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Original article

Predicting the yield of Douglas fir from site factors on better quality sites in Scotland

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Summary — In Scotland, as a result of recent changes in agricultural policy and grant schemes, there is now greater potential for planting a wider range of more productive forestry species on better quality land. In order to permit accurate production forecasting and financial appraisals for any such afforestation, it is necessary to develop predictive yield models. This article describes the development of a multiple linear regression model for the prediction of General Yield Class (GYC) of Douglas fir using readily assessed, or derived, site factors. Climate surfaces developed by spatial analysis of weather data were used to predict temperature and rainfall for 87 sample sites to a resolution of 1 km^2. Estimates of wind climate were derived from a regression model using geographic location, elevation and topographic exposure. Multivariate analysis of these and other soil and topographic variables indicate that temperature and exposure are most important in determining the productivity of Douglas fir on better quality sites in Scotland. As crop age increases, GYC declines and the possible reasons for this effect are discussed. Other factors are also discussed, such as the genetic variability of Douglas fir, and problems associated with establishment and form.

Douglas fir / productivity / yield models / site factors / climate

Résumé — Prédire la production du douglas à partir de facteurs stationnels sur des terrains de meilleure qualité en Écosse. *Suite aux récents changements de politique agricole et de schémas d'attribution des subventions, il existe actuellement en Écosse de nouvelles possibilités pour planter un éventail plus large d'espèces forestières plus productives sur des terres de meilleure qualité. Afin de prédire de façon précise les productions et les implications financières de tels reboisements, il est nécessaire de développer des modèles de prédiction des productions. Cet article présente le développement d'un modèle de régression multilinéaire de prédiction des classes générales de production du douglas en utilisant des facteurs stationnels mesurés directement. Des surfaces climatiques, obtenues par une analyse spatiale des données climatiques, ont été utilisées pour prédire la température et la pluviométrie de 87 sites échantillons à une résolution du km^2. Des estimations du vent ont été obtenues en appliquant un modèle de régression linéaire utilisant la localisation géographique, l'altitude et l'exposition. Une analyse multivariée incorporant les 2 précédents aspects plus des variables décrivant* *le sol et la topographie montre que la température et l'exposition sont les 2 principales variables expliquant la productivité du douglas sur des terrains de meilleure qualité en Écosse. On discute ensuite la contribution d'autres facteurs, tels que la variabilité génétique du douglas et les problèmes liés à l'établissement et à la forme.*

douglas / productivité / modèle de production / facteur stationnel / climat

INTRODUCTION

In the European Union, tree planting on agricultural land is seen as a way to reduce agricultural production, diversify farm income and provide a range of environmental benefits. In the United Kingdom, special grants to encourage afforestation are available under the Farm Woodland Premium Scheme and uptake by farmers has been high. Although timber production is an important objective, little is known about the potential productivity of species other than Sitka spruce for many agricultural regions of Scotland. These considerations, and the requirement for better strategic forecasts of wood flows, have given rise to the need for site yield models for species suitable for better quality land. Douglas fir (*Pseudotsuga manziesii* [F] Mirb) is a potentially high yielding species that presently provides an alternative to Sitka spruce for better quality sites, and was chosen as the subject of this study.

In its natural habitat, Douglas fir covers a very wide geographic and climatic range from British Columbia to New Mexico. It was first introduced to Britain in 1826–1827, and became more widely planted from the 1850s onwards (MacDonald *et al,* 1957). Due to the phenotypic variation observed within its natural range (Peace, 1948), and the fact that UK rainfall and temperature regimes are similar only to a very small part of the entire range of Douglas fir, the need for attention to seed sources for importation was soon realised. Good stands were produced from seed imported in the early 1920s from the Lower Fraser Valley in British Colombia, but the form of stands from some later importations has not been as good (Phillips, 1993).

Britain's climate is temperate oceanic, and wind is therefore an important factor limiting tree growth (Pears, 1967; Grace, 1977; Dixon and Grace, 1984), particularly in exposed situations (Worrell and Malcolm, 1990a). Scotland's position is at higher latitudes than the extent of Douglas fir on the American continent, and although the climate is moderated by the Gulf Stream, mean temperatures are well below the broad optimum of 20°C that has been recorded for Douglas fir (Clearly and Waring, 1969). In addition, a greater proportion of the annual rainfall in Scotland occurs during the summer months than in the Pacific Coast region (Wood, 1962).

Existing site yield models are limited in their coverage of Douglas fir, although a model for England and Wales has been developed recently (Forestry Commission, 1993). In Scotland, there has been one quantitative study limited to the Perthshire region (Dixon, 1971), although general guidelines have been produced for eastern areas (Busby, 1974). In Dixon's study, topex score (which is the sum of the angles to the horizon at the 8 cardinal points of the compass) was the single most significant factor affecting productivity, explaining 32–69% of the variation in yield. In a study in North Wales, elevation, soil type and texture, as well as indices of topographic position and shape, were all significantly related to top height at 50 years (Page, 1970).

The success of site yield studies aiming to elucidate the relationships between yield and environment for Douglas fir have been variable, even within its natural range. Monserud *et al* (1990) attributed part of the cause of poor correlations between site and soil factors, and height growth on the wide genetic variation of Douglas fir. Decourt *et al* (1979) had similar problems with poor correlations in a study in the Massif Central in France, and suggested that the absence of mycorihizal associations could also have contributed. Hill *et al* (1948) had better success correlating soils and site index within a single climatic region in Washington state. An investigation of the respective contributions of genotype and environment to site index variation by Monserud and Rehfeldt (1990), again in Washington state, indicated that genotype (as assessed by 3-year seedling heights) was a third more important than the current environment in determining the variation in dominant height in natural stands. Genetic variability is also evident in the United Kingdom. For example, an investigation of tree growth patterns within Forestry Commission permanent sample plots indicated that differences in growth rate were not attributable to site factors (Christie, 1988).

The aim of this study was to develop site yield models which could predict the potential productivity of Douglas fir at the stand, forest and regional level throughout Scotland. As end users differ in the information they have available, 2 regression models were developed, 1 incorporating climatic data developed using trend surface analysis and kriging (Matthews *et al,* 1995), and a second that employs data that can be readily collected in the field. Principal component analysis (PCA) was used to assist interpretation of the ecological nature of the relationships between yield and site factors. The precision and accuracy of the Douglas fir models were tested with an independent data set. These models aid the assessment of the economic costs and benefits associated with planting Douglas fir.

METHODS

General Yield Class (GYC) is conventionally used to estimate site productivity for forest crops in the United Kingdom and measures the mean annual growth rate of timber (m^{-3}), per hectare (ha^{-1}) per year (yr^{-1}), over the rotation period. It is derived from the relationship between height growth and volume and is estimated from the mean top height and age of the stand (Edwards and Christie, 1981).

Factors known to influence tree growth in Scotland were identified from previous studies and a review of the literature. Eighty-seven temporary sample plots of 0.04 ha were randomly located on sites throughout Scotland where site and soil factors could be accurately assessed. The procedure for the collection of field data and the derivation of climatic data are described later. (A full list of all the variables assessed for each site with abbreviations is given in *Appendix 1*.)

Sampling

As the study focused on better quality land, sampling targeted sites below 350 m in both state and private estate ownership. Pure stands between 20 and 60 years old were visited at the locations illustrated in figure 1. The lower age restriction avoids problems associated with estimating productivity accurately for younger stands from published GYC curves and the incomplete expression of site potential (Coile, 1952), while 60 years is generally the maximum rotation length. Plots were randomly located within compartments, avoiding possible edge effects, small scale variations in topography or drainage and areas of windthrow.

Field data collection

For each site, soil drainage, site drainage, major soil group and rooting depth were assessed from a soil pit at the centre of a 0.04 ha plot. The soil drainage classification is based on profile colours, position in the landscape and the permeability of underlying horizons. It consists of 5 categories: excessive, free, imperfect, poor and very poor (Soil Survey of Scotland, 1984). Site drainage consists of 3 categories: shedding, normal and receiving, which were determined by subjective assessment of the net moisture status of the site and its topography. Topex score was used as an objective measure of geomorphic shelter. It is assessed by summing the angle to the horizon at the 8 cardinal points of the compass. Other factors such as elevation, national grid reference, slope and aspect were also recorded for the 87 plots. For the purposes of analysis, aspect was transformed using sine and cosine functions into north-south and east-west components, and grid reference was converted to easting and northing by replacing the 100-km grid square letters with numbers. The precision of easting and northing is to the nearest 100 m.

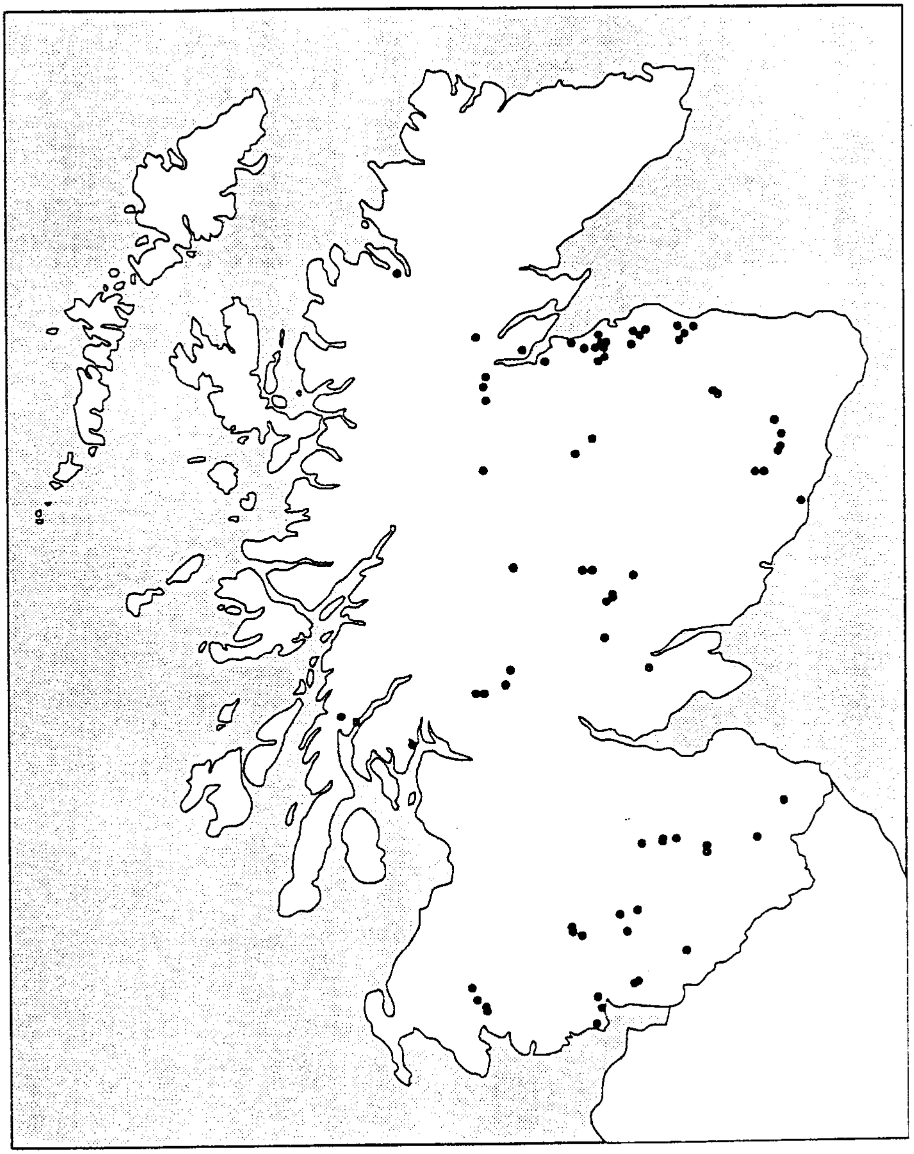

Fig 1. Location of Douglas fir sample plots (●) on better quality land in Scotland.

Climate data

The best relationships achieved to date for a site yield study in Britain used regression equations to spatially and altitudinally extrapolate meteorological station data (Worrell and Malcolm, 1990a). More recently, work by the Climate Change Group at the Macaulay Land Use Research Institute has taken this approach further. The regional climate in Scotland has been modelled to a kilometre grid square resolution using a combination of trend surface analysis and kriging for the spatial interpolation of meteorological station records (Matthews *et al,* 1995). These "climate surfaces" are based on data of 30-year means of monthly temperature records from 150 stations for the period 1951–1980, and 1 500 rainfall stations for the period 1941–1970. The kilometre grid cell estimates for each site were extracted from these surfaces, and adjusted to the specific elevation of each sample site using standard monthly lapse rates.

There are a large number of climate indices that can be derived from mean monthly records of temperature and rainfall, so consideration was restricted to those likely to promote or inhibit growth. The indices investigated were mean spring temperature (April to June), mean summer temperature (July to September), mean winter temperature (December to February), mean annual accumulated temperature above 5.6°C, mean spring rainfall, mean summer rainfall and mean total annual rainfall. The overall mean annual temperature was divided by mean rainfall to give a measure of the effectiveness of precipitation.

Cotton "tatter" flags are an established method for assessing wind climate in upland Britain, with the rate of attrition of the unhemmed flags dependant on mean wind speeds (Rutter, 1968; Jack and Savill, 1973). Differences in tatter rates between sites have been related to elevation and geographic location (Worrell and Malcolm, 1990a) and the Stability Project Group of the Forestry Commission Northern Research Station have used these relationships to develop a regression model for the prediction of tatter. It is their estimates of tatter that are used in this analysis.

REGRESSION ANALYSIS

End users vary in the information they have available for input to such models and differ in their requirements from the predictions. Models that predict productivity most accurately are often not readily applied in the field, so a "best fit" model and a model employing only field measurements will be developed.

Initially, all the independent variables listed in Appendix 1 were included in the analysis. Forwards stepwise multiple linear regression analysis was used to derive the models as this is one of the best procedures for deriving regression equations by Draper and Smith (1981). Only variables that were significant at the 5% level or better were included in the models. The effects of soil factors were investigated using dummy variables (see Digby *et al,* 1989). An "average" regression line is used to calculate the displacement from this line due to each soil factor. Confidence intervals for predictions were calculated, and the models validated using an independent data set of 10% of the samples collected.

The mean and range of each variable used in the model development are given in table I. The range indicates the intervals within which it is generally valid to apply the model.

"Best fit" model

Graphical analysis of the trends in individual site variables with GYC did not reveal any relationships that could be considered nonlinear for the range of data. The "best fit" multiple linear regression model was developed using all available site, soil and climate data. The resulting model explains 45.5% of the variation in GYC, and its form is presented in model 1 and table II.

model 1

$$\text{GYC} = -24.57 + 5.24 * \text{SPRT} + 0.04109 * \text{TOPEX} - 0.1163 * \text{AGE} - 2.061 * \text{WINT}$$

Adjustement for SITEDR (shedding): None

Adjustment for SITEDR (normal):

$+ 1.6\ \text{m}^3\text{ha}^{-1}\text{yr}^{-1}$ $R^2 = 0.455$ $n = 78$

Table I. Summary of ranges and mean values for the site and response variables.

Variable *(Abbreviation: units)*	*Minimum*	*Mean*	*Maximum*
Age (years)	20	36.3	54
Easting (EAST: m x 10^2)	1 867	2 966	3 840
Northing (NORTH: m x 10^2)	5 580	7 376	8 866
Elevation (ELEVN: m)	20	136	325
Slope (°)	0	13	30
Site drainage (SITDR)[a]	–1	–0.19	0
Major soil group (MSG)[b]	0	1.2	2
Topex (°)	3	50	144
Mean spring Temperature (SPRT: °C)	8.2	9.2	10.1
Total annual rainfall (TOTR: mm)	680	1 113	2 739
General Yield Class (GYC: $m^3ha^{-1}year^{-1}$)	10.6	17.3	24.2

[a] Site drainage classes: -1 shedding; 0 normal; 1 receiving; [b] major soil groups: 0 brown earth; 1 gley; 2 Podzol.

SPRT and TOPEX were most closely correlated with yield, together explaining 29.9% of the variation in GYC; AGE and WINT were selected subsequently. The slope *(b)* coefficient for mean spring temperature is positive, reflecting higher productivity of Douglas fir at lower elevations and at more southerly latitudes. The effect of age in the model is to increase productivity either for younger crops, or crops that have been planted more recently. This could be due to a number of factors, such as increased nitrogen deposition or genetic improvements, though advances in site amelioration techniques are most probable. The correlation between WINT and GYC is negative. This is unexpected but since SPRT and WINT are highly correlated, and the variation in GYC due to spring temperature has already been accounted for in the model, the effect of WINT may actually reflect a statistical relationship between GYC and another site factor not included in the final model but which is correlated to WINT. As could be expected, the effect of increasing geomorphic shelter is to increase productivity.

Tests of the effects of qualitative soil variables in the model resulted in the addition of SITEDR. The 2 drainage categories to which the model can be applied are shedding sites and sites with normal subsurface through drainage[1]. Model 1 predicts that GYC will be greater on sites with "normal" through-drainage by 1.6 $m^3ha^{-1}yr^{-1}$.

In order to assess the precision of the models over a range of sites, the GYC and

Table II. Estimates and *t* values of regression coefficients for "best fit" model (model 1).

	b *Estimate*	*Standard error*	*t value*	R^2
Constant	–24.57	8.13	–3.02	0.455
SPRT	5.24	1.06	4.94**	
Topex	0.04109	0.00852	4.82**	
Age	–0.1163	0.0387	–3.00**	
WINT	–2.061	0.831	–2.48*	
SITEDR (normal)	1.625	0.695	2.34*	

* $P < 0.01$; ** $P < 0.001$. Abbreviations as in table I.

associated confidence interval (CI) were predicted from the model for 3, quite different, hypothetical sites. Two of these are extreme sites, and the third is more typical (table III). The low yielding site is an older stand on a high, exposed site with low temperatures during the spring, and the high yielding site is the opposite: a younger stand at low elevation in the bottom of a sheltered valley.

Confidence intervals have been calculated for 2 situations; first, the prediction of the mean GYC for all cases in the population, and second, the estimate of a single new site. The intervals for a single new prediction are wider than for the mean as the variation of individual variables about their means (*ie* residual mean squares) is included. The first case is of interest when considering the average yield for large areas of land with a particular combination of site factors, such as for regional assessments of productivity. The second case arises when predicting GYC for single small blocks of land such as at replanting or prior to land acquisition.

The GYCs predicted for the low and high yielding sites are 14.4 and 22.5 $m^3ha^{-1}yr^{-1}$, respectively, and 18.2 $m^3ha^{-1}yr^{-1}$ for the typical site. The 95% CI for the mean GYC for the site ranged from ±0.7 for the typical site to ±2.4 $m^3ha^{-1}yr^{-1}$ for the high yielding site. The range for a single new site was greater and ranged from ±4.8 to ±5.3 $m^3ha^{-1}yr^{-1}$.

Validation

Nine independent plots were chosen randomly from the data set prior to model development to test the validity of model 1. One of these fell outside the 95% CI for a single new prediction (fig 2), although overall, the difference between the observed and predicted GYC values was small (–0.2 $m^3ha^{-1}yr^{-1}$). A single sample T test indicated this value was not significantly different from zero.

A "field" model

The regression model employing only site variables that can readily be assessed in the field is given in model 2 and table IV.

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[1] It proved difficult in practice to find sample sites that were "receiving", as such stands generally had inadequate survival or suffered windthrow. As there were only 2 "receiving" sites sampled, they were omitted from the data.

Topex and elevation explained 19.5% of the variation in GYC, and age increased the R^2 to 0.271. The addition of northing, and major soil group as a dummy variable, improved the R^2 to 0.413.

model 2

GYC = 32.3 – 0.04566 * TOPEX – 0.01332 * ELEVN – 0.1506 * AGE – 0.00156 * NORTH

Adjustments for Major Soil Group (brown earth): None

Adjustments for Major Soil Group (podzol): +2.6 $m^3ha^{-1}yr^{-1}$ $R^2 = 0.413$ $n = 78$

Again the effect of climate on GYC is evident with the inclusion of topex and elevation. The combination of elevation and northing appears to replace the role of the temperature indices by incorporating both the geographic location and elevation aspects of temperature variation. The slope coefficients for topex and age indicate that the variables are acting in the same manner as described for model 1.

Table III. Predicted General Yield Class (GYC) for a range of site types in Scotland using "best fit" model (model 1).

Variables	*Site type* *Low yielding*	 *Average*	 *High yielding*
SPRT (°C)	8.9	9.3	9.9
Topex (°)	10	60	110
Age (years)	51	38	27
WINT (°C)	1.8	2.7	3.0
SITEDR	–1	–1	0
Predicted GYC ($m^3ha^{-1}yr^{-1}$)	14.4	18.2	22.5
95% CI for mean estimate	± 2.0	± 0.7	± 2.4
95% CI for single estimate	± 5.1	± 4.8	± 5.3

CI = confidence intervals; other abbreviations as in table I.

Table IV. Estimates and *t* values of regression coefficients for "field" model (model 2).

	b *Estimate*	*Standard error*	*t value*	R^2
Constant	32.2	2.96	10.89	0.413
TOPEX	0.04566	0.00921	4.96*	
ELEVN	–0.01332	0.00373	–3.57*	
Age	–0.1506	0.0401	–3.75*	
NORTH	–0.0156	0.000363	–4.30*	
MSG	2.616	0.818	3.20*	

* $P < 0.001$. Abbreviations as in table I.

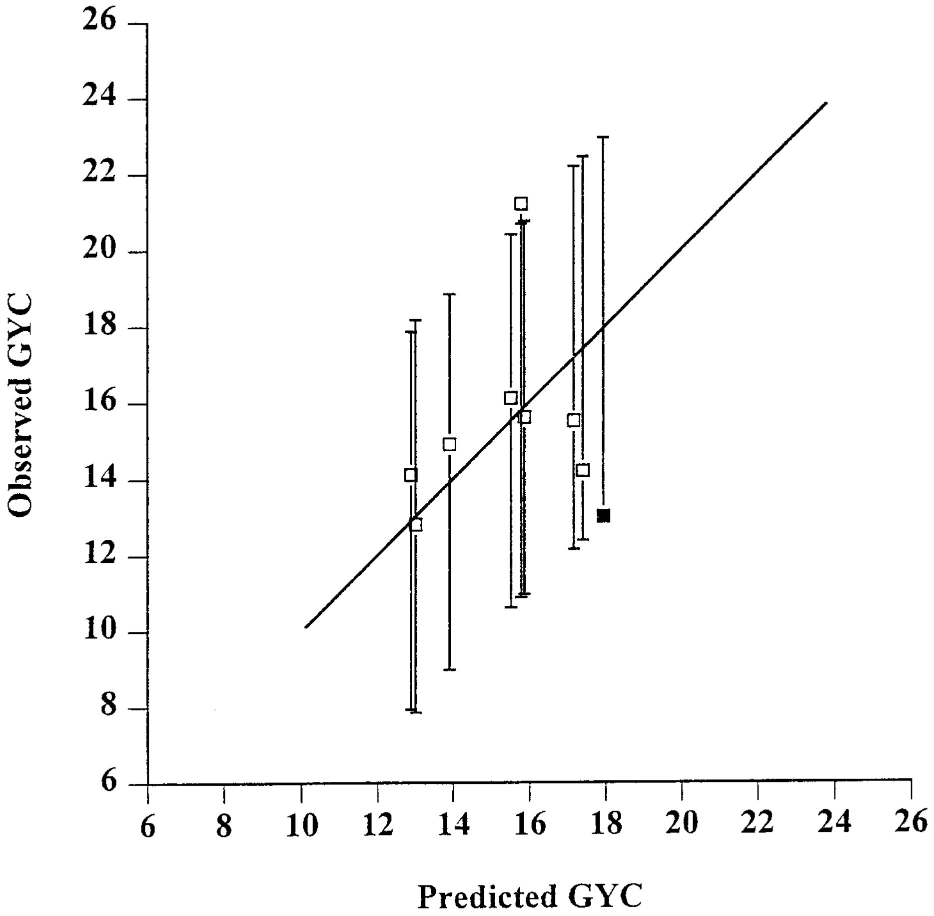

Fig 2. Predicted and observed General Yield Class (GYC) using the "best fit" model (model 1) with 95% confidence intervals. The range of observed GYC values is represented by the line.

As with SITEDR, the soil types to which model 2 can be applied are restricted. There were not suffificent sites with gley soils for analysis as the majority of sites were either brown earths or podzols. Model 2 predicts GYC for brown earth sites, with an adjustment of +2.6 $m^3ha^{-1}yr^{-1}$ being applied to the regression model for podzolic soils.

As for the "best fit" model, hypothetical site values were used to test the effectiveness of "field" model predictions for 2 extreme sites and a typical site (table V). The predicted GYCs were 10.4, 23.6 and 18.7 $m^3ha^{-1}yr^{-1}$, respectively. In 95% of the cases, the true mean GYC value will lie between ±0.9 and 2.3 $m^3ha^{-1}yr^{-1}$, which is sufficiently precise for practical application to large forest areas. The true value for a single site prediction will lie within a maximum range of ±5.1 to ±5.7 $m^3ha^{-1}yr^{-1}$, which is too wide a range to provide any improvement over a local forester's educated guess.

Validation

The same independent data set was used for validation. Again one site fell outside the 95% CI for single predictions (fig 3). Although there is a difference between observed and predicted values of GYC of -1.2 m^{3}ha^{-1}yr^{-1}, the single sample *t* test is not significant ($t\,\text{value}_{8\text{df}} = -2.03$). Models 1 and 2 do not predict accurately the high yield class observed for 1 site (shown as ■ in figs 2 and 3). This site was located on a moderate slope with a very good subsurface water supply.

PRINCIPAL COMPONENT ANALYSIS

Principal component analysis (PCA) is a data reduction technique which uses weighted linear combinations of each of the original variables to form a new set of independent variables. The first component will be oriented to explain as much of the variation as possible in the data by minimising the residual sum of squares, as will the second, and so on (Digby *et al,* 1989). The technique is most effective when there are strong gradients explaining a large proportion of the variation in the data, otherwise interpretation is less straightforward and the purpose is somewhat defeated. An advantage of PCA is the fact that each component is orthogonal, and employs some part of all the variables.

The principal components obtained from analysis were then correlated with GYC. The variables having the greatest effect on GYC were then determined from significance levels and the standard errors of the regression coefficients. The value and sign of the weights (or loads) of the variables in each component were used to interpret processes or relationships between variables.

Results

The fourth principal component 4 (PC[4]) was the component most highly correlated with GYC (table VI). The load values indicate that it is predominantly an age effect. The correlation coefficient is positive, reflecting a decrease in GYC as age or planting year increases. This effect is the same as that demonstrated in the multiple linear regression analysis. The load values of PC[2]

Table V. Predicted General Yield Class (GYC) for a range of site types in Scotland using the "field" model (model 2).

Variables	*Site type*		
	Low yield	*Average yield*	*High yield*
Topex (°)	10	60	110
ELEVN (m)	300	135	50
Age (years)	51	38	27
NORTH	8 500	7 300	5 700
MSG	2	2	0
Predicted GYC (m^{3}ha^{-1}yr^{-1})	10.4	18.7	23.6
95% CI for mean estimate	± 2.3	± 0.9	± 2.0
95% CI for single estimate	± 5.7	± 5.1	± 5.5

Abbreviations as in tables I and IV.

describe a trend of decreasing rainfall with a progression towards the northeast of Scotland. This acts in a negative manner, reflecting a decrease in GYC on more northerly and easterly sites a a result of lower annual rainfalls. The third component is also correlated with GYC, probably due to the high load value for topex. The effect on GYC is the same as in the previous models as both the load and correlation are negative, giving a net positive effect of increasing geomorphic shelter on GYC.

PC[1] has been included in table VI because it describes the negative relationship between elevation and temperature which features in the regression models, although, contrary to the results of models 1 and 2, it is not significantly correlated with GYC. It includes a topographic trend with sites at lower elevations, which tend to occur in areas with flatter terrain and lower topex scores. This may help to explain the apparently ambiguous load values for slope in PC[8].

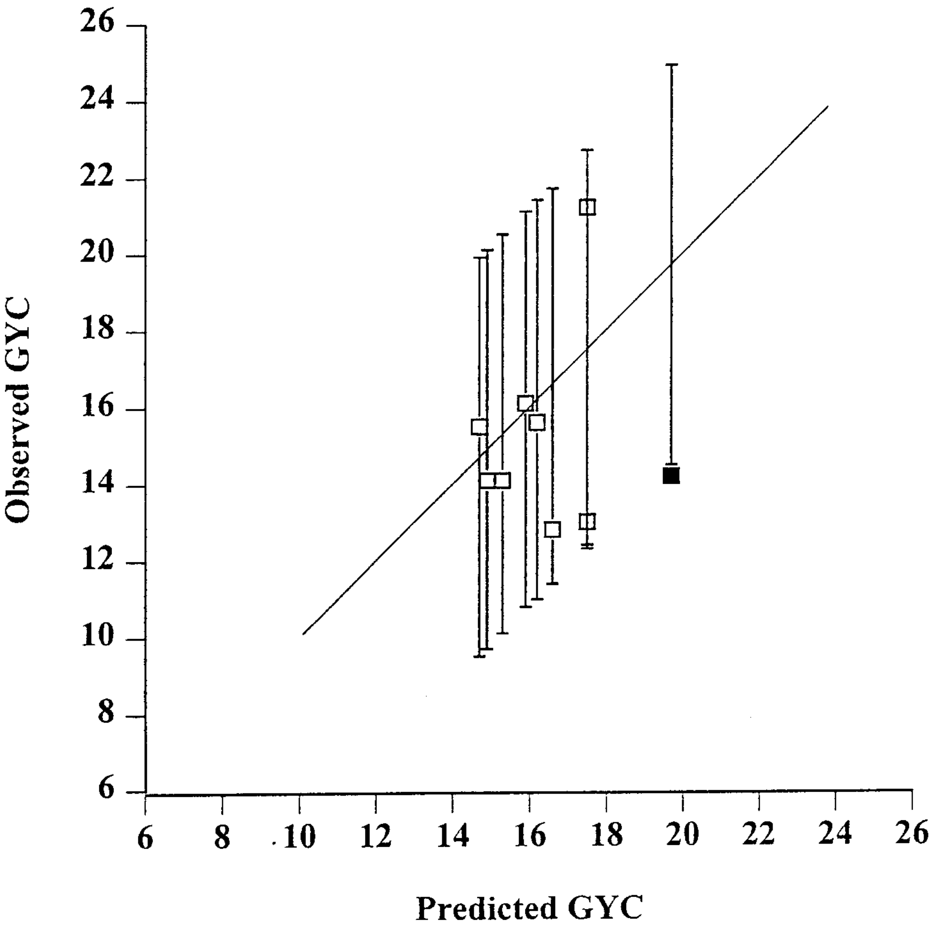

Fig 3. Predicted and observed General yield Class (GYC) using the "field" model (model 2), with 95% confidence intervals. The range of observed GYC is represented by the line.

Table VI. Load values, roots and correlation coefficients with General Yield Class (GYC) for 4 of the principal components (PC).

Variable	*PC load values*			
	4	*2*	*8*	*1*
EAST	0.0300	0.4634	0.1288	–0.1278
NORTH	–0.1018	0.4011	0.0844	–0.0628
ELEVN	–0.1277	0.0404	–0.2263	–0.5358
Age	–0.8999	–0.2287	0.0556	–0.0491
Slope	0.3004	–0.3027	0.6409	–0.4355
Depth	0.0045	0.2037	0.0082	–0.1958
Topex	0.1861	–0.3433	–0.6318	–0.4312
SPRT	0.1911	–0.2032	0.2076	0.5203
TOTR	–0.0361	–0.5274	0.2625	0.0746
Percentage variance	10.5	27.1	2.2	27.9
Correlations with GYC	0.452	–0.344	–0.217	0.083

Abbreviations as in table I.

DISCUSSION

From the results of the regression analysis, it is evident that both temperature and topographic exposure are 2 of the principal influences determining the productivity of Douglas fir on better quality sites in Scotland. This concurs with site yield studies on Douglas fir conducted over smaller areas for parts of Britain (Page, 1970; Dixon, 1971). When climatic data are not available, elevation performs a similar function to that of temperature without a major loss in predictive power in model 2. The selection of mean spring temperature over other temperature indices is not surprising since spring is the main period of height extension.

Regression model 1 explained 45.5% of the variation in GYC. For predictions over large areas such as might be done for regional wood flow, forecasting the 95% confidence intervals for predictions of mean GYC vary between ±0.7 $m^3ha^{-1}yr^{-1}$ for average sites to ±2.4 $m^3ha^{-1}yr^{-1}$ for more extreme sites. These intervals are reasonable and should provide adequate predictions for strategic wood flow forecasts. The CIs for predictions made for individual sites lie between ±4.8 and ±5.3 $m^3ha^{-1}yr^{-1}$, which are probably too wide to be of use as the entire range of observed GYC was 13.6 $m^3ha^{-1}yr^{-1}$. The combination of elevation and northing appears to replace the role of the temperature indices by incorporating both the geographic location and elevation aspects of temperature variation. The 95% confidence intervals for mean predictions are wider than those for the "best fit" model, reflecting a loss of precision of ±0.2 $m^3 ha^{-1}yr^{-1}$ for estimates made on a regional scale, and by ±0.3 to 0.6 $m^3ha^{-1}yr^{-1}$ for single site estimates.

The effect of age on GYC is consistently negative, so either younger crops, or more recent plantings, are higher yielding. It is not possible to determine from this study whether the effect arises from the crop age or the time at which the crop was planted.

The former case implicates the form of the GYC curves, and it should be possible to investigate this further through stem analysis of individual tree growth rates. Planting date is, however, a more likely cause since improvements in site amelioration techniques and seed provenance are likely to have raised the productivity of Douglas fir considerably over the past 40 years. Environmental pollution could be both an age and planting year effect because the deposition could change continuously both during crop rotation periods, and from one rotation to the next. The same effect has been reported in recent years for Sitka spruce (Worrell and Malcolm, 1990b; Macmillan, 1991) and other species (Forestry Commission, 1993).

Model 2 predicts that on sites with podzol soils, the average GYC will be higher than brown earths by ±2.6 $m^3ha^{-1}yr^{-1}$. This contrasts with Dixon (1971), who proposed that Douglas fir could tolerate exposure better on more fertile sites. This could be related to general differences in soil texture, as the best root penetration of Douglas fir occurs on fine, well-drained, dry, podzolic brown earths (Kupiec and Coutts, 1992). This agrees with Murray and Harrington (1990), who found that fertility did not appear to be a factor limiting growth on former farmland sites in western Washington state. Models 1 and 2 cannot be applied to peaty or gley soils, or moisture-receiving sites. Very few stands on such sites visited during this study were stocked to an acceptable level, as they had either suffered high mortality or windthrow.

The principal component analysis result was not in complete agreement with that of the regression analysis. The component describing age (PC[4]) was most highly correlated with GYC, although this could be due more to the fact that it acts on GYC directly. The second component (PC[2]) described a limitation in moisture supply in the northeast of Scotland. Although the limitation on growth imposed by moisture deficits have been demonstrated in the same area for Sitka spruce (Jarvis and Mullins, 1987), the rainfall indices were not significantly related to GYC in the multiple linear regression analysis in this study. Site drainage was significant in regression model 1, and provides a crude reflection of soil moisture supply. The influence of topex and temperature or elevation, indicated by the regression analyses, are not apparent in the PCA result. The effect of topex appeared to be confounded by gross regional differences in topography. Macmillan (1991) also found no single factor to have an overriding influence on the yield of Sitka spruce on better quality sites in Scotland.

A large proportion of the variation in GYC remained unexplained. Genetic differences due to provenance and seed origin were identified from the literature as likely causes. According to Forestry Commission annual records, there were several main North American seed exporters who supplied seed during the period 1943–1960. They were largely based in northwest Washington state, but, even within this region, there are extremes of climate and considerable variations in the growth of Douglas fir.

Total rooting depth was not important for the sites sampled in this study, despite a number of North American studies demonstrating total effective soil depth to be an important factor affecting the productivity of Douglas fir through its influence on water and nutrient supply, root respiration and physical space and stability (Hill *et al*, 1948; Lemmon, 1955; Steinbrenner, 1965). Related variables such as soil texture, density and aeration can also be important. Similarly, observations have been made relating adverse rooting conditions to a decrease in height increment and crown density in Britain (Day, 1963).

The ability of a soil to maintain a moisture supply to the roots during the summer months is important for high yields (Hill *et al*, 1948; Contreras and Peters, 1982; Murray and Harrington, 1990), although too much summer rain in Scotland could be the cause of the deterioration in form from northeast to southwest in the Great Glen. If growth continues through summer when moisture is available, new shoots would be vulnerable to deformation by wind (Fletcher, personal communication). This sensitivity to wind has been observed as dieback in new plantations and as damage to leading shoots in mature stands when tops extend above surrounding canopies (Darrah *et al,* 1965).

A general problem with site yield models and GYC system is that no account is taken of the quality of the timber, which can have important economic consequences in some instances. A number of stands were encountered during sampling which had above average height growth but tree form was poor. Typically, such trees were coarsely branched with waves or spirals evident in the trunks between nodes. Lines (1987) suggested that the summer rainfall, higher wind speeds or the long summer day lengths could be the cause of stem sinuosity. In addition, basal sweep occurs frequently in Scottish stands, although it is not always associated with other defects. The root spread of Douglas fir in Britain is very limited during the first 5 years of growth (Kupiec and Coutts, 1992), and this pattern of initial allocation of biomass to the crown at the expense of the root system could be a factor contributing to the basal sweep. Instability is evident in young stands in open field situations where good soil fertility could be promoting canopy development without corresponding development in the root system. Exposure to winds, poor planting techniques and a root restricting layer could all aggravate the problems. Similar problems with form have occurred in British Columbia with plantings on ex-arable fields, although the cause is not known (Nixon, personal communication).

Two principal areas requiring further investigation were identified during the course of the study. The crop age/planting year effect has been demonstrated consistently in recent studies and is an aspect of site yield studies in Britain that requires investigation if the future application of the models is to be valid. Additional unaccounted variation in GYC could have arisen in this study from the lack of a variable accurately reflecting plant available moisture. Rainfall indices are not good measures of moisture supply for forest conditions because major losses occur to interception, particularly during the summer months (Jarvis and Mullins, 1987). The synthesis of rainfall, interception losses, potential evaporation and soil water holding capacity on a regional scale may improve model predictions.

CONCLUSION

1) Temperature, topex and crop age are the main factors determining the productivity of Douglas fir on better quality sites in Scotland and can be used to predict GYC for brown earths and podzols on sites below 350 m in Scotland.

2) The level of precision of the predictions for GYC from regression model 1 are adequate for strategic modelling of wood flow. In 95% of the cases, the true value for the mean GYC will lie within 0.7 $m^3ha^{-1}yr^{-1}$.

3) When estimates of temperature indices are not available, elevation performs a similar function to temperature indices with a loss of precision of GYC estimates on the order of 0.2 $m^3ha^{-1}yr^{-1}$.

4) Neither the "best fit" model nor the "field" model was sufficiently precise to be of practical value in estimating GYC for an individual site.

5) The development of a methodology for estimating available water or soil moisture deficit for trees that can be applied on a

Appendix 1. The site, soil, climatic and response variables assessed for each site, and their units.

Abbreviation	*Continuous variables*	*Units*
ID	Plot number	
EAST	Easting	m x 10^2
NORTH	Northing	m x 10^2
ELEVN	Elevation	m
AGE	Age	years
SL	Slope	°
ASP	Aspect	°
TOP	Topex	°
RD	Rooting depth	cm
TAT	Tatter	$cm^2\ d^{-1}$
SPRT	Mean spring temperature (April to June)	°C
SUMT	Mean summer temperature (July to September)	°C
WINT	Mean winter temperature (December to February)	°C
ACCT	Accumulated temperature above 5.6°C	°C
SPRR	Spring rainfall (seasons as above)	mm
SUMR	Summer rainfall	mm
WINR	Winter rainfall	mm
TOTR	Total annual rainfall	mm
MR/MT	Mean rainfall/mean temperature	mm/°C^{-1}
TOPHT	Top height	m
GYC	General Yield Class	$m^3ha^{-1}yr^{-1}$

Abbreviation	*Factors*	*Note*
MSG	Major soil group	1
PM	Parent material	2
SITEDR	Site drainage	3
SO	Soil drainage	4
TC	Topographic class	5

Notes on factors:

1. Major soil group: brown earth (0), gley (1), podzol (2)
2. Parent material: sand (1), alluvial (2), fluvio-glacial sands and gravels (3), glacial drift and moranic deposits (4), glacial till (5), glacial drift and residual material (6), residual material (7)
3. Site drainage: shedding (–1), normal (0), receiving (1)
4. Soil drainage: excessive (–2), free (–1), imperfect (0), poor (1)
5. Topographic class: bank (0), brow (1), ridge (2), slope (3), toe (4), plain (5)

regional scale may improve model predictions.

6) The "age effect", which consistently appears in recent site yield studies in Britain, requires specific investigation before the cause can be determined.

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