Modelling and mapping the potential productivity of Sitka spruce from site factors in Ireland.

Niall Farrelly[a], Áine Ní Dhubháin[b], and Maarten Nieuwenhuis[b]

Abstract

The main objective of this study was to quantify the potential productivity of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland. Productivity data from 201 Sitka spruce stands were used to relate general yield class (GYC) to low resolution digitised data (climate maps, soil and subsoil maps), and easily assessable site quality variables (site and vegetation classifications). Three models were derived that explained 45-52% of the variation in GYC. A spatial model was used to derive spatial predictions of productivity and map the potential productivity of Sitka spruce throughout Ireland in a Geographical Information System (GIS). This model predicted that 73% or 5.103 million ha of the total land area in Ireland was capable of producing Sitka spruce growth of yield class 14 or greater. Furthermore, 62% of the total land area could potentially result in GYC 20 or higher yields. The results of the analysis indicated that significant potential exists for forestry development on marginal agricultural land where forestry expansion may not necessarily be in conflict with the achievement of growth targets from other agricultural subsectors (e.g. dairy and beef). A practical model was also developed, which may serve as a guide to evaluating the potential productivity of suitable sites for afforestation. Typically the confidence limits for fields with wet or dry grassland were ± 2.0 to 2.8 $m^3ha^{-1}yr^1$ and blanket bog was ± 2.4 to 2.9 $m^3ha^{-1}yr^{-1}$. A forecasting model, developed to derive predictions of productivity on forested land, might also be used to forecast timber yields.

Keywords: *Sitka spruce, Productivity models, Land-use, Spatial modelling, Site classification*

Introduction

At the beginning of the twentieth century only 1% of the land area of the Ireland was under forest (OCarroll 1984). A programme of state afforestation was introduced in 1922, but expansion was limited to sub-marginal and marginal agricultural land to avoid competition with agricultural production (Gray 1963). Sitka spruce (*Picea sitchensis* (Bong.) Carr.) was one of the exotic conifers used in the afforestation programme, and it quickly established itself as the workhorse of Irish forestry, being a highly adaptable species suited to the wide range of climatic conditions on the sites being afforested. The species grew well on difficult site conditions such as wet ground, exposed grassy areas, as well as on mountain and hills ranging from 150 to 550 m in elevation and on wet drumlin soils (O' Flanagan and Bulfin 1970; Bulfin et al. 1973; Joyce and OCarroll 2002).

Since the 1980s, the range of site types being afforested has expanded to include better quality enclosed land which had previously been in agricultural usage, as the

[a] Corresponding author: Forestry Research, Mellows Centre, Athenry, Co Galway (niall.farrelly@teagasc.ie).
[b] UCD Forestry, School of Agriculture and Food Science, University College Dublin, Belfield, Dublin.

most recent afforestation schemes are targeted to encourage private landowners to convert less productive agricultural land to forestry (Farrelly 2007). The strategic plan for forestry in Ireland, published in 1996, aimed to increase forest cover in Ireland to 17%, with a total productive forest area of 1.2 million ha by 2030 (Anon. 1996)[1]. The Irish Government, with co-financing for a period from the European Union, has since 1980, provided grants and premiums to incentivise the establishment of new forests. The prerequisite for receipt of grant aid is that the land must be capable of achieving a minimum growth rate of 14 $m^3ha^{-1}yr^{-1}$ for Sitka spruce.

Currently Sitka spruce is the most important species in Irish forestry occupying 52.3% of the total forest estate, or 327,000 ha, and accounting for 53% of all afforestation in 2010 (Forest Service 2010). Despite this widespread use of Sitka spruce in Irish forestry, relatively few studies have examined the growth potential of the species, the nature of relationships between its productivity and site quality variables, and the factors that limit the growth of the species in Ireland. Much of the previous research conducted in Ireland focused on measures to ensure successful plantation establishment or remedial measures to assist growth (i.e. cultivation, drainage and fertilization research experiments and trials) or the identification of the most appropriate provenances to plant. Other soil-site-yield studies focussed on quantifying the productivity of the species in relation to marginal agricultural land (Bulfin et al. 1973) or using process-based models to predict the relative sensitivity of forest production in Ireland to site quality and climate change (Goodale et al. 1998).

The prediction of productivity has become increasingly important in Ireland for: a) determining the suitability of land for afforestation to enable future forestry expansion under Government policy objectives; b) providing an objective means of assessing and comparing the potential productivity of land for forestry development; and c) aiding silvicultural decision making, forest management planning and production forecasting on forested sites. Several new studies have addressed Sitka spruce productivity, including Broad and Lynch's (2006) work on modelling of height growth, Farrelly's (2011) study on the relationship between site quality and productivity, and Farrelly et al.'s (2011a; 2011b) development of models to predict site index from site quality measures. However, while these latter models may have good statistical attributes, they rely on less readily available data (i.e. available magnesium, as well as soil moisture and nutrient regime). The development of practical models, only using variables that are easily available would make models more accessible to forestry practioners, to assist in site selection for afforestation or for production forecasting. Furthermore it is not possible to use such models to generate spatial predictions of productivity as many of variables are not yet digitized in a GIS. The development of practical models, using variables that are more readily available to forestry practitioners, would assist in site selection for afforestation or for production forecasting. Previous attempts to develop productivity maps used mean productivity values for soil series (Bulfin et al. 1973) or for soil classifications, which were then applied to mapped soil groups (Farrelly et al. 2002; Farrelly 2003).

[1] Forest cover in the Republic of Ireland in 2010 was 10.8% of the land area or 745,000 ha (Forest Service 2010).

The aims therefore of this study were (i) to derive productivity models for Sitka spruce to provide information for future afforestation projects; and (ii) assess the potential productivity of the species in Ireland, the area of land that is eligible for receipt of afforestation grant-aid, and the potential of the species in relation to different agricultural land-use types being afforested.

Materials and Methods

Sampling strategy

In total, 201 stands (greater than 1 ha in size) were visited between October 2006 and April 2009, covering the entire range of pure Sitka spruce stands, both publicly- and privately-owned, that were even-aged, uniformly stocked, and at post establishment stage in the Republic of Ireland, as described in Farrelly et al. (2009). The soil of each site was classified into one of the 41 soil associations from the General Soil Map of Ireland (Gardiner and Radford 1980). A soil association 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). Soil associations were then grouped into 13 soils groups, based on the principal soil types in each association (Table 1). Soil parent material was also taken from the General Soil Map of Ireland (Table 3). The sites were then stratified into five climate zones, based on annual accumulated temperature sum >5^{o}C and growing season potential water balance (see Farrelly et al. 2009 for further details). Sites were then randomly selected from each soil group and climate zone combination (stratified random sampling) to cover as many soil types across five climate zones as time and resources allowed. These sites were sampled in more detail, as described in the next section.

Data collection

The sites selected for field visits contained even-aged stands, uniformly stocked and were aged from 16 to 83 years (mean 31.4 years). Within each stand, sample plots were randomly located. Sample plots were 0.04 ha (20 x 20 m) in size; smaller plots of 0.02 ha (20 x 10 m) and 0.01 ha (10 x 10 m) were used in younger unthinned crops. The latitude and longitude coordinates for the centre of each site were determined using a Global Positioning System (GPS). Site elevation was determined from a GIS-based Digital Elevation Model (DEM), which had horizontal and vertical resolutions of 25 and 1 m, respectively.

Site classification information was derived using Ordnance Survey of Ireland (OSI) 6 inch to 1 mile (1:10,560) maps. These maps are furnished with historical information pertaining to vegetation and field boundaries. Using these maps, each site was classified into four land-use types according to OCarroll's (1975) site fertility classification, as follows: (A) fields and ornamental ground; (B) presence of furze (*Ulex* spp.); (C) rough pasture with or without outcropping rock; and (X) old woodland.

Table 1: *Soil groups used in the study with soil associations, associated soils, the number of samples and actual soils sampled in forest plots (number in parenthesis).*

Soil Group	Soil Assoc(s)	Soils[1]	No. Samples	Actual sampled forest soils (number)
1	12, 13, 14, 16, 17, 19, 29	Acid Brown Earth, Gley, Podzol, Grey Brown Podzolic, Peaty Gley, Brown Podzolic, Interdrumlin Peat, Regosol	21	Brown Earth (6), Gley (6), Podzol (5), Brown Podzolic (3), Lithosol (1)
2	44	Basin Peat	10	Basin Peat (10)
3	5	Blanket Peat (High Level)	23	Blanket Peat (13), Gley (6), Brown Earth (2), Brown Podzolic (1), Lithosol (1)
4	24	Blanket Peat (Low Level)	9	Blanket peat (8), Gley (1)
5	6, 8, 9, 15, 20	Brown Podzolic, Gleys, Podzol, Blanket Peat, Acid Brown Earth, Podzol	21	Brown Podzolic (4), Blanket Peat (6), Podzol (4), Gley (4), Brown Earth (3)
6	10, 28, 30, 31, 32, 34, 35, 36, 37, 38	Grey Brown Podzolic, Gley, Interdrumlin Peat, Peaty Gley, Brown Earth, Basin Peat, Podzol	24	Grey Brown Podzolic (8), Basin Peat (5), Brown Earth (4), Gley (4), Brown podzolic (1), Podzol (1), Rendzina (1)
7	11, 21, 22, 25, 26, 27, 39, 40, 41, 42, 43	Gleys, Acid Brown Earth, Interdrumlin Peat and Peaty Gley, Brown Earth, Peat, Brown Earth, Grey Brown Podzolic	20	Gley (9), Blanket Peat (9), Basin Peat (1), Grey Brown Podzolic (1)
8	4, 23	Lithosol, Rock Outcrop and Peat, Blanket Peat, Peaty Podzol	16	Blanket Peat (7), Podzol (3),Gley (2), Lithosol (2), Brown Earth (1), Brown Podzolic (1)
9	2	Peaty Gley, Blanket Peat, Peaty Podzol	8	Peaty Gley (3), Blanket Peat (2), Peaty Podzol (2), Brown Earth (1)
10	1	Peaty Podzol, Lithosol, Blanket Peat	21	Podzol (7), Blanket Peat (7), Brown Podzolic (3), Gley (2), Brown Earth (1), Lithosol (1)
11	18	Podzol, Gley and Peat	5	Blanket Peat (2), Brown Podzolic (1), Gley (2)
12	7	Rendzina & outcropping Rock, Lithosol, Shallow Brown Earth	7	Gley (4), Lithosol (1), Brown Earth (1), Blanket Peat (1)
13	33	Shallow Brown Earth and Rendzina, Grey Brown Podzolic, Gley and Peat	16	Brown Earth (11), Gley (3), Rendzina (1), Brown Earth (1)
		Total	201	

[1] The first soil listed is the principal soil type, which occupies 50 – 100% of association; other soils listed are associated soils.

These maps also provided information on previous land-use[2], based upon the presence (or absence) of enclosures (field boundaries) for each site. Sample plots were then classified into their original habitat type prior to afforestation (Irish vegetation classification - Fossit 2000), using a combination of ground vegetation taken within the plot, from sub-compartment boundaries or from the edge of plantations.

In each plot, the height and age of four, two or the single largest dbh tree(s) per 0.04 ha, 0.02 ha and 0.01 ha plot, respectively, were measured. Productivity was estimated by General Yield Class (GYC; max. m.a.i. $m^3ha^{-1}yr^{-1}$) using top height age curves for Sitka spruce (Edwards and Christie 1981).

Digitised site data

A number of low to medium resolution GIS digitised datasets were available to derive site quality variables for use in the study. These included all the climatic surfaces (1 km^2) raster grids for Ireland (Sweeney and Fealy 2003), which were used to derive mean annual growing season (April-September) summer and winter precipitation and temperature, as well as mean annual and growing season global solar radiation for all plots. Mean annual growing season degree-day sums >5°C were derived from the primary monthly temperature maps (Farrelly et al. 2009). Mean annual windspeed data were available from the National Wind Atlas of Ireland (Anon. 2003). Soil associations, soil groups and parent material was available from the General Soil Map of Ireland (1:575,000 scale; Gardiner and Radford 1980).

A GIS National Habitat Map of Ireland was available as a 25 x 25 m^2 raster (pixel based) map (Fealy et al. 2009). This map of habitat classes includes details about cutover bogs, upland and lowland blanket bogs, wet and dry grassland, wet and dry heaths, fens, forests, urban areas and water bodies, and was generated using thematic landcover mapping techniques (Loftus et al. 2002) augmented by using parent material, soil and climate boundaries at a nominal scale of approx. 1:100,000 (Fealy, R.M. 2011 pers. comm.).

A potential agricultural land-use map was also derived from the General Soil Map of Ireland, based on Gardiner and Radford's (1980) grouping of the 44 soil associations into six land-use classes. The classification grouped soils based on their suitability for Irish agriculture into six land-use categories as follows: Extremely Limited, Very Limited, Limited, Somewhat Limited, Moderately Wide and Wide land-use.

The modelling approach

Regression models to predict GYC were developed using the data from all sites (n = 201) to produce a spatial model [1], which included all digitised data (all climate, elevation, parent material, soil groups and habitat type); and a practical model [2] which included all available site data. Multiple regression analysis, using stepwise, forward and backward elimination was employed. Main effects and two-way interaction effects were included in the analysis, but higher-order interactions were

[2] This classification is used by the Forest Service as an indicator of previous agricultural use and has been linked to fertility status. Afforestation on enclosed land attracts a higher level of grant-aid than on unenclosed land.

excluded. Variables that had the least significant ($P<0.05$) effect in the type III sums of squares analysis were removed sequentially from the model. The goodness of fit statistics were further checked by comparing the log-likelihood difference (under maximum likelihood for fixed effects) with the variable included and removed (difference distributed as chi-square with degrees of freedom equal to the difference in the number of parameters fitted). The most appropriate model(s) and the model with the best explanatory power with the minimum number of variables was selected. The statistical validity of the modelling procedures was examined by checking the distribution of residual error variation, and that there was no evidence that any of the underlying assumptions had been violated.

Generating spatial predictions of GYC

To generate spatial predictions of general yield class, the spatial model [1] was used. The digitised information was analysed and processed using ArcGIS 9.3 (ESRI 2008). Firstly, digitised data were converted to raster grids (pixel maps) made up of 111,750,262 pixels at 625 m^2 spatial resolution. Then the value for the intercept of the model (i.e. the constant) was applied to all grid cells. The regression equation was then applied using ArcGIS, by multiplying the values of the predictor variables by their relevant coefficients to derive a new raster layer. The ArcGIS overlay function was used to construct a new data layer (i.e. the GYC layer) based on the regression model and the digitised data (Figure 1).

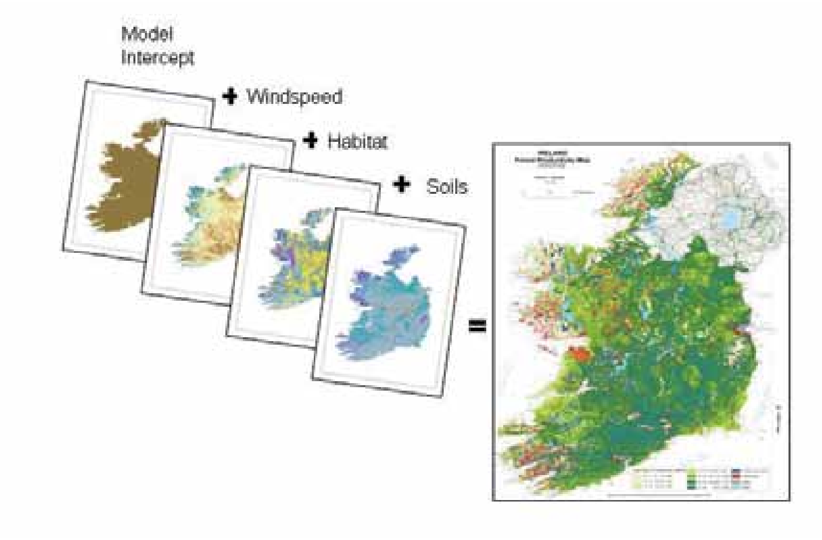

Figure 1: *Schematic representation of the generation of spatial prediction of GYC and the development of a national potential forest productivity map involves merging of spatial datasets of model intercept, windspeed, habitat and soils.*

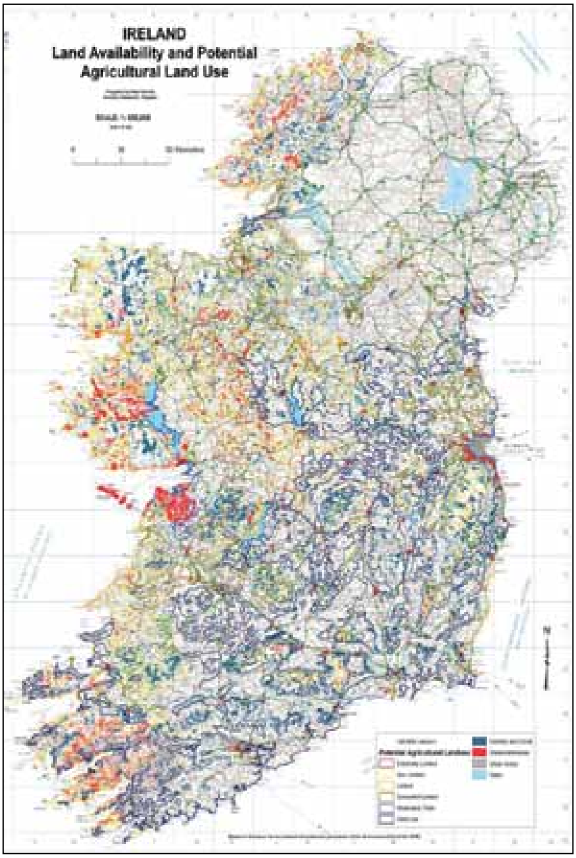

Figure 2: *Land availability for afforestation and potential agricultural land-use, courtesy of Gardiner and Radford (1980).*

Assessment of land eligible for grant aid and potential productivity

The GYC layer was overlain with the National Habitat Map of Ireland to produce a potential forest productivity map. The mean GYC for all plantable areas (all areas except urban, water, islands, bare rock, rocky complex, intact raised bogs, wetlands, coastal habitats, unreclaimed fens, salt marsh, sand, and existing forests) and the level of land availability for forestry were then calculated. In addition, the GYC layer was overlain with the potential agricultural land-use map to derive estimates of the mean GYC of Sitka spruce in the six potential agricultural land-use categories (Figure 2), as described earlier.

Results

GYC ranged from 4 $m^3ha^{-1}yr^{-1}$, on a wet, nutrient very poor site on unenclosed low level blanket peat (histosol) in the north west to a maximum of 34 $m^3ha^{-1}yr^{-1}$ on a very

Table 2: *Climate and site based variables assessed in the study, with proportion of variability in GYC explained by each variable (R^2_{adj}) and the significance of its relationships with GYC (P value).*

Variable	Units	Mean	Range	R^2_{adj}	P value
GYC	$m^3ha^{-1}yr^{-1}$	19.7	4.0 – 34.0		
Elevation (m)	m	195.3	9.0 - 583.0	0.11	<0.0001
Latitude	°N	53.2	52.0 – 55.2	0.02	0.025
Longitude	°W	7.8	6.1 – 9.8	0.00	0.0935
Annual mean windspeed	ms^{-1}	7.3	5.6 - 9.9	0.22	<0.0001
Annual mean temperature	°C	8.3	5.2 - 10.1	0.06	<0.0005
Growing season temperature	°C	11.4	8.5 – 12.9	0.07	<0.0001
Winter temperature	°C	3.9	0.4 – 5.9	0.04	0.0031
Spring temperature	°C	7.2	4.1 - 8.8	0.05	0.0009
Summer temperature	°C	13.4	10.6 – 14.8	0.08	<0.0001
Autumn temperature	°C	8.9	5.7 – 10.8	0.05	0.0007
Mean annual sum degree days >5°C	Day degrees	1348.9	706.9 - 1872.5	0.06	0.0002
Growing season sum degree days >5°C	Day degrees	1172.1	668.8 – 1453.0	0.07	0.0001
Annual global solar radiation	MJ/m^2	1.114×10^{-8}	9.412×10^{-7} - 1.286×10^{-8}	0.02	0.0194
Growing season global solar radiation	MJ/m^2	0.848×10^{-8}	7.122×10^{-7} -0.989×10^{-8}	0.02	0.0260
Annual mean precipitation	mm	1291.6	802.6 - 2044.2	0.14	<0.0001
Growing season precipitation	mm	544.9	366.0 – 834.7	0.13	<0.0001
Winter precipitation	mm	381.7	216.5 – 598.9	0.13	<0.0001
Spring precipitation	mm	273.3	178.4 – 414.1	0.12	<0.0001
Summer precipitation	mm	261.1	168.2 – 409.5	0.13	<0.0001
Autumn precipitation	mm	375.5	228.8 – 626.6	0.15	<0.0001

R^2_{adj}, Adjusted R^2.

moist, nutrient rich site on an old woodland site in the south east (Table 2). All the climatic variables tested showed significant relationships with GYC, with windspeed showing the strongest relationship. Of all the site factors examined, the strength of the relationship increased with the quality of the data used, with high resolution data providing best results. The field assessed habitat type category showed the strongest relationship with GYC, accounting for 38% of the variation (Table 3).

GYC Models

A spatial model [1] was developed following the stepwise regression procedure; this model explained 49% of the variation in GYC (Table 4). When all the site variables were tested, following the stepwise regression procedure, it was shown that wind speed, fertility class and habitat type were the key variables in this model. A practical model [2] which included these variables accounted for 52% of the variation in GYC (Table 4). The effect of fertility class varied significantly with wind speed, with GYC decreasing more rapidly on sites classed as rough pasture with or without outcropping rock (class C sites) for a given increase in windspeed ($P<0.05$) than on other site types. Since this habitat type model may be difficult to use in practice, a third model, the forecasting model [3], was developed. This model included windspeed, soil parent material and fertility class, and explained 47% of the variation in GYC.

Table 3: *Qualitative site quality variables recorded with proportion of variability in GYC explained by each variable (R^2_{adj}) and the significance of its relationships with GYC.*

Variable	Categories	Source of data (scale)	R^2_{adj}	P value
Soil Group[1]	Acid Brown Earth, Basin Peat, Blanket Peat High Level; Blanket Peat Low Level, Brown Podzolic, Gley, Grey Brown Podzolic, Lithosols and Rock, Peaty Gley, Peaty Podzol, Podzol, Rendzina, Shallow Brown Earth	General Soil Map (1:575,000)	0.19	<0.001
Parent Material	Sandstone and Shale, Basin Peat, Blanket Peat High Level, Blanket Peat Low Level, Granite, Mixed Granite-Rhyolite-Sandstone, Limestone, Mixed Limestone-Shale-Sandstone, Mica-Gneiss-Quartz-Sandstone, Shale, Shale-Schist-Sandstone, Sandstone, Sandstone-Granite-Mica Schist, Sandstone-Shale	General Soil Map (1:575,000)	0.20	<0.001
Closure type	Enclosed, Unenclosed	OSI Maps (1:10560)	0.27	<.0001
Site Fertility class	(A) Fields and ornamental ground, (B) Furze (Ulex spp.), (C) Rough Pasture with or without outcropping rock, and (X) Woodland	OSI Maps (1:10560)	0.32	<.0001
Habitat type	Cut bog, Fen, Dry grassland, Wet grassland, Dry heath, Wet heath, Lowland blanket bog, Upland blanket bog, Rocky complex, Old woodland, Scrub	Field survey (Plot)	0.38	<.0001

[1] Only principal soil types have been listed; associated soils are listed in Table 1. R^2_{adj}, Adjusted R^2.

Table 4: *Prediction models for Sitka spruce general yield class (GYC) using windspeed, habitat type and soil group (spatial model [1]), windspeed, site fertility class and habitat type (practical model [2]) and windspeed, site fertility class and parent material (forecast model [3]) (N = 201).*

No.	Model Name	Model	R^2_{adj}	SEE
1	Spatial	GYC = 41.85- 3.41(Wspd) + 0.62(CB) + 4.66(DG) + 5.0(DH) + 9.42(FEN) – 4.98(LBB) + 7.09(OW) + 0.46(RC) + 1.44(SC) + 0.76(UBB) + 5.40(WG) + 0.36 (ABE) – 2.93 (BP) – 2.57 (BPHL) -0.05 (BPLL) – 1.48 (BPOD) –1.64 (GLEY) + 1.32 (GBP) –2.39 (LITH) – 3.49 (PGLEY) + 0.09 (PPOD) +4.52 (POD) –2.18 (REND)	0.49	4.80
2	Practical	GYC = 37.72 -3.16(wspd) – 38.22(A) – 4.05(B) + 1.96(C) + 0.74(CB) + 5.34(DG) + 5.33(DH) + 8.15(FEN) – 4.53(LBB) + 8.32(OW) + 1.21(RC) + 5.63(SC) + 0.29(UBB) + 5.01(WG) + 6.09(wspd ×A) +0.79(wspd ×B) – 0.18(wspd × C)	0.52	4.65
3	Forecasting	GYC = 55.53 – 3.37(wspd) +0.76(A) – 3.62(B) – 5.04(C) + 0(Sandstone and Shale) – 3.37(Basin Peat) –10.54(Blanket peat High Level) – 12.76(Blanket peat Low Level) – 3.5 (Granite)-5.79(Mixed Granite-Rhyolite-Sandstone)-7.34(Limestone) – 4.6(Mixed Limestone-Shale-Sandstone) – 10.06(Mica-Gneiss-Quartz-Sandstone) – 8.95(Shale) – 6.67(Shale-Schist-Sandstone) – 12.97(Sandstone) – 4.5(Sandstone-Granite-Mica Schist) – 5.70(Sandstone-Shale)	0.47	4.91

Note that all independent variables are significant at $P < 0.05$; R^2_{adj}, Adjusted R^2; SEE, Standard error of the estimate (in $m^3ha^{-1}yr^{-1}$).

Abbreviations are as follows:

Spatial model: *Wspd*: annual mean windspeed, *Habitat Type*: CB: Cutover bog, DG: Dry grassland; DH: Dry heath, FEN: Fen, LBB: Low blanket bog, OW: Old woodland, RC: Rocky outcrops, SC: Scrub, UBB: Upland blanket bog, WG: Wet grassland, WH: Wet heath. *Soil Group*: ABE: Acid Brown Earth, BP: Basin Peat, BPHL: Blanket Peat High Level, BPLL: Blanket Peat Low Level, BPOD: Brown Podzolic, GLEY: Gley, GBP: Grey Brown Podzolic, LITH: Lithosols and Rock, PGLEY: Peaty Gley, PPOD: Peaty Podzol, POD: Podzol, REND: Rendzina.

Practical and forecast model, *Site Fertility Class*: A: Fields and ornamental ground; B: Furze (*Ulex* spp.); C: Rough pasture with/without outcropping rock.

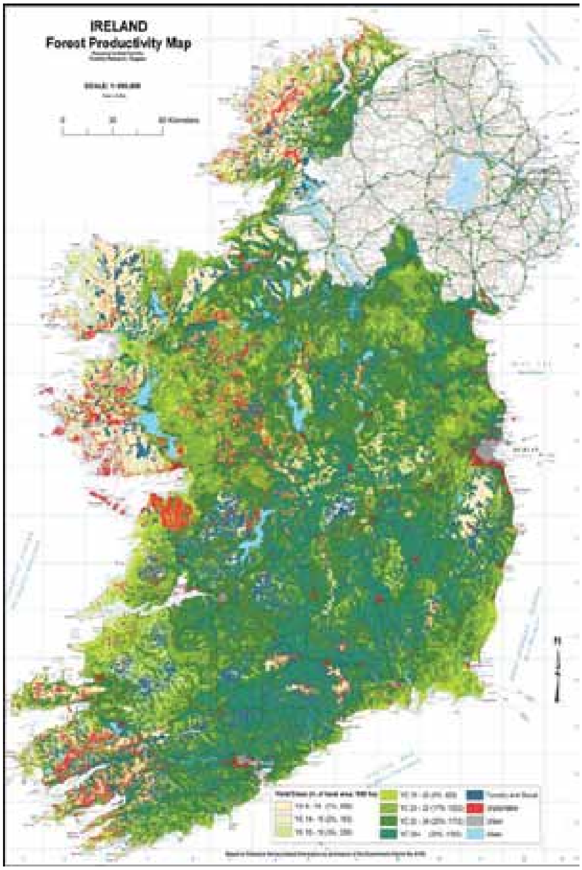

Figure 3: *Map of the potential productivity of Sitka spruce in Ireland*.

The spatial model [1] was used to derive a national forest productivity map for Sitka spruce in Ireland (Figure 3). The map indicates lower levels of productivity in the north-west, west, south-west and upland areas of the country.

Land availability and potential productivity

When the area already planted and the unplantable areas were excluded from the total land area of Ireland, 5.59 million ha (80% of the Republic of Ireland) was shown to be potentially suitable for forestry (Table 5). It is estimated that a potential 5.10 million ha of this land area could be used to grow Sitka spruce with a yield class of 14 or higher (threshold for receipt of grant-aid). Furthermore, a GYC of 20 or greater could be achieved on 4.29 million ha (62% of the total land area). On the 1.381 million ha of better quality land, this species has the potential to reach yield class 24 or greater (Table 6).

Table 5: *The maximum potential land availability for afforestation in Ireland*.

		Habitat Type	Area (ha)
		Cutover Bog	74,856
		Cutover Fen	283
		Dry Heath	181,652
		Lowland Blanket Bog	273,754
		Upland Blanket Bog	214,481
		Wet Heath	78,685
	Limited potential[1]		823,711
		Dry Grassland	3,266,859
		Wet Grassland	1,503,499
	Large potential		4,470,358
Total plantable area			*5,594,068*
	Forest and Scrub[2]		33,988
	Forestry		729,366
Total Forest and Scrub			763,354
		Bare Rock and Rock outcrop	235,907
		Intact Raised Bog	109,431
		Wetlands	34,275
		Coastal Complex	7,053
		Unreclaimed Fen	1,597
		Salt Marsh	275
		Sand	626
		Island not surveyed	7,784
		Urban/Built Land	89,015
		Water	141,005
Total unplantable area			*626,968*
		Total land area	**6,984,391**

[1] Although these areas are classed as productive, nutritional problems or environmental considerations may prohibit some of these areas from being planted. As the study considered potential rather than actual land availability, no environmental constraints were considered in the analysis.

[2] This classification covers unenclosed forest outside of managed plantations.

Table 6: *The potential productivity of Sitka spruce in Ireland classified according to grant threshold and general yield class categories.*

Productivity class	**Potential GYC ($m^3ha^{-1}yr^{-1}$)**	**Area (ha)**	**Land area (%)**
Below grant threshold (<14 $m^3ha^{-1}yr^{-1}$)	<14	457,774	7%
	14 – 16	142,683	2%
	16 – 18	235,991	3%
	18 – 20	428,721	6%
	20 – 22	1,202,136	17%
	22 – 24	1,711,730	25%
	24+	1,381,762	20%
Above grant threshold (≥14 $m^3ha^{-1}yr^{-1}$)	14+	5,103,023	73%
Productive and unproductive area	4+	5,560,798	80%
Total plantable area		5,594,068	80%

Of the 5.10 million ha that could produce a yield class of 14 or greater, a significant proportion (i.e. 38%), was classed as marginal agricultural land (Extremely Limited, Very Limited and Limited for agriculture) (Table 7). The trends in the predicted yield class reflected the quality of the land, with higher yield class values of 24 or greater predicted for the "moderately wide" and "wide" agricultural land-use types (Table 7).

Discussion

The criterion for judging the success of a productivity model is that it must be capable of explaining at least 50% of the variation in GYC from a few easily measurable variables (Blyth and MacLeod 1981b; OCarroll and Farrell 1993; Klinka and Chen 2003). The results from this study indicate that models derived from available GIS digitised data and readily assessable site factors were moderately successful in explaining the variation in the productivity of Sitka spruce. The best model (i.e. the practical model [2]) explained 52% of the variation in GYC, considerably lower than the percentage variation explained by other models for Sitka spruce developed by Pearson (1992) and Farrelly et al. (2011), but higher than models developed in Great Britain by MacMillian (1991) and Hassall et al. (1994). Increases in predictive power were evident from the inclusion of higher resolution data (i.e. fertility class, habitat type) compared to lower resolution data (i.e. principal soil type). Thus, models using local site conditions as predictors were often better at a large geographic scale than models using low resolution generalised site information (Farrelly 2011). Nevertheless two of the developed models, the spatial model [1] and the practical model [2], were adequate predictors of GYC, in that they explained c. 50% of the variation in the productivity of Sitka spruce. The forecast model [3] was less successful, explaining less than 47% of the variation in GYC, owing to the nature of the low resolution map data used.

Table 7: *The potential productivity of Sitka spruce in Ireland classified according to grant threshold and general yield class categories.*

Potential Agricultural Land use	Total Area (ha)	Forest & Scrub (ha)	Not Plantable (ha)	Plantable (ha)	≥ YC 4 Area (ha)	≥ YC 4 Mean GYC1	≥ YC 14 Area (ha)	≥ YC 14 Mean GYC5
Extremely Limited	217,579	13,960	79,922	123,697	114,719	15.5 (16)	71,676	19.2 (20)
Very Limited	1,760,416	341,300	240,975	1,178,141	1,158,877	16.0 (16)	762,186	19.3 (20)
Limited	1,322,639	165,859	49,334	1,107,446	1,106,351	21.4 (22)	1,094,061	21.5 (22)
Somewhat Limited	1,153,834	107,830	46,237	999,768	998,267	22.6 (22)	995,498	22.6 (22)
Moderately Wide	802,072	41,039	43,056	717,977	717,482	23.2 (24)	715,297	23.2 (24)
Wide	1,606,694	91,070	48,585	1,467,039	1,465,101	23.9 (24)	1,464,305	23.9 (24)
Not surveyed	7,900	116	7,784					
Urban	18,706	398	18,308					
Water	94,552	1,783	92,769					
Total Area	**6,984,391**	**763,354**	**626,969**	**5,594,068**	**5,560,798**		**5,103,023**	

The values reported refer to arithmetic averages of GYC values ($m^3ha^{-1}yr^{-1}$), values in parenthesis report nearest GYC values.

However, the requirement that the model explain at least 50% of the variation in productivity is only one criterion influencing the choice of model. If a model is to be applied in practice, ideally it should use data that are easily obtainable and rely on a small number of variables. The function of the model also will influence the choice of model, i.e. is it to guide an individual land owner as to the potential productivity of a specific site, or is it to be applied on a national or regional basis?

Application of models

The models developed in this study are generally easy to use in practice, with each having a different objective. The spatial model [1] can be used primarily to derive spatial predictions of productivity and to generate a potential forest productivity map. National statistics and shifts in regional trends can be detected using this model, which might also be useful for policy and planning purposes. It is not suitable for on-site assessment because of the lowest scale of mapping used (1:575,000; General Soil Map).

For on-site assessment, the practical model [2] is more appropriate and uses variables that are readily available to foresters (i.e. wind speed, site fertility class and habitat type). The 95% confidence limits for yield class, calculated from the standard errors associated with the practical model [2], ranged from ±1.6 to 5.8 $m^3ha^{-1}yr^{-1}$. Typically the confidence limits for (A) fields with wet grassland or dry grassland were small ± 2.0 to 2.8 and for (B) unenclosed land with blanket bog were ± 2.4 to 2.9 $m^3ha^{-1}yr^1$, as they were most frequently represented in the data. The confidence limits for more common site types being afforested were generally low (± 2.0 – 3.5 $m^3ha^{-1}yr^1$), but for less-well represented combinations the confidence limits were wider (i.e. rocky outcrops). The practical model [2] is not, however, suited to assessing productivity on already afforested sites as it requires knowledge of habitat type prior to afforestation. The forecast model [3] was developed to address this shortcoming.

The level of precision of all the models presented here is adequate for use in operational forestry, but in some cases the predictions may not be any better than the subjective assessment of a site by an experienced forester who is familiar with the locality. However, the use of the model may be preferable. Subjective assessments are not always consistent or reliable and there are fewer foresters who have sufficient knowledge of enough local site factors to permit an accurate subjective site quality assessment. However, the models developed in this study may not adequately cope with the changing environmental conditions, i.e. climate change; thus a more specific process-based modelling approach may be required in future (e.g. Goodale et al. 1998).

Policy implications

The recent "Food Harvest 2020" report published by the Department of Agriculture, Fisheries and Food (DAFF 2010) has set dramatic growth targets for the agriculture, fishery and forestry sectors. The growth target for output from these three primary sectors is €1.5 billion by 2020. Within agriculture, the most ambitious growth target set is for milk output, where volume is set to increase by 50% by 2020. Importantly the growth targets set for all other sectors of agriculture are value rather than volume targets, which will mean that the achievement of these targets need not necessarily require the use of more or even the same amount of agricultural land. The question arises as to whether the achievement of these targets will negatively influence the attainment of forestry expansion targets, requiring an area of 22,850 ha to be planted per annum from 2010-2030. Given that forestry competes primarily with non-dairy farming enterprises, and given the high potential productivity of non-dairy land for forestry identified in this study, the achievement of the Food Harvest 2012 output growth targets are unlikely to conflict with the achievement of sectoral growth targets set for the Irish forestry sector.

Results of this study indicate that it is reasonable to assume that further forestry expansion can be achieved and that sectoral targets can be met by all sectors with adequate land-use planning. The results of our analysis suggests that the planting of an additional 457,000 ha of forests could likely be achieved using predominately marginal agricultural land, without greatly compromising agricultural productivity.

Acknowledgements
This study was funded by the Teagasc under the National Development plan 2007–2012.

The authors would especially like to thank Toddy Radford and Michael Bulfin (formerly of Teagasc, now retired) for permission to use data from the General Soil Map of Ireland and who provided much of the inspiration for this study carrying out much of the earlier soil and forest productivity work in Teagasc.

Thanks are also extended to John Connolly of the UCD School of Mathematical Sciences and Jim Grant of Teagasc for statistical advice. Special thanks to Coillte for access to stand information and forest sites, the Forest Service, Johnstown Castle, Co. Wexford for access to planting records, and private forest owners for access to their plantations. Thanks also to Rowan Fealy and the National University of Maynooth for permission to access and utilise climatic data and maps.

References

Anon. 1996. *Growing for the Future - A Strategic Plan for the Development of the Forestry Sector in Ireland*. Department of Agriculture, Food and Forestry. The Stationery Office, Government Publications Sales Office, Molesworth Street, Dublin.

Anon. 2003. *Wind Atlas of Ireland*. Technical report No. 4Y103A-1-R1, Sustainable Energy Ireland, Glasnevin, Dublin 9.

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

Blyth, J.F. and MacLeod, D.A., 1981b. Sitka spruce (*Picea sitchensis*) in North-East Scotland: 2. Yield prediction by regression analysis. *Forestry* 54: 63-73.

Bulfin, M., Gallagher, G. and Dillon, J. 1973. Forest Production. In *County Leitrim Resource survey, Part 1- land-use Potential (Soils, Grazing Capacity and Forestry)*, Soil Survey Bull.

29, An Foras Talúntais (now Teagasc), Oakpark, Co. Carlow. pp. 49-56.

DAFF. 2010. *Food Harvest 2020: A Vision for Irish Agri-Food and Fisheries*. Department of Agriculture, Fisheries and Food, Dublin.

Edwards, P.N. and Christie, J.M. 1981. Yield Models for Forest Management. Forestry Commission Booklet No. 48, HMSO, London, UK.

ESRI. 2008. *ArcGIS 9.3 Users Guide*. Environmental Systems Research Institute, Redlands, CA, USA.

Farrelly, N. 2003. Forest Productivity a Key Layer in the Forest Inventory and Planning System. *COFORD Forest Policy and Planning Conference*, Tullamore 23rd May 2003. Presentation available online at http://www.teagasc.ie/forestry/docs/research/2003%20COFORD%20Forest%20planning%20and%20policy%20conference%20May%202003.pdf

Farrelly, N. 2007. The farm forest resource in Ireland: opportunities and challenges for rural development in Ireland. *Small-scale Forestry* 6: 49-64.

Farrelly, N. 2011. *Site quality and the productivity of Sitka spruce*. Unpublished Ph.D. Thesis, University College Dublin, Belfield, Dublin 4.

Farrelly, N., Bulfin, M. and Radford, T. 2002. Using geographical information systems and field classification methods to establish relationships between site, climatic factors and growth of Sitka spruce in Co. Mayo, Ireland. In *Proceedings of FAO/ECE/ILO seminar on afforestation in the context of sustainable forest mananagement*. Ennis, Co. Clare. 15th September 2002, pp. 191-207.

Farrelly, N., Ní Dhubháin, Á., Nieuwenhuis M. and Grant, J. 2009. The distribution and productivity of Sitka spruce (*Picea sitchensis*) in Ireland in relation to site, soil and climatic factors. *Irish Forestry* 66: 51-73.

Farrelly, N., Ní Dhubháin, Á. and Nieuwenhuis, M. 2011a. Site Index of Sitka spruce in relation to different measures of site quality in Ireland. *Canadian Journal of Forest Research* 41: 265–278.

Farrelly, N., Ní Dhubháin, Á. and Nieuwenhuis, M. 2011b. Sitka spruce site index in response to varying soil moisture and nutrients in three different climate regions in Ireland. *Forest Ecology and management* (in press). doi:10.1016/j.foreco.2011.08.012

Fealy, R. M., Green, S., Loftus, M., Meehan, R., Radford, T., Cronin, C. and Bulfin, M. 2009. Habitat indicator mapping. In *Teagasc EPA Soil and Subsoils Mapping Project - Final Report*. Volume I. Teagasc. Dublin.

Forest Service. 2010. *Forestry Statistics for Ireland 2010*. Forest Service, Johnstown Castle Estate, Co. Wexford.

Fossit, J.A. 2000. *A Guide to Habitats in Ireland*. The Heritage Council, Kilkenny.

Gardiner, M.J. and Radford, T. 1980. *Soil Associations and their land-use Potential. Explanatory Bulletin to Accompany the General Soil Map of Ireland*. An Foras Talúntais (now Teagasc), Oakpark, Co. Carlow.

Goodale, C.L., Aber, J.D. and Farrell, E.P. 1998. Predicting the relative sensitivity of forest production in Ireland to site quality and climate change. *Climate Research* 10: 51–67.

Gray, H.J. 1963. The Economics of Irish Forestry. *Journal of the Statistical and Social Enquiry Society of Ireland* 21(2): 18-24.

Hassall, R.B., MacMillan, D.C. and Miller, H.G. 1994. Predicting Sitka spruce yields in the Buchan area of north-east Scotland. *Forestry* 67: 219-235.

Joyce, P.M. and OCarroll, N. 2002. *Sitka spruce in Ireland*. COFORD, Dublin.

Klinka, K. and Chen, H.Y.H. 2003. Potential productivity of three interior subalpine forest tree species in British Columbia. *Forest Ecology and Management* 175: 521-530.

Loftus, M., Bulfin, M., Farrelly, N., Fealy, R., Green, S., Meehan, R. and Radford, T. 2002. The Irish Forest Soils project and its potential contribution to the assessment of biodiversity. In *Proceedings of the Royal Irish Academy, Dublin*, 102B:151-165.

MacMillan, D.C. 1991. Predicting the general yield class of Sitka spruce on better quality land in Scotland. *Forestry* 64: 359-372.

OCarroll, C. and Farrell, E.P. 1993. Relationships between soil characteristics and yield for Norway spruce on fen peat in central Ireland. *Forest Ecology and Management* 57: 61-70.

OCarroll, N. 1975. Fertiliser prescriptions (2nd ed.). *Research Communication No. 13*. Forest and Wildlife Service, Research Branch, Newtownmountkennedy, Co. Wicklow.

OCarroll, N. 1984. *The forests of Ireland – History, Distribution and Silviculture*. Society of Irish Foresters, Dublin.

OFlanagan, L.P. and Bulfin, M. 1970. Spruce growth rates on drumlin soils. *Irish Forestry* 27: 4-9.

Pearson, A. F. 1992. *Relationships between site index of Sitka spruce* (Picea sitchensis *(Bong.) Carr.) and measures of ecological site quality in the eastern Queen Charlotte Islands*. M.Sc. Thesis. Faculty of Forestry, University of British Columbia, Vancouver, British Columbia.

Sweeney, J. and Fealy, R. 2003. Establishing reference climate scenarios. In *Chapter 2: Climate change scenarios and impacts for Ireland*. Final report. Environmental Protection Agency, Johnstown Castle Estate, County. Wexford, Ireland. pp. 5-31.