and Fealy 2003). The maps were developed from climate models derived from Met Eireann's climatological station data, and based on 30-year averages of annual and mean monthly temperature, annual and monthly precipitation, and monthly potential evapotranspiration covering the period 1961-1990. A map of annual accumulated temperature above 5^{o}C was derived for use in the study and calculated as the sum of monthly accumulated temperature from January to December (Figure 2), where monthly accumulated temperature is:

(Mean monthly temperature – 5^{o}C) x days in month (1)

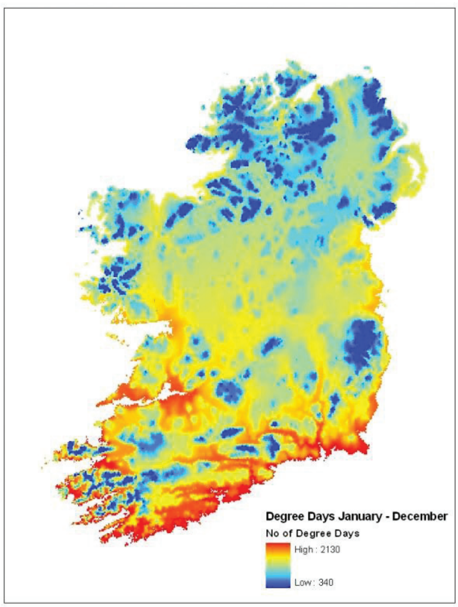

Figure 2: *Annual accumulated temperature above 5^{o}C (degree days) 1961-1990.*

The annual accumulated temperature above 5°C map was used to derive two temperature subzones for Ireland[b], designated Cool and Warm, based on temperature zones defined for Great Britain (Pyatt et al. 2001) (Table 3).

Table 3: *Description of temperature subzones, associated number of degree days and total and proportionate area occupied by each zone.*

Temperature subzone	*Degree days*	*Area km²*	*%*
*Alpine**	< 375	1	0.0
*Sub-alpine**	375 - 575	10	0.0
Cool	575 - 1200	7,668	9.1
Warm	> 1200	76,209	90.8

*Alpine and sub-alpine zones merged with cool subzone for analysis.

Growing season potential water balance was calculated as the difference between monthly precipitation and monthly potential evapotranspiration (PE) and summing months where PE exceeded precipitation. The balance between monthly precipitation and monthly potential evapotranspiration is presented in Table 4. Growing season potential water balance is in Figure 3.

Table 4: *The potential water balance by month (rainfall minus potential evapotranspiration), indicating a surplus (positive values) or deficit (negative values), with the cumulative deficit or surplus for months April-August, 1961-1990.*

Month	*Range of rainfall-potential evapotranspiration values mm*	*Deficit (yes/no)*	*Cumulative deficit mm*	*cumulative surplus mm*
January	61 - 398	no		
February	33 - 270	no		
March	16 - 257	no		
April	-11 - 135	yes	-11	135
May	-36 - 147	yes	-41	282
June	-47 - 116	yes	-89	398
July	-48 - 130	yes	-136	528
August	-13 - 177	yes	-149	705
September	11 - 241	no		
October	37 - 323	no		
November	52 - 331	no		
December	63 - 387	no		

b Although the categorisation resulted in four temperature subzones, the Alpine and Subalpine subzones were amalgamated with the Cool temperature subzone because of the small area each occupied.

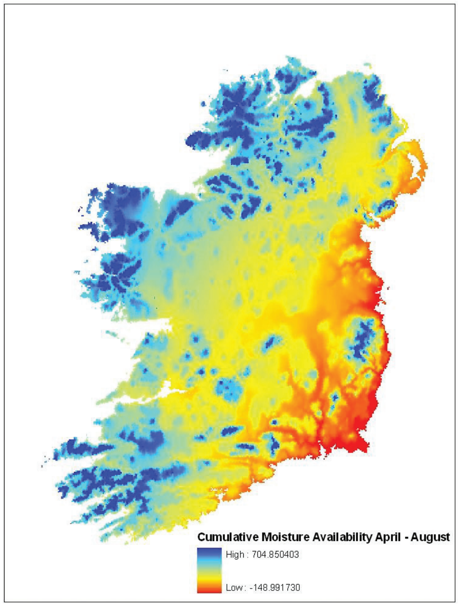

Figure 3: *Potential growing season water balance, April–August, 1961-1990. Low values (negative) are deficits, high values are surpluses.*

Results from previous research have shown that growing season water supply is a key factor influencing the growth of Sitka spruce in Scotland and Douglas fir in Canada (Jarvis and Mullins 1987, Klinka and Carter 1990). For the purposes of evaluating growing season water balance, three growing season potential water balance subzones were derived for Ireland: areas with growing season water deficit, areas with growing season water surplus 0-150 mm, and areas with growing season water surplus >150 mm. Proportionate area breakdowns for the three subzones are in Table 5.

Table 5: *Designation of growing season potential (GSPot) water balance subzones by area in Ireland.*

GSPot water balance subzone	*Water Balance (April – August)*	*Area km²*	*%*
Deficit	Water deficit occurs (potential evapotranspiration > rainfall)	19,994	23.8
Surplus 0-150 mm	Water surplus (0 – 150mm of rainfall> potential evapotranspiration)	49,754	59.4
Surplus >150 mm	Water surplus (150+mm of rainfall>potential evapotranspiration)	14,140	16.8

Climate zonation

The two temperature subzones, cool and warm (Table 3), and the three growing season water balance subzones (Table 5) were intersected to create five climate zones (Table 6).

Table 6: *Five climatic zones of Ireland based on annual degree days and growing season potential (GSPot) water balance, associated range of annual degree days >5°C, GSPot, annual rainfall, mean elevation and mean annual temperature.*

Climate zone	*Area km²*	*Annual accumulated temp degree days*	*GSPot. water balance mm*	*Annual rainfall mm*	*Mean elevation m*	*Mean annual temp °C*
Warm deficit	19,994	1318 - 2114	-149 - 0	672-1366	75.5	9.3
Warm surplus 0-150 mm	48,563	1200 - 2130	0-150	891-1872	94.6	9.0
Warm surplus > 150 mm	7,652	1200 - 1828	151-318	1320-2310	154.0	8.6
Cool surplus 0-150 mm	1,191	979 - 1200	47 - 150	1169 -1617	285.0	7.5
Cool surplus > 150 mm	6,488	340 - 1200	151 - 705	1317 - 3299	305.3	7

Stands were allocated to one of the five climate zones based on accumulated temperature above 5°C and growing season potential water balance.

Analysis of site, soil and climatic characteristics of Sitka spruce stands

The distribution of the Sitka spruce stands by elevation bands and landscape type, and climate zones was assessed using GIS (as previously described). Soil associations were grouped by principal soil type to aid presentation of results. Missing data were described as unclassified. Summary statistics are presented in Results.

Analysis of potential productivity of Sitka spruce stands

A total of 201 sample plots were established in Sitka spruce stands between October 2006 and April 2009 covering all the major Great Soil Groups across the range of climate zones in Ireland. A two way sampling matrix of principal soil type by climate zone was developed to aid with the selection of samples for field analysis (Table 1, Appendix). In the absence of detailed soil information, the principal soil type within a soil association was used as a guide to locate Great Soil Groups in the field. Stands for field visit were randomly selected from each principal soil type and climate zone combination and were visited in the field, with a target of achieving at least three samples for each Great Soil Group and climate zone combination (stratified random sampling). Within each stand, plots were randomly allocated. Three plot sizes were used, 20 x 20 m, 20 x 10 m and 10 x 10 m (Table 7); smaller plots sizes were allocated in younger crops or where there were time constraints. A soil pit was excavated at the plot centre and the Great Soil Group was described from detailed soil profile analysis (Gardiner and Radford 1980). Elevation bands and climate zones of stands were available from the GIS system described.

Table 7: *Number of sample plots by size.*

Plot dimension *m*	*Number of plots*
20 x 20	145
20 x 10	15
10 x 10	41
Total	201

Within each plot the number and dbh (diameter at breast height) of all live stems of 7 cm dbh and greater was recorded. Top height was assessed as the mean height of the four, two or single largest dbh tree(s) per plot, in descending order of plot size. Age was obtained from management records or from ring counts. General Yield Class (GYC) was estimated from Sitka spruce top height/age curves in the Forestry Commission Yield Tables (Edwards and Christie 1981). The maximum GYC is 24 $m^3ha^{-1}a^{-1}$. In a number of stands where the GYC exceeded this value, extrapolation was used by fitting polynomials in top height and age for each yield class (6-24). The coefficients were regressed against yield class to predict the coefficients for yield classes greater than 24. Using the predicted coefficients GYC curves were derived for each yield class greater than 24.

An analysis of variance model was used to test the effects of soil type, elevation class and climate zone on productivity (SAS 2004). A national yield class, and mean yield class for each climate zone and elevation band were derived by weighting productivity values by the proportion of the area occupied by each in the sampling matrix, in order that climate zones or elevations were not over-represented in the sample (Table 1, Appendix). A survey means weighting procedure was performed (SAS 2004).

Results

Distribution of stands by elevation

Sitka spruce plantations were planted predominately below the 450 m contour (Figure 4) - only 68 ha were planted above 600 m.

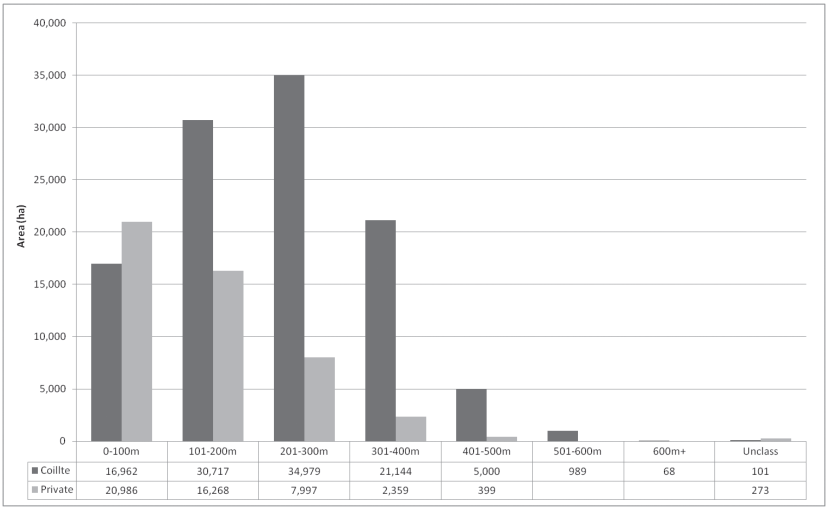

Figure 4: *Distribution of Sitka spruce stands by elevation category and ownership type.*

Privately-owned stands occurred at lower elevations (mean 122 m) than Coillte-owned stands (mean 212 m). The latter were planted over a greater range of elevations, with 25% having been established at elevations over 300 m. High elevation plantations occurred on the leeward slopes of Mount Leinster in Co Carlow, where the stand at the highest elevation was planted up to 651 m. Sitka spruce was planted in the Glenmalure valley in Co Wicklow at over 640 m, while a stand at Temple Hill in the Galtee Mountains in Co Limerick was at just over 600 m. Stands at elevations over 500 m occurred more frequently in the valleys and on mountain sides in Cos Wicklow and Dublin, and Cork on Mullaghanish and Musheramore Mountains near Ballyvourney and Macroom respectively. At these elevations, stands were generally planted on the leeward side of mountains, and in sheltered valleys in the Wicklow Mountains and other areas in the east of the country. To the west of the river Shannon, pure Sitka spruce stands were rarely planted at elevations above 400 m.

Distribution of stands by landscape type and soil association

Sitka spruce was most commonly planted on Mountain & Hill sites, with a total of 71,000 ha planted, representing 7% of the total national land area of Mountain & Hill land (Figure 5). On other landscape types, the proportion of the total area occupied by the species were respectively, Hill land (4%), Rolling Lowland (2%), Drumlin (2%) and flat to undulating lowland (1%). The species was also planted extensively on peats (Table 1, Appendix). Stands on high level and low level blanket peats, soil associations 5 and 24, occupied 38,851 ha and 15,160 ha, respectively. A full breakdown of stands by soil association is provided in Table 1 in the Appendix.

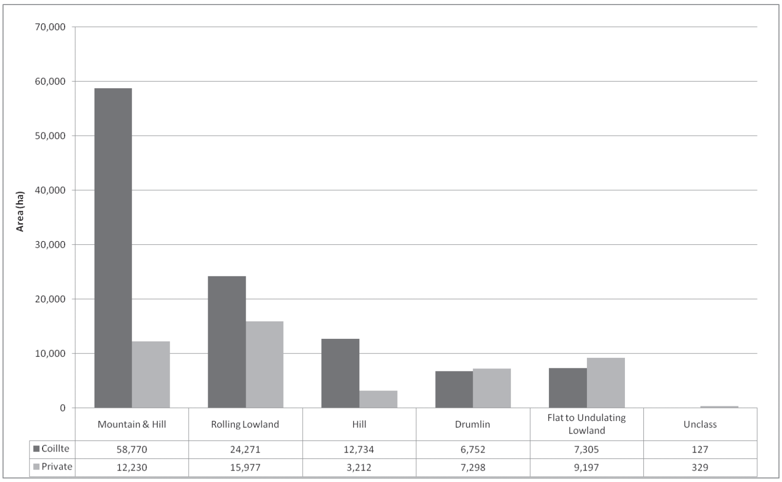

Figure 5: *The distribution of Sitka spruce stands by general landscape type and ownership category.*

Distribution of stands by climatic factors and zones

Annual rainfall where Sitka spruce was planted ranged from 678 mm at the east coast, in Cos Dublin and Louth, to 2946 mm at Molls Gap in Co Kerry, with an mean of 1391 mm. Rainfall was evenly distributed throughout the year, with 11% of the total annual average rainfall falling in January (the wettest month) and 6% falling in April (the driest month), respectively.

The mean temperature of the coldest month, February, was 3.7°C while the mean temperature of warmest month, July, was 15.7°C. The range in mean annual temperature was 4.6°C, at Molls Gap in Co Kerry (546 degree days above 5°C) to 10.7°C (2113 degree days above 5°C), just 46 km from this site at Schull in West Cork. Differences in elevation, increased exposure and lower levels of solar radiation are the main reasons for this difference. The mean annual temperature for all stands was 8.4°C, (1362 degree days above 5°C).

The water balance model predicted that the maximum potential water deficit (147 mm) occurred in Co Wexford, at a stand near Courtown Harbour in that county. The maximum surplus of rainfall over potential evapotranspiration was modelled as having occurred at Molls Gap, Co Kerry. Summary climate statistics for stands are in

Table 8. Seventy percent of Sitka spruce stands were planted in the warm temperature subzone (>1200 degree days per year). Only 7% of the area (10,601 ha) was classified as having a growing season potential water deficit. Sitka spruce was most frequently associated with the warm, surplus (0-150 mm) climate zone (46% of the total area), (Table 1, Appendix).

Table 8: *Values of modelled climate variables associated with Sitka spruce stands.*

Variable	*Mean*	*Range*	*Std dev*
Annual rainfall mm	1391	678-2947	274
Rainfall during wettest month - (January) mm	155	67-354	36
Rainfall during driest month - (April) mm	82	64-169	14
Mean Annual temperature ^oC	8.4	4.6-10.7	1
Mean temperature coldest month (February) ^oC	3.7	-0.5-6.8	1
Mean temperature warmest month (July) ^oC	15.7	10.1-14.0	1
Accumulated Temperature (degree days) >5 ^oC	1362	546-2113	214
Potential Water Surplus mm	120	0-577	80
Potential Water Deficit mm	-35	-147-0	-31

Productivity

Productivity was assessed at each of the 201 sample points. It ranged from 4 to 34 $m^3ha^{-1}a^{-1}$. The weighted mean GYC of Sitka spruce was 17.0 m^3ha^{-1} a-1 (confidence interval +/- 1.8 $m^3 ha^{-1}a^{-1}$ at the p <= 0.05 level). The weighted mean GYC for private sector stands was 21.2 $m^3ha^{-1}a^{-1}$ (confidence interval +/- 3.7 $m^3ha^{-1}a^{-1}$ at the p <= 0.05 level.

Sitka spruce productivity in relation to soil type

The highest productivities were found on grey-brown podzolic soils (mean GYC 27.6 $m^3ha^{-1}a^1$), while the lowest were associated with low level blanket peats (mean GYC 14.1 $m^3ha^{-1}a^1$ (Table 9)). General yield class varied significantly with soil type ($p\leq0.01$). Grey brown podzolics, acid brown earths, brown earths and gleys had significantly higher productivities than low level and high level blanket peats ($p\leq0.05$) (Figure 6). Stands on grey brown podzolics and acid brown earths had significantly higher productivities than those on lithosols, while crops on podzols had significantly lower productivities than those on grey brown podzolics or acid brown earths ($p\leq0.05$), (Figure 6).

Table 9: *Sitka spruce sample plots by Great Soil group, elevation and GYC.*

Number of plots	*Great Soil Group*	*Elevation (range) m*	*GYC range $m^3ha^{-1}a^{-1}$*
15	*Acid brown earth*	199 (50-354)	14-30
17	*Basin peat*	65 (41-86)	8-30
40	*Blanket peat high level*	297 (187-516)	4-30
15	*Blanket peat low level*	89 (22-146)	4-24
15	*Brown earth*	45 (9-140)	12-28
14	*Brown podzolic*	243 (31-357)	12-30
46	*Gley*	205 (33-583)	8-34
9	*Grey-brown podzolic*	92 (65-128)	22-32
6	*Lithosol*	231 (131-342)	8-24
22	*Podzol*	278 (116-457)	12-32
2	*Rendzina*	55 (34-75)	16-22

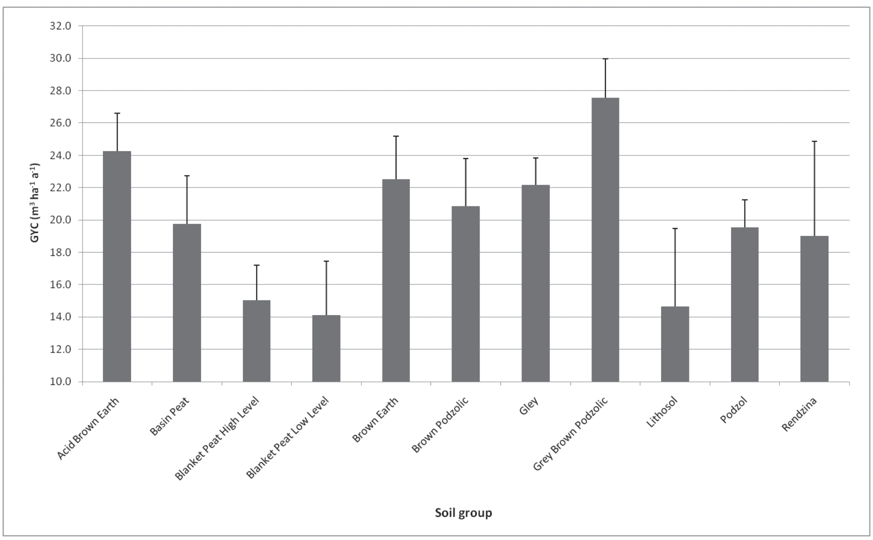

Figure 6: *Mean GYC by soil group (vertical bars are 95% confidence intervals).*

Sitka spruce productivity in relation to elevation

Productivity (GYC) varied significantly between elevation classes ($p \leq 0.05$). Yield classes were significantly lower ($p \leq 0.05$) in the 501-600 m category compared with the 0-100 m, 101-200 m, 201-300 m and 301-400 m classes ($p \leq 0.05$) (Figure 7).

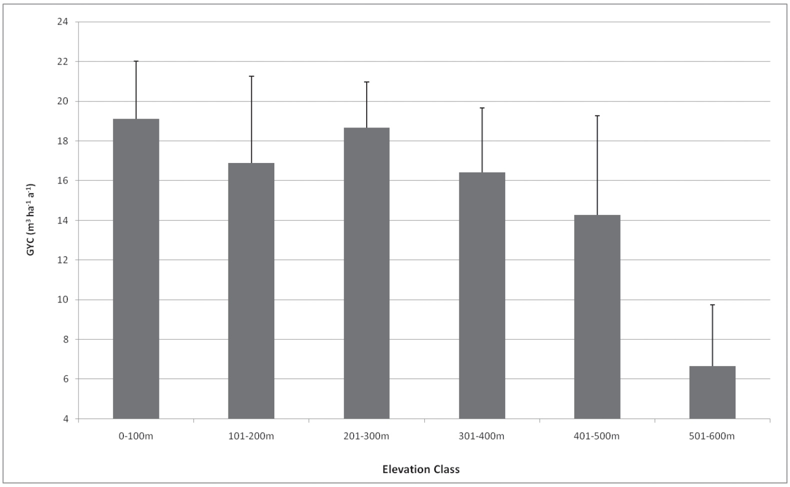

Figure 7: *Relationship between elevation and Sitka spruce productivity (vertical bars are 95% confidence intervals).*

Sitka spruce productivity in relation to climate zone

Productivity (GYC) varied significantly between climate zones ($p \leq 0.05$). The highest yield classes occurred on average in the Warm Deficit, the Warm Surplus 0-150 mm, and the Cool Surplus 0-150 mm climate zones. Productivity was significantly lower ($p \leq 0.05$) in the Cool Surplus >150 mm and the Warm Surplus >150 mm climate zones (Figure 8).

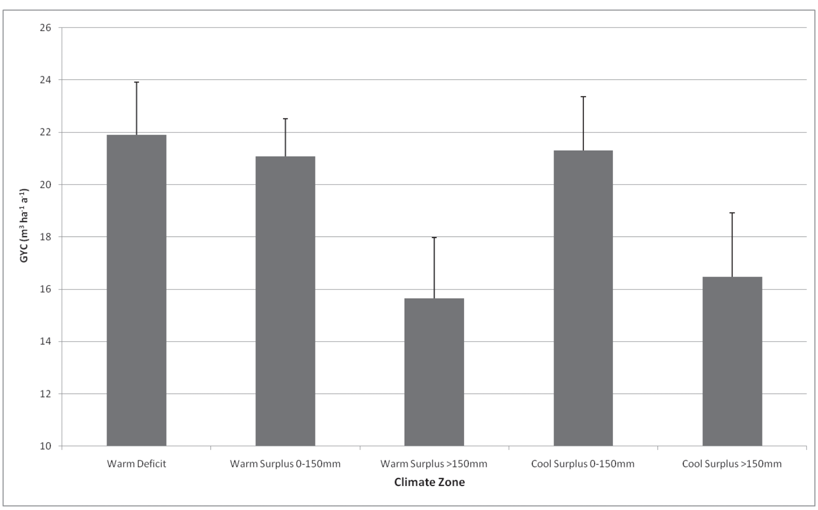

Figure 8: *Relationship between climate zone and Sitka spruce productivity (vertical bars are 95% confidence intervals).*

Discussion

Sitka spruce has been planted on a very wide range of sites in Ireland. Stands planted from 1924-1991 (inclusive) were typically established in upland areas, with 61% of stands (91,953 ha) occurring above 150 m. In those areas the species was found most frequently on high level blanket peats, and soil associations dominated by gleys and peaty podzols. Such soils are characteristic of Mountain and Hill areas (Gardiner and Radford 1980). An artefact of forest policy in Ireland is that Sitka spruce is most commonly associated with Mountain & Hill landscapes (7% of the 1.0 m ha of Mountain & Hill land), and Hill Land (4% of the 0.4 m ha in this category). The species occupies lower levels of the Rolling lowland (2% of the 2.1 m ha) and Drumlin landscapes (2% of the 0.7 m ha). The lowest level of planting has been on the Flat to undulating lowland landscapes (just 1% of the 2.5 m ha) and this mainly a result of planting in the 1980s, reflective of the greater involvement of farmers and institutions in afforestation over that period. In fact, forest policy from the 1980s has targeted better quality land at lower elevations, and a minimum productivity threshold (GYC 14 for Sitka spruce) for grant-aid purposes has been set by the Forest Service since that time. Nevertheless, the very wide range of site types on which Sitka spruce was found to grow above that threshold illustrates the ability of the species to grow successfully across a wide range of sites.

The species has been planted across a similar range of accumulated temperature classes as occurs in its natural range in western North America. At the northern end of its range at Cold Bay in north-east Alaska, annual accumulated temperature above 5°C is 577 degree days (Farr and Harris 1979). Similar accumulated temperatures were found in Ireland, and were associated with increasing elevation and wind exposure. Accumulated temperature rarely exceeded 1200 degree days above the 300 m contour in Ireland, resulting in a similar climate at these elevations as occurs from Cold Bay to Haines in Alaska (where the range in accumulated temperature above 5°C is from 577–1159) (Farr and Harris 1979). The corresponding areas in Ireland - the cool temperature subzone - are also moist even during the growing season, with potential water surpluses ranging from 48–577 mm. Accumulated temperature above 5°C in the central lowland region of the country, and lowland areas of the west and south-west of Ireland rarely exceeded 1700 per year; these areas had accumulated temperatures similar to those of southern Alaska - Ketchikan (1472) and Quotsino (1697), and Vancouver Island in British Columbia (1696). Only in coastal areas of the south and south-west of Ireland does the accumulated temperature above 5°C exceed 1700 degree days. Accumulated temperatures in these areas are similar to southern British Columbia and northern locations in Washington, where accumulated temperatures are 1942 per annum. The few areas that experience accumulated temperature above in excess of 2000 per annum were in the extreme south-west of Co Cork where accumulated temperatures above 5°C reached a maximum (2113) similar to those experienced at Otis, Oregon (2131).

The range in accumulated temperature above 5°C estimated for the Sitka spruce sites is of interest especially for provenance selection in Ireland. Sites above 300 m (25% of the Coillte and 6% of the private sites examined in this study) have less than 1200 degree days per year, and have similar accumulated temperature above

5°C as those experienced in north Alaskan stands (Farr and Harris 1979). The use of more southerly provenances of Sitka spruce from southern British Columbia and Washington below the 300 m contour (where 75% of stands were exposed to accumulated temperatures above 5°C of 1200 or more per annum) in subsequent restocking of sites after clearfell or for afforestation purposes would seem to be a wise decision. Washington provenances may be the most appropriate in the south and potentially Oregon provenances in the extreme south-west of the country. Recent results from Irish Sitka spruce provenance trials seem to support this viewpoint, with recommendations encouraging the planting of Washington provenances of Sitka spruce (Thompson et al. 2005, Pfeifer 2009).

In terms of growing season potential water balance, the model showed that the maximum deficit between April and August occurred in the east and south-east of the country. The danger of drought during the growing season may not be a major concern at present for Sitka spruce, as the species is more commonly planted outside drought prone areas, with only 7% of stands on sites classified as having a growing season potential water deficit (ranging from 146 mm to 0 mm from April to August). In the light of climate change predictions of drier summers, increases in growing season water deficits are likely, resulting in an increase in severity and duration of growing season potential water deficits. For Sitka spruce stands planted after 1991 (outside the study scope), or for new afforestation in these drier areas, water deficits during the growing season may be a concern on soils with low available water capacities. Almost 24% of the land area of Ireland is classed as having some sort of growing season potential water deficit. It must be stressed that the range of climate data used was based on the period 1961–1990.

The most productive Sitka spruce stands, achieving productivity in excess of 27 $m^3ha^{-1}a^{-1}$, were found on free draining grey-brown podzolics. Sitka spruce requires a moderately fertile soil (Miller and Miller 1987). It needs relatively high amounts of available calcium, magnesium and phosphorus, and grows best where soils are derived from parent materials rich in calcium and magnesium (Krajina 1969). Grey-brown podzolics, which are derived from limestone, satisfy the nutrient requirements of the species. Productivities on acid brown earths, brown earths and brown podzolics were also high. These soils, which are moderately fertile, occurred at low to medium elevations: acid brown earths and brown podzolics on lowland to hill areas, with brown earths occurring on lowland areas. These results agree with the findings of Day (1958), who in a study of Sitka spruce in British Columbia, observed that the best development of the species was on deep, moist, well-aerated soils. Average GYC values for gley soils were impressive, with values in excess of 22 $m^3ha^{-1}a^{-1}$. This productivity is similar to those observed by Bulfin et al. (1973) on gley soils in Leitrim. In a later work, Bulfin (1987) indicated that these gleys had a high afforestation potential. The high growth potential of Sitka spruce on moist and nutrient rich sites has been confirmed by measurements of growth rates within its natural range in British Columbia (Green and Klinka 1994, Omule and Krumlik 1987). The productivity of Sitka spruce on cutaway basin peats, GYC 20 $m^3ha^{-1}a^{1}$, concur with the findings of Carey et al. (1985), and indicate the potential of the species on cutaways, once adequate nutrition is provided at establishment. Podzols and peaty podzols are also very suitable for Sitka spruce with an average productivity in excess of 20 $m^3ha^{-1}a^{-1}$. A surprising result was the higher productivity of stands on high level blanket peat (GYC 16) compared with low level blanket peats (GYC 14). The contributing factor may be poorer drainage on flatter, deeper low level peats. Poor drainage has been shown to contribute to poor growth of Sitka spruce (Odekoven, 1957). On lithosols productivity was relatively low (GYC 14). The poor growth on such sites soils may also be related to their exposed nature.

The effect of elevation on productivity was only significant above the 500 m contour, with no significant differences in growth below that level. These results concur with research carried out in Scotland (Worrell 1987, Worrell and Malcolm 1990), where the effect of elevation in reducing general yield class was more pronounced at higher elevation and northerly locations. This effect is probably explained by the more adverse climatic conditions that are associated with high elevation northerly sites, as elevation may be regarded as a composite indicator of climatic conditions. On high altitude sites, Malcolm and Studholme (1972), Worrell (1987) and Worrell and Malcolm (1990) found that productivity decreased with increasing elevation, by an average of 3.0 to 4.0 $m^3ha^{-1}a^{-1}$ per 100 m. Productivity was also higher at inland or southern sites than at coastal or northern sites. Results from this study indicate that the effect of elevation on productivity resulted in mean GYC declining by on average just over 2 $m^3ha^{-1}a^{-1}$ from 201-300 m to 301-400 m and from 301 to 401-500 m. The decline in yield class was much more pronounced at the higher elevation range, declining by on average 7.6 $m^3ha^{-1}a^{-1}$ for the 501-500 m elevation, class compared with the 401-500 m elevation class (Figure 7).

This compares with Malcolm and Studholme (1972) who found that in Britain Sitka spruce productivity declined by an average of 6.6 $m^3ha^{-1}a^{-1}$ per 100 m increase in elevation over 450 m. Indications are that the rate of decrease in productivity of Sitka spruce in Ireland may be higher over similar ranges in elevation than in Britain, perhaps the adverse climatic conditions are more severe in Ireland than in Britain for higher elevations with higher average windspeeds. Increasing elevation had no significant impact on productivity at lower elevations. Similar findings have been reported by MacMillian (1991) and Hassall et al. (1994) in Scotland. The former reported average decreases of 0.8 $m^3ha^{-1}a^{-1}$ per 100 m increase in elevation on sites ranging from 15 to 333 m, while the latter study reported average decreases of 1.0 $m^3ha^{-1}a^{-1}$, for sites ranging from 30 to 180 m. Similar results have been found for Douglas fir on sites less than 267 m in elevation in Ireland (Dunbar et al. 2002) and on better quality sites less than 350 m in elevation in Scotland (Tyler et al. 1996). This could be explained by the fact that climatic gradients are lower in lowland areas compared with uplands, and so other limiting factors such as soil fertility play a larger part in influencing crop productivity.

The effect of climate zone on productivity was significant, with lower yields encountered on the cool surplus >150 mm and the warm surplus >150 mm climate zones compared to the other climate zones. The lower yield classes appear to be associated with areas with excess moisture, rather than areas with low accumulated temperatures, as there was no difference between the cool surplus 0-150 mm and the warm surplus 0-150 mm climate zones. The temperature gradient in Ireland is without the extremes of temperature found in continental North America, Europe or even Britain; probably an explanation of why it had did not have a significant effect on productivity. The difference in mean annual temperature, mean February temperature and mean July temperature between the coldest and warmest locations in Ireland is low, at only 6.1, 6.3 and 3.9 ºC respectively (Table 8).

Variability in climate in Ireland is mostly associated with rainfall, with annual values ranging from 678 to 2947 mm, with the highest levels in the west and upland areas of the country. Climate zones with a surplus >150 mm of rainfall over precipitation tend to have poorer soils, predominately blanket peats, lithosols and peaty podzols (Table 1, Appendix). Sitka spruce productivity in the warm deficit climate zone was on average the highest observed, 22.4 $m^3ha^{-1}a^{-1}$. A cross section of all soils were sampled in the warm deficit zone, these soils were acid brown earths, brown podzolics, basin peats and gleys. It seems that the establishment of Sitka spruce plantations has largely has been confined to soils with high available water storage capacities or soils with high seasonal water tables. The maritime climate of Ireland limits the severity of potential growing season water deficit, thus the impacts of water deficits on Sitka spruce productivity is minimal on soils with sufficient water storage capacity.

Conclusion

Sitka spruce has a wide climatic and edaphic amplitude in Ireland, with plantations growing from sea level right up to 650 m, and across a wide range of soils. It has also been successfully established across a range of sites with widely varying accumulated temperature, from 540 to 2000 degree days, showing it is tolerant of low temperature associated with exposure and elevation. Productivity does however decline above 400 m, with sharp reductions over 500 m. The economic planting limit (GYC 14) is likely to be between 400-500 m in sheltered valleys in the east of Ireland, and at a lower elevation, between 300–400 m in the west and northwest.

Bearing in mid the ranges found for climatic variables, the use of southern British Columbia, Washington and indeed Oregon provenances should be further encouraged in Ireland, given the similarity of climate in Ireland (below 300 m) to the areas referred to.

Higher productivity can be achieved by targeting certain soils, which, having been used for pasture and arable crops, offer excellent potential for the species, affording as well the potential for reduced rotation length and a shorter payback on investment. On peats productivity was satisfactory on cutaway basin peats, and to a lesser extent on high level blanket peats. However spring frost may result in poor survival on such sites. Productivity was poorer on low level blanket peats, possibly due to poor drainage and low nutrient levels.

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Appendix

Table 1: *Sampling matrix showing the distribution of Sitka spruce stands by climate zone and soil association (soil associations have been grouped by principal soil types, with percentage of the principal soil within each association in brackets).*

Group	*Soil Assoc(s)*	*Principal Soil Type*	*Associated Soils*	*Principal Soil in Association*
				%
1	12, 13,14, 16,17,19,29	Acid Brown Earth	Gleys, Podzols, Grey Brown Podzolics, Peaty Gleys, Brown Podzolics, Interdrumlin Peat, Regosols	70 – 90
2	44	Basin Peat		100
3	5	Blanket Peat (High Level)		100
4	24	Blanket Peat (Low Level)		100
5	6, 8, 9, 15, 20	Brown Podzolics	Gleys, Podzols, Blanket Peats, Acid Brown Earths, Podzols	60 - 80
6	10, 28, 30, 31, 32, 34, 35, 36,37,38	Grey Brown Podzolics	Gleys, Interdrumlin Peats, Peaty Gleys, Brown Earths, Basin Peats, Podzols	50 - 80
7	11, 21, 22, 25, 26, 27, 39, 40, 41, 42, 43	Gleys	Acid Brown Earths, Interdrumlin Peat and Peaty Gleys, Brown Earths, Peats, Brown Earths, Grey Brown Podzolics	50 - 90
8	4, 23	Lithosols	Rock Outcrop and Peats, Blanket Peats, Peaty Podzols	70 – 80
9	2	Peaty Gleys	Blanket Peats, Peaty Podzols	70
10	1	Peaty Podzols	Lithosols, Blanket Peats	75
11	18	Podzols	Gleys and Peats	70
12	7	Rendzinas + outcropping Rock	Lithosols, Shallow Brown Earths	90
13	33	Shallow Brown Earths and Rendzinas	Grey Brown Podzolic , Gleys and Peats	60
	Unknown			
			Total	

Warm Deficit	*Warm Surplus 0-150 mm*	*Warm Surplus >150 mm*	*Cool Surplus 0-150 mm*	*Cool Surplus >150 mm*	*Unclassified*	*Total*
ha						
1,712	1,405	83	5	6	44	3,256
1,850	5,447	6	0	0	0	7,302
18	8,857	14,741	515	14,721	0	38,851
0	5,538	8,730	0	877	15	15,620
3,290	11,782	402	2,389	715	42	18,620
1,653	5,340	94	104	18	9	7,219
1,579	24,769	2,952	406	2,649	55	32,406
67	642	761	561	2,351	25	4,406
0	1,690	73	471	380	0	2,615
364	5,210	6,556	4,955	8,458	38	25,581
19	642	188	60	89	0	998
10	356	141	0	44	0	550
26	702	26	0	26	0	780
19	246	19	30	0	182	496
10,601	72,627	34,773	9,496	30,334	410	158,241